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Voorwoord (Preface)

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Sofie Verbrugge

Gent, 8 januari 2007.

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List of Acronyms

A

ADM	Add-Drop Multiplexer
ADSL	Asymmetric Digital Subscriber Line
AI	Augmentation Interval
AM	Administration
ASON	Automatically Switched Optical Network

B

B&S	Black and Scholes
BE	Break-Even
BIPT	Belgian Institute for Post and Telecommunications
BOM	Bill Of Material
BU	Bottom-Up

C

CapEx	Capital Expenditures
CAPM	Capital Asset Pricing Model
CC	Cable-Cuts
CCA	Current Cost Accounting
CD	Chromatic Dispersion
CI	Cost calculation Interval
CPE	Customer Premises Equipment
CWDM	Coarse Wavelength Division Multiplexing

D

DEMUX	demultiplexer

DF	Dark Fibre
DTA	Decision Tree Analysis
DWDM	Dense Wavelength Division Multiplexing
DXC	Digital Cross-Connect

E

E2E	End-to-End
EDFA	Erbium Doped Fibre Amplifier
EPM	Enterprise Management
ES	External Suppliers
eTOM	enhanced Telecom Operations Map
ETSI	European Telecommunications Standards Institute

F

FAC	Fully Allocated Cost
FCAPS	Fault, Configuration, Accounting, Performance, Security
FIT	Failures In Time
FLC	Forward Looking Cost

G

GMPLS	Generalized Multi-Protocol Label Switching
GbE	Gigabit Ethernet

H

HCA	Historical Cost Accounting
HR	Human Resources
HW	Hardware

I

IBBT	Interuniversitary Institute for Broadband Technology
IBCN	INTEC Broadband Communication Networks
IC	Incremental Cost
IETF	Internet Engineering Task Force
INTEC	Information Technology
ION	Intelligent Optical Network
IP	Internet Protocol
IRR	Internal Rate of Return
IRU	Indefeasible Right of Use
ISDN	Integrated Services Digital Network
ITU	International Telecommunication Union
IWT	Institute for Innovation through Promotion of Science and Technology

L

LbL	Link-by-Link
LION	Layers Interworking in Optical Networks
LR	Long Run
LRAIC	Long Run Average Incremental Costing
LRIC	Long Run Incremental Costing
LT	Line Terminal
LTE	Line Terminal Equipment
LTP	Long Term Planning

M

MEA	Modern Equivalent Asset
MEMS	Micro-Electro-Mechanical Systems
MPLS	Multi-Protocol Label Switching

MTBF	Mean Time Between Failures
MTL	Maximum Transparency Length
MTP	Medium Term Planning
MTTR	Mean Time To Repair
MUX	Multiplexer

N

NEM	Network Element Management
NM	Network Management
NMS	Network Management System
NNI	Network-Network Interface
NO	Network Operation
NOBEL	Next-generation Optical Networks for Broadband European Leadership
NOC	Network Operations Centre
NPV	Net Present Value
NRI	National Regulatory Instance

O

OADM	Optical Add-Drop Multiplexer
OAM	Operation Administration Maintenance
O/E	Optical-Electrical
O/E/O	Optical-Electrical-Optical
OIF	Optical Internetworking Forum
OpEx	Operational Expenditures
OPS	Operations
OSI	Open Systems Interconnection
OSS	Operations Support System
OTN	Optical Transport Network

OXC	Optical Cross-Connect

P

PC	Personal Computer
PFA	Produced Fixed Assets
PI	Prediction Interval
PM	Project Management
PMD	Polarization Mode Dispersion
POS	Packet Over SONET
PXC	Photonic Cross-Connect

R

RO	Real Options
ROADM	Reconfigurable Optical Add-Drop Multiplexer

S

SD	Sales Department
SDH	Synchronous Digital Hierarchy
SIP	Strategy, Infrastructure and Product
SLA	Service Level Agreement
SML	Security Market Line
SMP	Strong Market Position
SR	Short Run
STM	Synchronous Transport Module
STP	Short Term Planning
SW	Software

T

TBONES	Transparent Backbone Optical Network Simulator

TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TD	Top-Down
TDM	Time Division Multiplexing
TMF	TeleManagement Forum

U

UNI	User-Network Interface

V

VPN	Virtual Private Network

W

WDM	Wavelength Division Multiplexing

Nederlandstalige samenvatting (Dutch Summary)

Deze doctoraatsverhandeling bestudeert planningstechnieken die toelaten het dynamische en onzekere karakter van de inputparameters in rekening te brengen tijdens het proces van netwerkplanning. Gedurende de voorbije jaren zijn een aantal fundamentele veranderingen opgetreden in de telecomwereld. We kunnen drie drijvende krachten identificeren die deze wijzigingen in de hand hebben gewerkt. Ten eerste is er de voortdurende, snelle groei van de trafiek over het internet. Ten tweede zijn er een aantal belangrijke technologische doorbraken onder andere in het domein van de optische netwerktechnologie. Tot slot is er ook de wereldwijde liberalisering en globalisatie van de markt die het telecomlandschap substantieel gewijzigd heeft. Rekening houdend met deze vaststellingen is het duidelijk dat de planning van een huidig telecommunciatienetwerk een zeer complexe taak is. Het aantal gebruikers en de gevraagde services veranderen over de tijd. Dit beïnvloedt de trafiekhoeveelheden die moeten gerouteerd worden over het netwerk, evenals de te verwachten inkomsten voor de operatoren. Daarnaast veranderen ook de kosten om het netwerk uit te bouwen en operationeel te houden voortdurend. Een bepaald type netwerkapparatuur wordt typisch goedkoper met de tijd, terwijl een innovatieve technologie met nieuwe mogelijkheden op de markt kan komen. Toekomstige netwerktrafiek en componentkosten variëren niet enkel over de tijd, ze zijn bovendien ook nooit precies vooraf gekend. Om die reden wordt er met voorspellingen gewerkt, die van nature onnauwkeurig zijn. Deze onnauwkeurigheid wordt bovendien ook groter naarmate men verder in de toekomst tracht te voorspellen. Zowel met het dynamische als het onzekere karakter van de inputparameters moet rekening gehouden worden tijdens het netwerkplanningsproces.

Een netwerkoperator heeft als doel de wensen van de klanten te vervullen tegen zo laag mogelijke kosten om op die manier de vereiste inkomsten te genereren. Het doel van het netwerkplanningsproces bestaat erin de operator enkele richtlijnen aan te reiken om deze kosten-baten afweging op een gefundeerde manier te kunnen maken. Het gedurende dit doctoraatswerk verrichte onderzoek wil precies bijdragen tot het afleiden van enkele planningsrichtlijnen, die toelaten enkele specifieke aspecten van het planningsprobleem bij optische netwerken te beheersen.

De studies beschreven in deze doctoraatsverhandeling beschouwen optische telecommunicatienetwerken, die vandaag de basis vormen van heel wat kernnetwerken van belangrijke operatoren. Een optisch netwerk is immers een geschikt transmissiemedium om grote hoeveelheden trafiek over te versturen. Binnen de wereld van de optische netwerken, zien we een trend van punt-tot-punt optische communicatie tussen netwerkknopen die werken in het elektrische

domein naar schakelfaciliteiten op de optische netwerklaag, die toelaten grote hoeveelheden doorgaande trafiek aan hoge snelheden optisch door te sturen in intermediaire knopen. Recent kreeg het optische netwerk ook meer flexibiliteit dankzij het introduceren van een controlevlak, wat toelaat om geschakelde connecties op te zetten, naast de traditionele semi-permanente. Deze technologische doorbraken laten toe de manier waarop optische netwerken bestuurd worden fundamenteel te wijzigen.

Wat betreft het dynamische karakter van de netwerktrafiek en de componentkosten, vergelijkt ons onderzoek het gebruik van éénperiode planning, anticiperende planning en meerperiode planning en hun relatie met investeringsselectiemethoden. We tonen aan dat anticiperende planning, mits een geschikte keuze van het voorspellingsinterval, tot duidelijk betere resultaten kan leiden dan éénperiode planning, terwijl de rekencomplexiteit van meerperiode planning toch wordt vermeden. We beschrijven ook de resultaten van een kostenefficiënt migratieschema om optische kruisschakelaars (OXCs) te introduceren in het IP-over-optisch netwerk. Voor kleine trafiekhoeveelheden is link-per-link grooming het meest geschikt, wat toelaat de beschikbare capaciteit op de golflengten zo efficiënt mogelijk op te vullen. Als de trafiek toeneemt, komt er echter een punt waar de door eind-tot-eind grooming gerealiseerde besparingen op de IP-laag gecompenseerd worden door de extra kosten voor het introduceren van optische kruisschakelaars. Eiland-gebaseerde grooming vormt een tussenliggende oplossing, die geleidelijk aan meer optische kruisschakelaars introduceert op de meest geschikte plaatsen in het netwerk en op die manier toelaat de kosten te spreiden over de tijd.

Een tweede groep van planningsproblemen die in deze verhandeling beschreven wordt, bestudeert het onzekere karakter dat inherent is aan de voorspelling van toekomstige trafiek en kosten. We hebben een veelgebruikte planningstechniek geëvalueerd die gebruik maakt van een veiligheidsmarge om onzekerheid in rekening te nemen en hebben aangetoond dat deze techniek met omzichtigheid gebruikt dient te worden. We hebben ook de relatieve impact van onzekere trafiek en netwerkkosten bestudeerd en aangetoond dat statistische afhankelijkheden tussen inputvariabelen een grote invloed kunnen hebben op de planningsresultaten en de performantie van traditionele planningstechnieken. Tot slot hebben we de techniek van Reële Opties toegepast om de flexibiliteit in het planningsproces te modelleren. We hebben verschillende mogelijke netwerkmigratiepaden geïdentificeerd die gebruik maken van dark fiber of golflengte leasing en hebben aangegeven hoe traditionele planningstechnieken de mogelijkheden van flexibel inspelen op toekomstige evoluties gemakkelijk over het hoofd kunnen zien.

Ten derde hebben we gewerkt aan de ontwikkeling van een kostenmodel voor een netwerkoperator, met bijzondere aandacht voor de operationele kosten. We beschrijven de verschillende stappen die nodig zijn om de totale kosten voor het uitrollen van een bepaald netwerkscenario te bepalen. Na het definiëren van kapitaal- (CapEx) en operationele kosten (OpEx) voor een netwerkoperator en het beschrijven van enkele kostenmodelleringsmethodologieën, introduceren we een activiteitsgebaseerd kostenmodel dat toelaat de operationele kosten van een netwerkoperator te kwantificeren. We onderscheiden hiertoe verschillende operationele processen zoals onderhoud, reparatie, service levering en prijszetting/facturatie. Deze procesgebaseerde OpEx kosten vormen samen met de continue infrastructuurkosten het totale OpEx kostenplaatje. Continue infrastructuurkosten omvatten kosten voor het huren van ruimte, energieverbruik, enz. We geven referentiegetallen voor de duurtijd van activiteiten en beschikbaarheidparameters voor een IP-over-Optisch netwerk, die kunnen dienen als inputwaarden om de proceskosten van een aantal realistische netwerkscenarios te bepalen. Om de bruikbaarheid ervan aan te tonen, hebben we ons OpEx kostenmodel toegepast op een Duits referentienetwerkscenario, waarvoor we de verwachte CapEx en OpEx kosten hebben berekend. We geven ook aan hoe de introductie van een controlevlak in het optische netwerk de operationele kosten doet afnemen.

Tot slot geven we aan hoe de voorgestelde kostenmodellen toegepast kunnen worden in een vrijgemaakte telecommarkt. Ze kunnen toelaten om aan de rapporteringsvereisten, opgelegd door de regulator, tegemoet te komen. Ze kunnen ook een inzicht geven in de interne kostenstructuur bij de operator, wat belangrijk is om een sterkere marktpositie te kunnen verwerven.

English Summary

This thesis focuses on planning techniques to handle dynamic and uncertain inputs to the network planning process of optical core networks. During the last years, major changes to the telecom network environment could be observed. Three driving forces for these changes can be identified: first of all the huge, ongoing growth of data traffic over the Internet, secondly the major technological breakthroughs, especially in the field of optical networking and finally the worldwide liberalization and globalization that have changed the telecom landscape substantially. Network planning in this environment is a complex task. The number of customers and the desired type of services is constantly changing. This has an impact on the traffic to be routed over the network and also on the expected revenue for the operator. Apart from this, also the cost to build and maintain the network is constantly changing. Equipment of a certain type becomes cheaper over time, whereas new technologies with new possibilities become available. Moreover, future demands and costs are not known exactly, so that we have to make use of predictions, which are inaccurate in nature. Both dynamics and uncertainty should be taken into account during the network planning process.

As a network operator aims at fulfilling customer requirements (in order to obtain the required cash in-flows) while minimizing his costs (cash out-flows), a thorough knowledge of relevant planning techniques is extremely important. The goal of network planning is to provide the operator with guidelines to handle this trade-off between cash in-flows and cash out-flows. Our research exactly aims at deriving some guidelines for network planners, in order to tackle some specific aspects of the network planning process.

The studies carried out in the framework of this thesis deal with optical telecommunication networks, which form the basis of most core networks of big network operators today, because the optical networks form a suitable medium to transport huge amounts of aggregated traffic. We see a trend from point-to-point optical networking between electrical nodes towards switching on the optical layer, allowing high capacity transit traffic in the core network nodes. Recently, also more flexibility is brought into the optical network by the introduction of a control plane, allowing to set up switched connections, in addition to the traditional semi-permanent ones. These advances create opportunities to fundamentally change the way optical networks are operated.

Concerning the dynamic character of network traffic demands and equipment costs, our work focuses on the comparison of single period planning, anticipated planning and multi-period planning and their relation with investment decision techniques. We show that anticipated planning can lead to remarkable better results than single period planning, while avoiding the complexity of multi-period planning. The correct choice of the prediction interval is important in this

respect, because too short a prediction interval does not allow to sufficiently take into account the future evolutions and too long a prediction interval suffers from uncertain predictions. We also present a cost-efficient migration scheme to introduce optical cross-connects (OXCs) in an IP-over-Optical network. For small traffic demands, the link-by-link grooming approach (efficiently filling the capacity of the wavelengths) is shown to be most interesting. As traffic increases, however, there comes a point where the savings in IP layer expenses realized by end-to-end grooming compensate the extra expenses of introducing the needed optical cross-connects. An intermediate solution is found in the technique of island based grooming, which gradually installs OXCs in the network at the most interesting locations and in this way allows to spread costs.

A second group of problems discussed in this thesis handles the uncertainty inherent to planning input forecasts. We have evaluated a common approach using safety margins to cope with uncertainty, which need to be used with care. Based on a risk analysis for an optical network operator, we studied the impact of both uncertain traffic demands and network costs on the position of the network operator and emphasised that correlated uncertain input variables lead to important deviations from the estimated output value. Finally, we have applied the ideas of Real Options thinking to deal with flexibility in uncertain planning problems. We have considered several possible network migration approaches using dark fibre or wavelength lease and indicated how traditional, static planning approaches can easily overlook the value originating from flexibility in the future network deployment plan.

Third, we developed a cost model for a network operator, paying special attention to the operational expenditures. We outline the different steps required to estimate the costs for realistic network scenarios. After defining the total capital (CapEx) and operational expenditures (OpEx) for a telecom operator and describing several cost modelling approaches, we present an activity-based approach to quantify the cost of the network operator operational processes like routine operation, repair, service provisioning and pricing and billing. This process-based OpEx cost complements the continuous cost of infrastructure that represents the constantly required OpEx to keep the network up and running, like floor space and power consumption. We suggest reference numbers for activity duration and availability parameters for an IP-over-Optical network, which can serve as an input to calculate process costs for realistic network scenarios. In order to show its applicability, we apply our model to a German reference network scenario, for which we calculate the estimated CapEx and OpEx costs. We also indicate how the introduction of a control plane in the optical network layer can reduce the OpEx costs.

Finally, we show how the cost models presented can be applied in a liberalised telecom market. They can be helpful to fulfil the cost reporting requirements imposed by the regulator and can also give an insight in the internal cost structure of the telecom operator, which is important in order to be able to obtain a stronger market position. We suggest a cost allocation scheme to map the distinguished CapEx and OpEx cost parts to the different service cost classes.

1 Introduction and Publications

1.1 Situation

During the last years, major changes to the telecom network environment could be observed. We identify three driving forces: first of all the huge, ongoing growth of data traffic over the Internet [1.1], secondly the major technological breakthroughs, especially in the field of optical networking and finally the worldwide liberalization and globalization. Network planning in this environment is a complex task [1.2]. The number of customers and the desired type of services is changing constantly. This has an impact on the traffic to be routed over the network and on the expected revenue for the operator. Besides this, also the cost to build and maintain the network is constantly changing. Equipment of a certain type becomes cheaper over time, whereas new technologies with new possibilities become available. Moreover, future demands and costs are not known exactly, so that we have to make use of predictions, which are inaccurate in nature. Both dynamics and uncertainty should be taken into account during the network planning process. An important part of long term network planning is the choice of the appropriate technology. Therefore, a trade-off has to be made between the expected costs (for installation as well as maintenance) and the revenues for the operator.

Our focus is on the planning of optical telecommunication networks [1.3], which form the basis for most core networks of big network operators today, because the optical networks provide a suitable medium to transport huge amounts of aggregated traffic. Based on some technological advances, we see a trend from point-to-point optical networking between electrical nodes towards switching on the optical layer, allowing high capacity transit traffic in the core network nodes. Recently, also more flexibility is brought into the optical network by the introduction of a control plane, allowing to set up switched connections, in addition to the traditional semi-permanent ones. These advances create opportunities to fundamentally change the way optical networks are operated.

The telecom industry value chain includes network service providers, equipment suppliers, component vendors and end customers. Within this competitive environment, according to [1.4] two approaches are crucial. The first is to achieve disruptive technological innovations that contribute to reducing network construction costs. The second is to improve network functionality to reduce operational expenditures (OpEx) and generate revenues through new services. The former is taken as an input for our studies, the latter is one of the drivers of our research. We believe that internet traffic demand will keep growing and therefore network expansion and migration will remain key tasks for a network operator. After the explosion of the internet bubble, however, some realism has come into the market and exuberant investments belong to the past. In this climate, the application of intelligent network planning techniques is crucial. Network planning should have a long term view on the effects of an investment in the network, taking into account both expected future capital and operational expenditures. The application of an appropriate network planning technique together with a suitable cost model is essential when performing service profitability calculations, or when allocating costs to services for regulatory purposes.

1.2 Overview of This Work

In this thesis, a general overview is given of the long term network planning process, indicating the most important research results obtained in this field during the course of our work. For more details on the individual case studies, we refer to the publications added in the appendices. An overview of all publications realised during the course of this research is given in Section 1.3. Below, we give an overview of the most important contributions made in the different chapters of this thesis.

Chapter 2 describes the required background information for the next chapters of the thesis. It introduces the planning problem for telecommunication networks. The most important inputs to the planning process, i.e. traffic demand and equipment costs, are introduced. Different planning phases are distinguished, leading to the definition of strategic network planning, which we focus on in our work. Secondly, also the basics of optical networking are described. The different layers in the IP-over-WDM network and the types of network switches are discussed, in order to indicate the migration from link-by-link optical networks towards real optical switching networks with full flexibility. Several possible migration steps in this process are handled in the remainder of our work: the introduction of optical cross-connects and the decreasing importance of link-by-link traffic grooming, the possibility to build an optical network based on available dark fibre and the introduction of the control plane in the optical network.

Chapter 3 explains how the dynamic character of network traffic demands and equipment costs can be taken into account during the planning process. It describes several important forecasting techniques and explains the reference traffic model used throughout our work. A reference equipment cost model for an IP-over-Optical network is also described, together with a technique to model cost erosion. The techniques of single period planning, anticipated planning and multi-period planning are weighed against one another. We indicate that anticipated planning is no more complex than single period planning, but leads to remarkable better results. We also indicate the relation between traditional investment decision techniques and long term network planning approaches, e.g. by using the concept of Net Present Value when performing multi-period planning. We report results on cost-efficient migration from link-by-link towards end-to-end grooming. Therefore, we introduce the concept of island based grooming, which gradually installs OXCs in the network at the most interesting locations and in this way allows to spread costs. Our research results in these fields contributed to the publications [5][11][17][20][24][34]. The publication [5] is added at the end of this thesis as appendix A.

Chapter 4 deals with forecast uncertainties. We evaluate a straightforward and commonly used approach to handle uncertainty via the use of safety margins and indicate that they need to be used with care. We discuss the results of a risk analysis for an optical network operator, indicating the impact of uncertain traffic and costs and emphasizing that statistical correlation between input parameters can have an important impact on the expected results of the planning exercise. Finally, we apply the idea of Real Options Thinking to deal with flexibility in uncertain planning problems. We consider several possible network migration approaches using dark fibre or wavelength lease and indicate how traditional, static planning approaches can easily overlook the value originating from flexibility in the future network deployment plan. Our research results in these fields contributed to the publications [3][6][12][14][18][19][26][36][45]. The publications [3] and [6] are attached at the end of this thesis as appendices B and C, respectively.

Several steps required to estimate the costs for realistic network scenarios are handled in Chapter 5. After defining the total capital (CapEx) and operational (OpEx) expenditures for a telecom operator and describing several cost modelling approaches, we present an activity-based approach to quantify the cost of the event-driven network operator operational processes, including repair and service provisioning. We suggest reference numbers for activity duration and availability parameters for an IP-over-Optical network, which can serve as an input to calculate process costs for realistic network scenarios. In order to show its applicability, we apply our model to a German reference network scenario, for which we calculate the estimated CapEx and OpEx costs. We also indicate how the introduction of a control plane in the optical network layer can reduce the OpEx costs. Our research results in these fields contributed to the publications [2][4][21][25][27][32][33][35]. The publications [2] and [4] are added at the end of this thesis as appendices D and E, respectively.

Chapter 6 shows how the cost models discussed in Chapter 5 can be applied in a liberalised telecom market. First, they can be helpful to fulfil the cost reporting requirements imposed by the regulator, which only allows cost-based tariffs in order to increase competition. On the other hand, they can also give an insight in the internal cost structure of the telecom operator, which is important in order to be able to obtain a stronger position. We suggest a cost allocation scheme to map the distinguished CapEx and OpEx cost parts to the different service cost classes. Finally, we briefly indicate how cost models can serve as a basis for pricing decisions. Our research results in these fields contributed to the publications [38][40][42][43][44]. The publication [44] is added at the end of this thesis as appendix F.

The conclusions of our work are summarized in Chapter 7, together with some directions for future work.

1.3 Publications

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

1.3.1 Articles in Journals Included in the Science Citation Index (a1)

[1] S. De Maesschalck, M. Pickavet, D. Colle, Q. Yan, S. Verbrugge, B. Puype, P. Demeester: “Efficient multi-layer traffic grooming in an IP/MPLS-over-optical network,” European Transactions on Telecommunications, ISSN 1124-318X, July-August 2005, vol. 16, no. 4, pp. 329-347.

[2] S. Pasqualini, A. Kirstädter, A. Iselt, R. Chahine, S. Verbrugge, D. Colle, M. Pickavet, P. Demeester: “Influence of GMPLS on network providers’ operational expenditures: a quantitative study,” IEEE Communications Magazine, ISSN 0163-6804/05, July 2005, vol. 43, no. 7, pp. 28-34.

[3] S. Verbrugge, D. Colle, S. De Maesschalck, M. Pickavet, P. Demeester: “On planning of optical networks and representation of their uncertain input parameters,” Photonic Network Communications, ISSN 1387-974X, January 2006, vol. 11, no. 1, pp. 49-64.

[4] S. Verbrugge, D. Colle, M. Pickavet, P. Demeester, S. Pasqualini, A. Iselt, A. Kirstädter, R. Hülsermann, F-J. Westphal, M. Jäger:

"Methodology and input availability parameters for calculating OpEx and CapEx costs for realistic network scenarios," Journal of Optical Networking, Feature Issue: Optical Network Availability, June 2006, vol. 5, no. 6, pp. 509-520.

[5] S. Verbrugge, D. Colle, M. Pickavet, P. Demeester: "Techno-economic evaluation of the introduction of optical cross-connects in an IP-over-WDM network," accepted for publication in Photonic Network Communications

[6] S. Verbrugge, D. Colle, W. De Maeseneire, M. Pickavet, P. Demeester: "The options behind dark fibre and wavelength lease," submitted to Journal of Optical Networking

1.3.2 Articles in Journals with Peer Review, Not Included in a1 (a2)

[7] T. Wauters, D. Colle, E. Van Breusegem, S. Verbrugge, S. De Maesschalck, J. Cheyns, M. Pickavet, P. Demeester: "Virtual topology design issues for variable traffic," IEICE Electronics Express, Electronic journal, http://www.elex.ieice.org/, September 25, 2004, vol. 1, no. 12, pp. 328-332.

1.3.3 Articles in National Journals (a4)

[8] I. Lievens, D. Colle, S. De Maesschalck, A. Groebbens, S. Verbrugge, M. Pickavet, P. Demeester: "Survivable communication networks," Revue E tijdschrift, Tijdschrift voor Elektriciteit en Industriële Elektronica, "Telecommunicatie en veiligheid," Driemaandelijks tijdschrift, February-March-April 2003, vol. 119, no. 1, pp. 9-17.

1.3.4 Chapters in Books (b2)

[9] D. Colle, E. Van Breusegem, S. Verbrugge, J. Cheyns, C. Develder, S. De Maesschalck, M. Pickavet, P. Demeester: "Chapter 7: Evolution of next-generation optical networks," Advanced Infrastructure for Photonic Networks, Extented Final Report of COST Action 266, ISBN 953-184-064-4 by the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia, Edited by R. Inkret, A. Kuchar, B. Mikac, 2003, pp. 205-219.

1.3.5 Articles in Proceedings of International Conferences (c)

[10] M. Pickavet, A. Ackaert, E. Baert, J. Cheyns, D. Colle, S. De Maesschalck, P. Demeester, C. Develder, A. Groebbens, I. Lievens, E. Van Breusegem, S. Verbrugge, Q. Yan: “Design of communication networks using heuristics,” (Invited paper), Book of abstracts of "Arbeitskreis Mathematik in Forschung und Praxis," the 23^{rd} Symposium on Mathematik in der Telekommunikation, Gerhard Mercator Universität Duisburg, Duisburg, Germany, March 18-19, 2002.

[11] J. Derkacz, M. Leszczuk, K. Wajda, R. Leone, G. Monari, I. Lievens, S. De Maesschalck, S. Verbrugge, D. Colle: “IP/OTN cost model and photonic equipment cost forecast - IST Lion Project,” the 4^{th} Workshop on Telecommunications Techno-Economics, Rennes, France, May 14-15, 2002, pp. 126-138.

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Capacity Optical Networks: opportunities and challenges," Turin, Italy , October 15-16, 2002.

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[18] S. Verbrugge, D. Colle, M.Pickavet, P. Demeester: “Common planning practices for network dimensioning under traffic uncertainty,” DRCN 2003, the 4th International Workshop on the Design of Reliable Communication Networks, ISBN 0-7803-8118-1, Banff, Alberta, Canada, October 19-22, 2003, pp. 317-324.

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1.3.6 Publications on National Conferences

[48] S. De Maesschalck, D. Colle, A. Groebbens, S. Verbrugge, Y. Qiang, M. Pickavet, P. Demeester: “Design of survivable IP/OTN networks,” the 2nd FTW PhD Symposium, Gent, Belgium, December 12, 2001, proceedings available on CD-ROM, interactive poster session, paper no. 20.

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[51] B. Lannoo, S. Verbrugge, J. Van Ooteghem, D. Colle, M. Pickavet, P. Demeester: “Evolution of Access Networks: FTTH and WiMAX,” presented at the 7th FirW PhD Symposium, Gent, Belgium, November 29, 2006.

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2 Basic Concepts concerning Optical Network Planning

"In preparing for battle I have always found that plans are useless, but planning is indispensable"- Dwight D. Eisenhower

This chapter describes the required background information for the next chapters of this thesis. Section 2.1 introduces the planning problem for telecommunication networks. The most important inputs to the planning process, such as traffic demand and equipment costs, as well as the different planning phases, are described. In Section 2.2, the basics of optical networking are introduced. The migration from link-by-link optical networks towards a real optical switching network with full flexibility is described, as well as the use of the optical network layer to transport an IP traffic demand. Finally, in Section 2.3, we indicate how the different aspects of the planning process for the optical network are studied in our work and how this differs from related publications.

2.1 Telecommunication Network Planning

2.1.1 The Network Planning Process

The goal of the *network planning process* [2.1] is to make sure that the network meets the requirements of the network operator at any moment in time. Moreover, as most decisions made in network deployment have a long term impact (as investments in a certain technology set the framework for network deployment for some years into the future), sensible planning is even more important in this field than it is in some others. An overview of the network planning process is given in Figure 2.1.

The *demand* imposed on the network by the customers is a first important input for the planning process. The number of customers as well as the required bandwidth for each customer increases over time; the requested services change. Also the geographic distribution of the traffic over the network is time varying. During office hours, for instance, the traffic will mainly flow between big administrative centres, whereas the traffic in the evening hours is mainly generated by home users. Although general trends may be predictable to some extent, the exact future network demand evolution is very difficult to predict. A network operator will never know the future situation concerning total traffic demand and market share beforehand (at the time of the planning decisions).

The second important input for the planning process is the *cost* the operator has to pay to be able to cope with the demand. This includes capital as well as operational expenditures. The CapEx cost is strongly related to the technological evolution. A gradual price decrease of technology that has been on the market for a while can be expected. The entrance of a competitor or a technological breakthrough, on the other hand, can lead to abrupt price changes. OpEx costs for a network with a new type of equipment are even more difficult to forecast than the costs of the equipment itself.

The technical and physical limitations form important edge *constraints* when deploying a network. Attention needs to be paid to the compatibility of different technologies as well as to the geographical limitations concerning placement of new network nodes or links. Very often, the network planning will take into account the existing network situation, which needs to be expanded or migrated. Also the requirements concerning resilience of some services or the traffic of some customers need to be taken into account. Finally, also the available budget or the maximum amount that can be spent may be an important constraint.

The resulting *network plan* should be a detailed time scheme concerning the decisions to install and expand the future telecom network. Note that, in practice, a network planning technique or tool will provide the network planner with useful information on which he can base his decisions. A network planner is usually averse of black-box planning tools, but wants to have an insight in what the recommendations are based on. He might also want to add some individual or strategic preferences, e.g. his attitude towards risk.

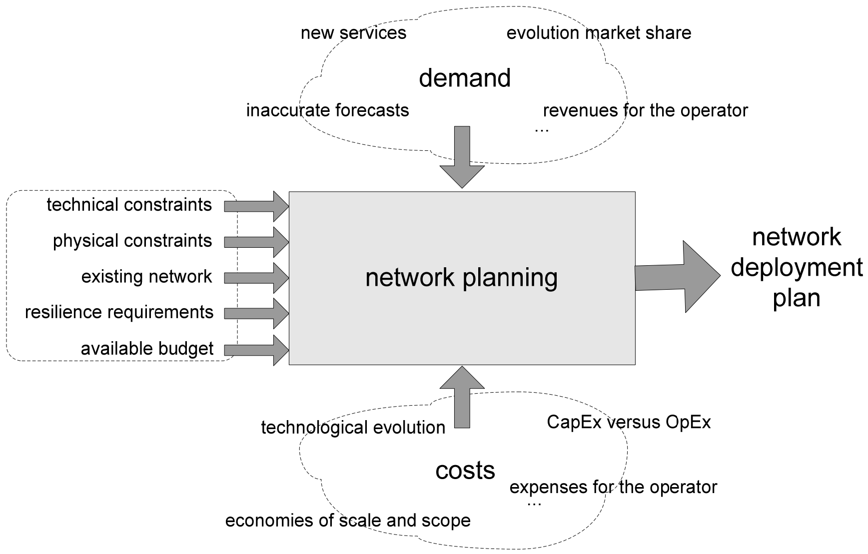

Figure 2.1: network planning process

2.1.2 Different Phases in Network Planning

The field of network planning mainly originates from the telephone industry. Most telephone companies tackled the network planning problem in three phases [2.2]. The resulting categorization is still useful when planning current telecom networks. The three considered phases differ in the length of the considered planning horizon, as well as the considered level of detail, the uncertainty associated with the planning data and the risk associated with the decisions and the geographical scope of the decisions, as shown in Figure 2.2.

- *Strategic or long term planning (LTP)* considers periods of 5 years or longer. The uncertainty concerning the planning data is big, because long term forecasts need to be used. Abstraction up to a certain level of detail is possible. The decisions that are taken at this level have a company-wide impact.

- *Tactical or mid term planning (MTP)* considers periods of nearly one up to two years. The uncertainty is already a bit smaller, so that a higher level of detail can be obtained in the problem description. The overall impact of the decisions is still important.

- *Operational or short term planning (STP)* is also called day-to-day planning. The horizon is no longer than a few weeks. The input data can be specified at a reasonable level of detail. The impact of the decisions on the long term future of the company is limited.

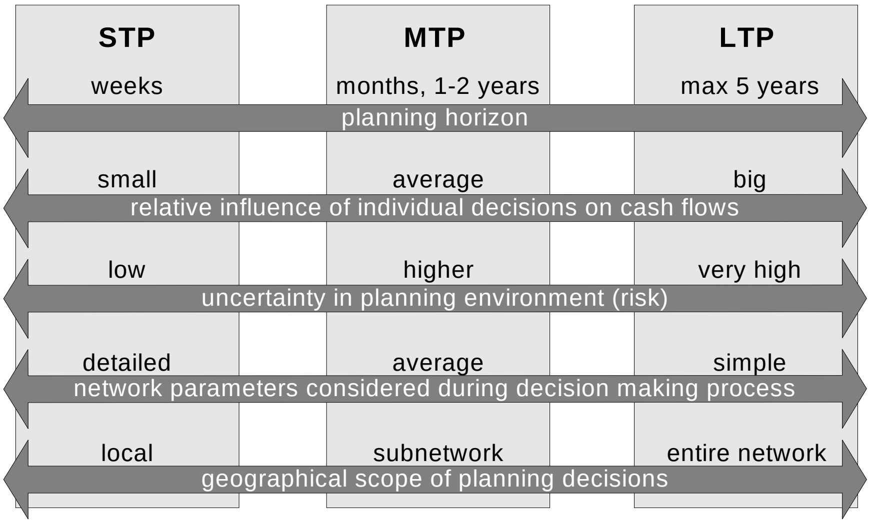

Figure 2.2: different network planning phases

2.1.3 Business Modelling

The telecom industry is a complex interaction between network service providers, equipment suppliers, component vendors and end customers. Everyone in the value chain needs good business strategies to survive, among which improving network functionality to reduce OpEx costs and generating revenues through new services [2.3]. In order to grasp the complexity of this interaction, it is important to understand the impact of the microeconomic environment it belongs to. The different industry forces at work in a competitive environment are described by Porter [2.4][2.5]. Porter states that an organization's behaviour in a competitive environment is impacted by the interaction of five different forces:

- *Force 1: the degree of rivalry.* Head-to-head competition between existing sellers in the market may destroy some of the value created by a company, e.g. a telecom operator. The impact of competition on the situation for the company under study depends on the number of competitors, the quality difference between the different products, the potential switching costs for the customer to change suppliers, the customer loyalty, etc. The telecom landscape has been reshaped by the effects of liberalization during the last decades. Today margins have decreased and competition is strong.

- *Force 2: the threat of new entry.* New sellers entering the market impose a potential threat to the considered company, as it might lose part of its customers. The amount and power of new entrants depend on the time and cost of entry, the impact of economies of scale and some potential entry barriers. In the telecom market, some entry barriers have been removed by legislation requiring the former incumbent to give newcomers access to the network.
- *Force 3: the threat of substitutes.* Substitute products becoming available in the market, either from existing or new competitors, can attract some customers. The strength of this threat depends on the performance of the substitute product compared to the original and the potential cost of change. In telecom, several important examples of this type were observed. Fixed line telephony is in strong competition with mobile telephony. ISDN (Integrated Services Digital Network) narrowband products have completely been replaced by ADSL (Asymmetric Digital Subscriber Line) and cable broadband alternatives. When introducing a new service with a higher level of quality, we often see it cannibalizing the existing service.
- *Force 4: buyer power.* The power exercised by the customers in the market is a function of the number and size of customers, their price sensitivity and aversion of change. In telecom, customers have gained power thanks to number portability, lower switching costs to switch network providers, etc. Concerning the importance of the customer base, Metcalfe's law is often cited, stating that the value of the network grows as n^2, with n being the number of users. Although the actual value growth might be more like $n \cdot log(n)$ [2.6], the value of a network is most probably growing faster than linear with the number of customers.
- *Force 5: supplier power.* The impact of the suppliers on the sellers depends on the number and size of the suppliers, the uniqueness of the service they offer, etc. Right now, we are witnessing a consolidation push amongst the telecom suppliers [2.7], e.g the mergers Alcatel/Lucent, Nokia/Siemens and Ericsson/Marconi. Together with the advent of new players like Huawei, this indicates that the supplier market is changing fundamentally and that traditional strong players have lost some of their power.

An overview of the five forces is given in Figure 2.3. Porter's model is a strategic tool used to identify whether new products, services or businesses have the potential to be profitable. However, it can also be very illuminating when used to understand the balance of power in other situations.

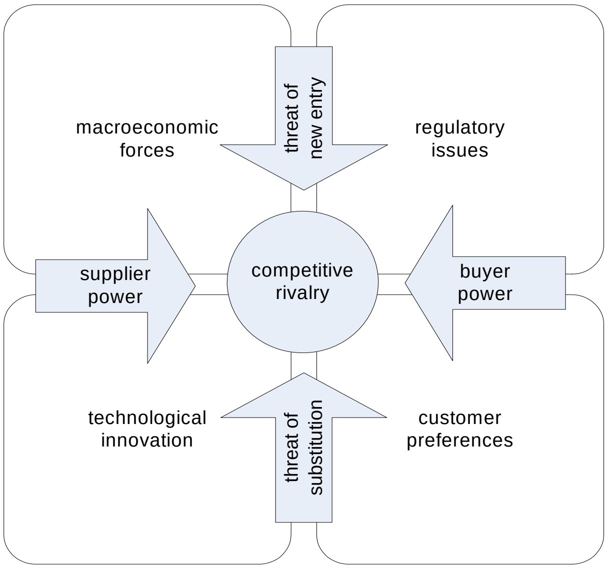

Figure 2.3: Porter's five forces model

2.2 Optical Telecommunication Networks

2.2.1 Optical Transport Network

A telecommunication network is typically split into two segments: the transport or core network and the access network. The *transport network* links the nodes in the important cities with each other to form an international or global network. The *access network* is the part of the network allowing the individual customer to connect to the nearest network node. Between the transport and the access network, we can also find a *metro network*, expanding over a big city or an entire region. An illustration is given in Figure 2.4.

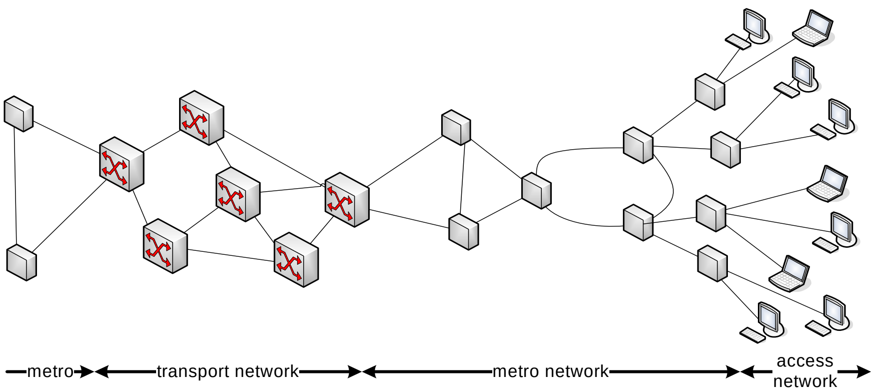

Figure 2.4: different network segments

The term *optical network* [2.8][2.9] indicates a network where the information is sent over the network links as an optical signal. In the network nodes, the signal can be treated optically or converted to the electrical layer, as explained later.

Light emitters are a key element in any fibre optic system. They convert the electrical signal into a corresponding light signal that can be injected into the fibre. The laser is a common light emitter because of its wavelength selectivity.

An optical fibre has a core in pure glass (SiO_2). However, even in this pure glass, the signal will loose some of its intensity during transmission [2.10]. The power of the signal is reduced when it propagates over some distance. This effect is called *attenuation*. The receiver sensitivity indicates the minimum power required by a receiver to detect the signal. In order to compensate for the effect of attenuation, the optical signal can be amplified within the optical domain. Several *amplifier* technologies exist, like Erbium-Doped Fibre Amplifiers (EDFA) and Raman amplifiers [2.11]. In general, amplifiers are placed immediately after the transmitting node (*power booster*), on the fibre in between two nodes (*inline amplifier*) and immediately before the receiving node (*preamplifier*). Figure 2.5 shows a typical optical link with amplifiers.

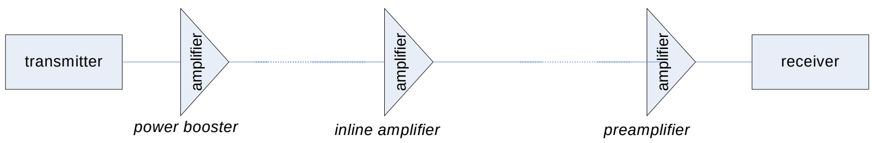

Figure 2.5: optical link with amplifiers

An optical signal is also distorted by the effects of *dispersion*. This is the widening of the pulse duration as it travels through a fibre. As a pulse widens, it can broaden enough to interfere with neighbouring pulses on the fibre, leading to inter-symbol interference. Two important types of dispersion can be compensated. *Chromatic dispersion (CD)* is caused by the fact that different wavelengths have different transmission speeds, leading to a time shift in the optical signal when it is transmitted over a long distance, whereas *polarization mode dispersion (PMD)* is caused by the fact that different polarization states of the signal in different densities of the fibre are transmitted at a different speed. The effects of both dispersion types get worse over longer distances: the longer the distance, the less clear the signal becomes. *Regenerators* allow to compensate for dispersion. They transform the optical signal to an electrical one, perform a so-called 3R regeneration and transform it again to the optical layer. *3R-regeneration* stands for re-amplification, reshaping and retiming[1]. It removes the inaccuracies and shifts in the incoming signal. 3R-regeneration is, up till now, not possible in the optical domain. The maximum distance the signal can be transmitted without the need for regeneration is indicated by the maximum transparency length (MTL). Today, on a typical 40 channel WDM system with 10 Gbps per wavelength, a MTL of 1100 to 2800 km is possible [2.12]. This means that regeneration is not required for a Belgian scale network. However, it will be unavoidable if we want to provide an optical network connection between Stockholm and Madrid in a pan-European network.

2.2.2 Point-to-Point Optical Communication

In the most straightforward configuration, one fibre carries one optical signal. However, the available bandwidth (i.e. the optical fibre) can be used more efficiently thanks to the concept of multiplexing. *Multiplexing* combines several data streams into a single stream, using a *multiplexer*. Two important different multiplexing techniques can be distinguished:

- *Space Division Multiplexing (SDM)* uses multiple fibres on a single cable. This situation leads to a higher bandwidth than the situation with a single fibre, but still, with increasing traffic, fibre exhaust can soon become a problem. An illustration of an optical network carrying one optical 2.5 Gbps signal per fibre (thick black line) is given in Figure 2.6.
- *Wavelength Division Multiplexing (WDM)* [2.14] allows to transmit different data streams on different optical frequencies. In case there are more than 8 or 16 (depending on the definition) wavelengths per fibre, this is called *Dense WDM (DWDM)*, otherwise it is called *Coarse WDM (CWDM)*. At present,

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[1] *1R-regeneration* is simple amplification, using EDFAs or other amplifiers as described above. *2R-regeneration and reshaping* includes converting the signal to an electrical signal which is then used to directly modulate a laser. Reshaping reproduces the original shape of each bit, eliminating the noise. Finally, *3R-regeneration, reshaping and retiming* (also called reclocking) also includes synchronizing the signal to its original bit timing pattern and bit rate [2.9].

DWDM systems of up to 160 wavelengths are available. Whereas DWDM systems use channel spacing as close to 0.4 nm, CWDM uses a spacing of 20 nm. The more stringent technical requirements for DWDM cause this technology to be more expensive than the CWDM alternative. When using WDM on the network fibres, a *multiplexer (mux)* is required to combine all signals coming out of a certain node on a signal fibre, using different wavelengths. A *demultiplexer (demux)* demultiplexes the signals before entering the node. This architecture is illustrated in Figure 2.7, where the thick black lines indicate fibres (in this case carrying multiple wavelengths), the thin lines depict individual wavelength signals.

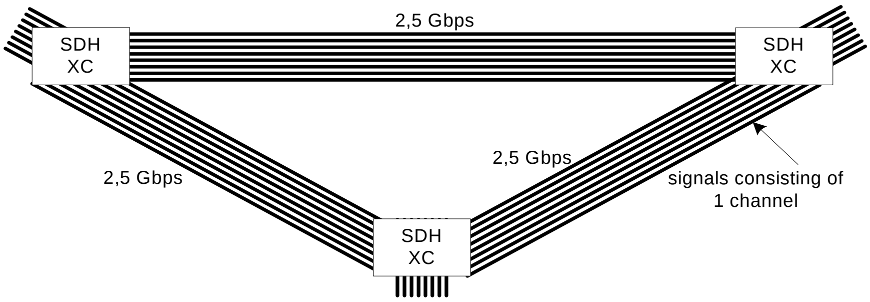


Figure 2.6: point-to-point optical network using SDM

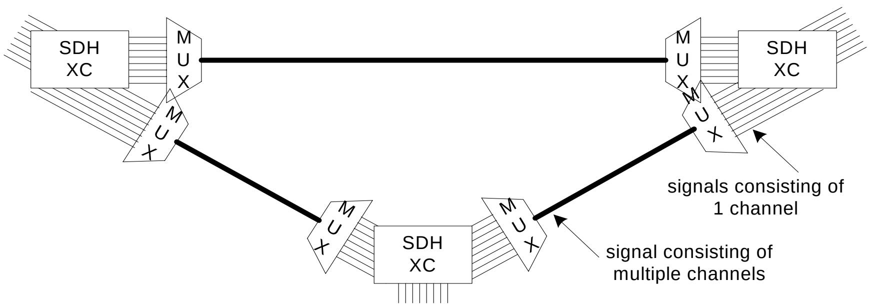
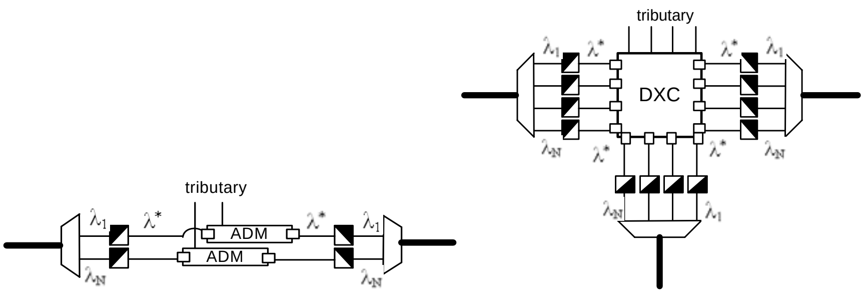


Figure 2.7: point-to-point optical network using WDM

In the optical networks described above, WDM is used purely for capacity increase and the information is converted to the electrical layer (e.g. the *Synchronous Digital Hierarchy (SDH)* layer [2.13]) in every node. The incoming electrical signal (e.g. coming from a local network) is converted in an optical signal (light) by a *transponder*. This signal is then transmitted over an optical fibre to the next node on the path. If necessary, the signal is amplified in its way (to compensate for loss). At the receiver side, the signal is again transformed into an electrical signal and, when its destination is reached, sent further onto the local (electrical) network.

Figure 2.7 illustrates this type of optical point-to-point network where the optical signal is converted to the electrical domain in every node. Figure 2.8 illustrates some typical electrical nodes to be used in this context. Figure 2.8(a) illustrates the use of an electrical Add-Drop Multiplexer (ADM), mainly deployed in networks with ring topologies. Figure 2.8(b) illustrates the use of a digital cross-connect (DXC), mainly deployed in mesh topologies. The long-reach transponders are indicated in the figures by the half-shaded boxes, they perform the translation of the coloured light signal (indicated by wavelength λ_i) into the grey light signal (wavelength λ^*), which is the wavelength which was traditionally used in case of point-to-point optical transmission without WDM in the SDH equipment in the nodes. As it is desirable to be able to keep the available SDH equipment whereas WDM uses multiple wavelength, the lambda conversion in the transponders is required. Besides those, there are also short reach transponders required to perform the conversion of the optical signal into the electrical signal (O/E) before entering the cross-connect itself. They are indicated in the figure by the small unshaded boxes.



(a) ADM node **(b) DXC node**

Figure 2.8: electrical node in WDM point-to-point network

2.2.3 Evolution towards End-to-End Optical Networking

As the network nodes are the bottlenecks in a WDM point-to-point network, a necessity arises to introduce optical switching nodes into the network. Optical switching elements allow “wirespeed”, i.e. signals pass through them at the same bit rate as through the fibre itself. Secondly, they also lead to *data transparency* as well as *protocol transparency*: they cannot sense the presence of individual bits that are flowing through them.

The most straightforward optical switching element is the *optical add/drop multiplexer (OADM)*. An OADM allows to provide a direct optical connection between a number of node pairs in the optical network, which is called a *light path* [2.15]. Some wavelengths coming into the OADM are transmitted on the optical layer to the next node on their path. Other wavelengths are dropped at the considered node (going up to the optical layer). Some new wavelengths coming from the electrical layer can be added to the outgoing optical signal as well. The OADM is often used to build optical rings. Figure 2.9 illustrates how some transit wavelengths can be switched on the optical layer, whereas tributary traffic (add/drop) is sent through the electrical layer (the DXC in the figure). Transponders are only required for the tributary traffic in this case. In the example of Figure 2.9, only *2* out of the *N* wavelengths for each ring are terminated in the considered node, so that their content can be switched over the DXC to one of the other rings or to the local client (via the tributary ports).

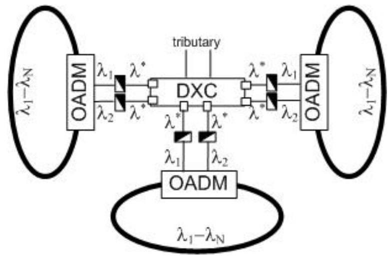


Figure 2.9: optical add-drop multiplexer for ring configuration

Several types of optical switches can be distinguished [2.16], depending the fact whether or not the relation between the input and the output ports is fixed. In the example of Figure 2.9, in a *non-reconfigurable* OADM it is always the wavelengths λ_1 and λ_2 which are terminated, whereas in a *reconfigurable* OADM (ROADM), the exact wavelengths being terminated can change over time, e.g. one time it can be λ_1 and λ_2, the next time λ_3 and λ_4.

When the cross-connected traffic between rings increases, there is a benefit in more flexible optical layer nodes. *Cross-connects* provide an answer to this need. They have a switching step between the demultiplexer and the multiplexer in the switch, so that the wavelength coming in on any input port can be switched to any output port. This means that the relation between input and output ports changes over time. An optical cross-connect (OXC) is the typical node in an optical mesh network. An illustration of an optical network using OXCs is shown in Figure 2.10.

Several types of OXCs exist, differing in the character of their switching matrix [2.16]:

- *Optical cross-connects with electrical core* also called *opaque OXCs* receive an optical signal, transform it into an electrical signal, process the signal (route it to the appropriate port or to the tributary port), transform it again to the optical domain and transmit it again. OXCs with an electrical core do not scale well, in principle, as fast electronics are expensive. The advantage of OXCs with an electrical core is that they allow 3R-regeneration and support lambda conversion and bandwidth grooming, SONET/SDH standards can be applied for framing. The disadvantages are the significant power consumption and the limited scalability.

- *Optical cross-connects with an optical core*, also called *Photonic Cross-connects (PXCs)* don't transform the signal to the electrical domain. They rather transmit it directly to its destination port. This process is more transparent than in the case of an electrical core (the signal is not read), however, other transformations cannot be performed on the signal either. The lack of transponders makes this approach a lot cheaper than the previous one. Several implementations for PXCs exist: bubble switching, thermo-optic switching, acousto-optic, etc. [2.17]. However, the MEMS (micro-electro-mechanical systems) technology is the most common one. It consists of very small mirrors that can be turned in order to reflect the optical signal to the correct output port. OXCs with an optical core have the advantage to be bit rate and protocol independent, scalable and less power consuming (power as well as cooling). In principle they are also cheaper than the ones with the electrical core, as there is no need for transponders. Also the long term costs for network migration may be smaller thanks to protocol transparency. The disadvantages are the lack of wavelength conversion capabilities, management functions and grooming capabilities.

Hybrid Cross-connects are a combination of the two types mentioned above. If possible the signal is transmitted on the optical layer (optical core), however, in case regeneration is required or the signal needs to be added or dropped, it is sent to the electrical core.

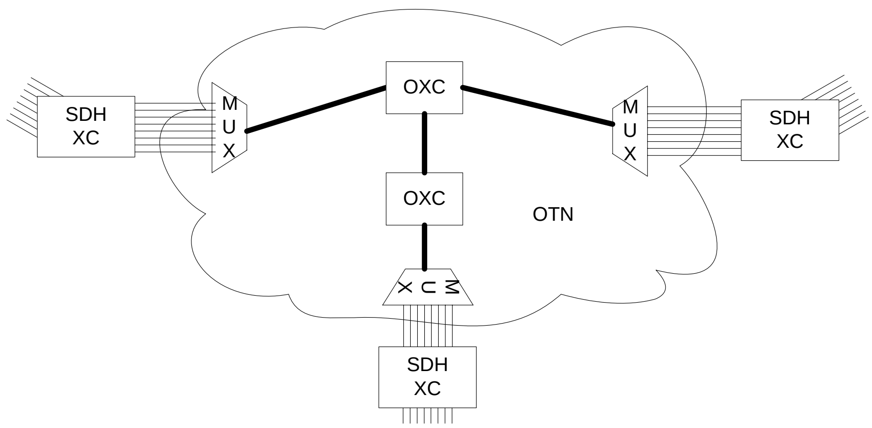
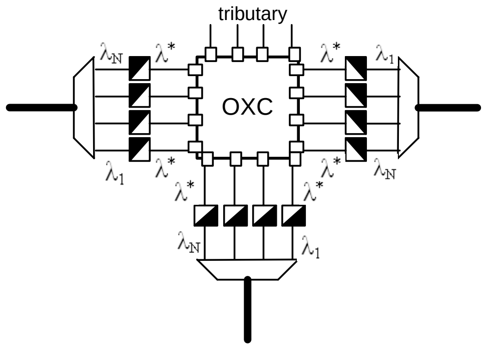


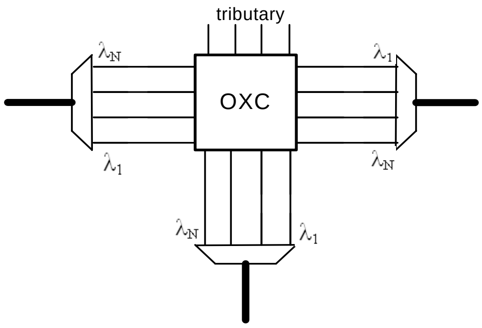
Figure 2.10: optical network using OXCs

An illustration of an OXC based node is given in Figure 2.11. Figure 2.11(a) displays an opaque OXC (OXC with electrical core). Here, the fibre is fed into the demultiplexer and split into the individual coloured wavelengths. The individual wavelengths are then fed into the long-reach transponders which convert them from the coloured wavelength to electrical and then to a standard short reach wavelength (grey light). The grey signal is then fed into a short-reach interface on the cross-connect to be converted in an electrical signal in case of a cross-connect with an electrical node. In case of a photonic cross-connect (OXC with optical core), the transponders are not needed, as shown in Figure 2.11(b). Finally, Figure 2.11(c) indicates a hybrid cross-connect with transponders in the opaque part of the node (upper part in the figure), not in the photonic part (lower part in the figure).

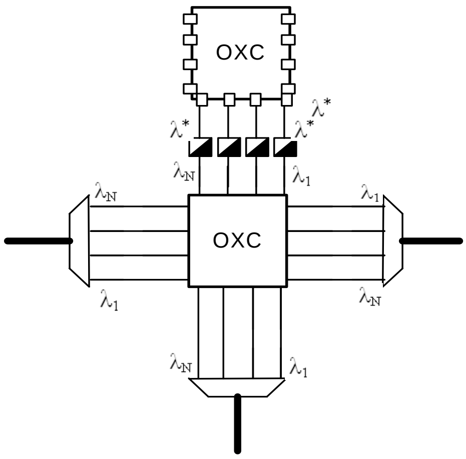
Normally, a light path operates on a single wavelength across all links between its source and destination. This is the so-called *wavelength continuity constraint*. If the optical switch is equipped with a *wavelength converter*, however, this constraint disappears and the light path may switch between different wavelengths between source and destination. Therefore, an additional distinction can be made between OXCs with and without wavelength conversion capabilities. Today, wavelength conversion is typically performed by O/E/O conversion.



(a) opaque optical cross-connect



(b) photonic cross-connect



(c) hybrid optical cross-connect

Figure 2.11: OXC node

2.2.4 Introduction of the Control Plane

A next step in the evolution of the optical layer is the transition from the static network towards the more flexible and intelligent optical layer. This layer is called the *Intelligent Optical Network (ION)*, it allows to set up and tear down new connections quickly and efficiently and to use flexible and efficient restoration schemes. An ION is also referred to as an optical network with a control plane [2.18].

A network can be decomposed into a data, control and management plane. The *data plane* is the network plane through which the end-user information is flowing. Sometimes this is called the transport plane, when the network is a transport network. The network *management plane* could be decomposed into at least a network management (NM) and a network element management (NEM) level. The management plane allows to monitor and administer the network including autodiscovery, equipment monitoring and polling, corrective actions and diagnostic tools. Network management typically consists of the 5 FCAPS areas: fault, configuration, accounting, performance and security and can be more or less sophisticated depending on the considered network. In order to provide switched in addition to (semi-) permanent connections in the transport network, a *control plane* can be introduced. The switched connection setup/teardown is initiated by a user request, whereas the permanent connections are initiated via the management/operations support system (OSS). The control plane can take over some of the tasks of the management plane.

To determine the appropriate control plane architecture, two efforts have been carried out simultaneously.

- *Generalized Multi-Protocol Label Switching (GMPLS)* was developed by the Internet Engineering Task Force (IETF) in [2.19]. Traditionally, each specific technology has its own control protocols. This requires knowledge of each technology domain, provisioning of each layer and separate management of per-domain operations functions. GMPLS is a set of protocols that will provide interoperable end-to-end provisioning of optical network devices as well as others. The idea of the GMPLS architecture is to define a common set of control functions and interconnection mechanisms that allow unified communication, routing and control across different types of underlying transport technologies like IP, ATM, SDH and WDM. The Multi-Protocol Label Switching (MPLS) label switching concept was extended in GMPLS to include other types of forwarding planes, like wavelengths. GMPLS enables seamless interconnection across different networking technologies as well as the capability to perform end-to-end “one-touch” provisioning across the heterogeneous network.
- *Automatically Switched Optical Network (ASON)* was developed by the International Telecommunication Union (ITU) in [2.20]. It defines the

different components in an optical control plane and the interaction between those components. The purpose of the ASON control plane is to facilitate fast and efficient configuration of connections within a transport layer network. It allows to support both switched and soft permanent connections, to reconfigure or modify connections that are previously set up and to perform a restoration function. The points of interaction between different domains defined in an ASON are reference points (User-Network Interface UNI, Network-Network Interface NNI). The ITU does not define any protocol specifications for ASON.

A third standardization body, the Optical Internetworking Forum (OIF) has extended several GMPLS components and defined a set of UNI and NNI protocols to address ASON requirements (which have also been fed back to the IETF)

The control plane provides the ability to automate network resource management and the service provisioning of end-to-end traffic-engineered paths, which has an important economic impact. Service provisioning has traditionally been a manual, lengthy, and costly process. The deployment of a control plane allows carriers to automate the provisioning and management of the network and promises to significantly lower the cost of operation.

2.2.5 The Optical Layer as a Server Layer to Transport IP Traffic

The transport part of the network is typically constituted of a number of layers, the optical layer being the lowest of those. The common terminology for describing layered networks is introduced in Figure 2.12. The server layer (lower layer) network makes its services available to its client layer network. Logical links connect nodes on the client layer (higher layer), i.e. client network equipment. These logical links are realised as connections through the server layer network. The client layer is only concerned about the fact that two nodes on the client layer network are indeed connected somehow, not about how this is realised in practice.

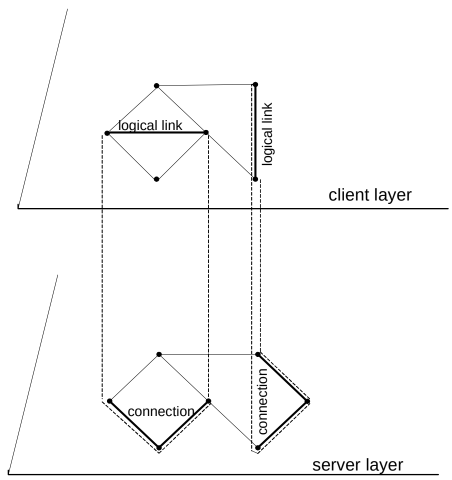


Figure 2.12: client-server model for multilayer network

Based on this general description of a layered network, two important network architectures can be distinguished: the Open Systems Interconnection (OSI) reference model [2.21] and the Transmission Control Protocol/ Internet Protocol (TCP/IP) reference model [2.22]. The former is important for the model it represents, the latter for the protocols which are widely used[2]. This leads to a hybrid reference model [2.23], as illustrated in Figure 2.13. The different levels in the observed layer stacks represent different tasks to be performed by the protocol stack, different technologies, etc.

[2] For a complete discussion on the differences between both models, we refer to [2.24].

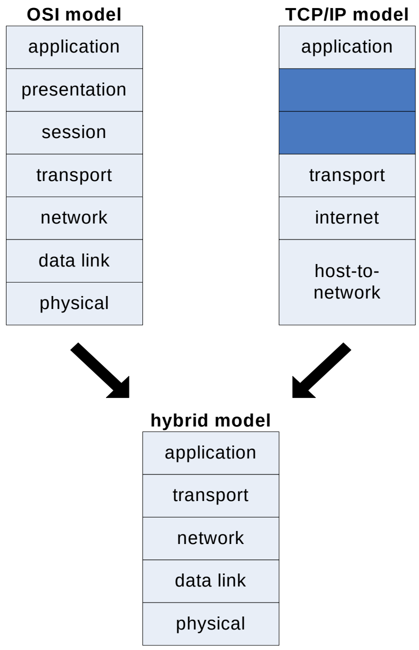


Figure 2.13: reference models for layered network architectures

Within the OSI model, the physical layer is concerned with transmitting raw bits over a communications channel. The aim of the data link layer is to provide reliable and transparent transfer of data between network entities (error detection, flow control). The network layer provides end-to-end connectivity, an important task is traffic routing. The transport layer accepts data from the higher layers and splits it into smaller units in order to provide reliable and transparent transfer of data (flow control, error correction, re-transmission). The session layer allows users on different machines to establish sessions between them. This includes session synchronization and token management. The presentation layer is concerned with the syntax and the semantics of the information transmitted. Finally, the application layer allows an exchange of application messages. The presentation and session layer are not present in the TCP/IP and the hybrid model. Also what happens below the internet layer is not specified in the TCP/IP model.

The most relevant layers for the remainder of this thesis are the network and the physical layer. The optical layer can serve as a server layer to transport higher layer traffic, in most transport networks today this is IP traffic. [2.25] distinguishes different ways to transport IP-traffic over an optical network. However, there is a trend toward layer reduction, so that only the IP layer (with Multi-Protocol Label Switching (MPLS) extensions) and the optical network are considered as full layers.

An important difference between the optical and the IP layer is that the former is a transmission layer, whereas the latter is a switching layer. A transmission layer allows to transport data from one location to another, a switching layer, on the other hand, allows to dynamically interconnect the end users and equipment connected to the network. Whereas transport network technologies like WDM and SDH are circuit switched, IP networks are packet switched. The main difference between both types is that a circuit always has a fixed bandwidth available, while packets only occupy capacity when they are actually transmitted. As a consequence, there is a difference in the way the tributary signals arriving in the multiplexer can be multiplexed in the aggregate signal. Packet flows can be statistically multiplexed onto a link (different signals are sent when the line is free) in contrast to circuits which are staticly multiplexed (e.g. based on Time Division Multiplexing (TDM), which assigns different time slots to different data streams and composes them to a new signal consisting of a cyclic consecution of different time slots, i.e. the time frame is split in parts for the different signals). Statistical multiplexing ensures that slots will not be wasted, whereas in TDM this cannot be guaranteed.

2.3 Scope of Our Work

In this thesis, we examine how the dynamic and uncertain character of the main planning inputs can be taken into account in the planning process of optical networks. Of course, the problem of network planning in general and planning optical networks in particular has already been studied in the past. The fundamentals of the network planning problem were described in [2.26] and [2.2]. Some important early references handling dynamics and uncertainty in theoretical network planning include [2.27][2.28][2.29]. More recently a number of subproblems of some practical planning issues are tackled, like the availability of multiple alternative technologies during the planning process [2.30][2.31][2.32]. The problem of network planning with uncertain inputs was studied at several fronts. Results of multiple case studies were published: planning approaches using stochastic programming [2.33][2.34], the use of sensitivity analysis when considering uncertain inputs [2.35] and network dimensioning under traffic uncertainty [2.36][2.37]. Consulting companies emphasized the importance of handling uncertainty in strategic decisions [2.38][2.39]. The traffic grooming problem in optical networks has also gained interest over the last years. Most publications, however, study the problem at a single point in time [2.40][2.41], some studies handle a dynamically changing traffic demand [2.42][2.43]. Although most planning studies typically only consider capital expenditures, some attempts were made also to include operational expenditures [2.44][2.45][2.46][2.47]. The idea of activity-based costing was introduced in the economic literature [2.48][2.49], but applications in the telecom domain are rare.

The goal of our research is to deal with some specific problems in the context of long term planning of optical networks that have not been studied in detail in the past. We study the traffic grooming problem (efficiently packing low-capacity traffic in high-capacity streams) in an IP-over-Optical network aiming at a cost-efficient migration path (Chapter 3). We study the flexibility of different types of wavelength and dark fibre lease contracts and model them using the ideas of Real Options thinking, originating from the world of stock option valuation (Chapter 4). We propose a model for operational expenditures of a telecom operator and quantify the impact of the introduction of a control plane in the optical network on the operational expenditures (Chapter 5). We aim at deriving useful practical guidelines that can be used by network planners in practice.

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3

Handling Expected Evolutions of Main Planning Inputs

“A goal without a plan is just a wish” - Antoine de Saint-Exupéry

This chapter explains how the dynamic character of network traffic demands and equipment costs can be taken into account during the planning process. Section 3.1 elaborates on the traffic demand by describing several important forecasting techniques and explains the reference model used throughout our work. We also describe what traffic demand on the optical network layer may consist of. Section 3.2 focuses on the equipment costs. A reference equipment model for an IP-over-Optical network is described, together with a technique to model cost erosion. Section 3.3 discusses the different planning methodologies to use for long term network planning together with some examples of how they are used in practice. Section 3.4 introduces the relation between traditional investment decision techniques and long term network planning approaches. We report results on cost-efficient migration from link-by-link towards end-to-end grooming. Our research results in these fields directly contributed to the publications [3.1][3.2] [3.3][3.4][3.5][3.6]

3.1 Dynamic Character of Traffic Demand

3.1.1 Traffic Growth

Over the last decade, the internet traffic has known a tremendous growth. Unfortunately, there is no single, unbiased source of information on IP traffic growth. The National Science Foundation in the US stopped measuring the growth of the IP traffic on the Internet backbone in 1995. Nevertheless, some numbers can be found in literature. Growth rates till *150%*, *200%* or even more were often cited before the Internet bubble exploded [3.7]. In the beginning of the years 2000, we witnessed a yearly growth of around *100%* [3.8]. In [3.9], Odlyzko reports on multi-year traffic growth. He indicates a more or less constant growth rate of *100%* (i.e. between *70%* and *150%*) for the period 1990 till 2002. That means he sees a Moore's law for IP traffic, similar to the one for semiconductor processing power, that defines IP traffic growth as doubling every year [3.10]. Recently, according to some sources, the growth rate seems to slow down. TeleGeography's latest survey of Internet backbone providers [3.11] reports a decrease in the global cross-border internet traffic growth rate to *49%* in 2005 (compared to *103%* in 2004). The fastest growing regions, Asia (*76%*) and Latin America (*70%*), produced only modest traffic growth by the standards of previous years. On the other hand, Cohen believes applications based on grid computing will largely compensate the decline in traditional IP traffic [3.12]. He predicts an overall IP traffic growth rate of *150* to *200%* until 2008. No matter what reports are closest to reality, internet traffic growth rates are definitely remarkable, compared to the *4%* growth rate in former telephone traffic.

In order to take the expected traffic into account during planning efforts, the use of a traffic forecast model is indispensable. Several kinds of forecasting methods are distinguished in the literature [3.13][3.14]. The most important ones are briefly discussed below.

- *Intuitive forecasting*, also known as the *Delphi method*, is a qualitative forecasting method based on independent inputs of selected experts, who contribute their subjective opinions on a particular issue. Typically, a series of questionnaires is provided to the experts, and they are encouraged to repetitively revise their answers in several rounds of questioning until they reach a consensus (reduce the variance). This technique permits to find sets of valid starting points for normative techniques (see below).
- *Trend forecasting*, or *time-series forecasting*, assumes that the future can be extrapolated from past observations. This means a predictable relationship between past and future statistics is adopted. An example is the use of least squares curve fitting to find a curve or a mathematical function that fits a set of data points.
- *Normative forecasting* relies on a set of parameters to develop forecasts, instead of using past values. When estimating future network traffic, these parameters could include population of cities, gross domestic product, consumer index, interest rate, tariffs, disposable income per area, etc.
- *Exploratory forecasting* uses the explanation of the phenomenon as the basis to forecast future values for it. The explanation can either be found in new technological information, e.g. via extrapolation of technical parameter and functional capability trends, learning curves, etc, or it can be found in

structuring and processing given technological information, e.g. via historical analogy, comparison, scenario-writing, etc. A complete technological forecast ideally should match normative forecasting (needs, desires) against exploratory forecasting (opportunities).

- *Feedback forecasting* may be constructed out of the elements of exploratory and normative forecasting. This leads to forecasting in multiple levels, where human intervention between different levels is required.

In our work, traffic forecasts are based on the normative approach described in [3.15][3.16]. This model distinguishes between three traffic types: voice traffic, transaction data traffic (mainly business generated modem and IP traffic) and Internet traffic (IP traffic not related to a business environment, e.g. people downloading web pages at home). The parameters under consideration are population for voice traffic, the number of non-production business employees for data traffic and the number of internet hosts for IP traffic. The model is specified by formula (3.1), where the constants K_v, K_t and K_i have to be determined based on the total volume of respectively voice, transaction data and IP traffic and the parameters P_i, E_i, H_i denote the population, the number of non-production business employees and the number of Internet hosts in city region i, respectively. D_{ij} is the distance between the cities i and j.

$$\begin{aligned} \textit{voice traffic} &= K_v \cdot P_i \cdot P_j / D_{ij}^2 \\ \textit{transaction data traffic} &= K_t \cdot E_i \cdot E_j / D_{ij} \\ \textit{IP traffic} &= K_i \cdot H_i \cdot H_j \end{aligned} \tag{3.1}$$

This model has been applied to a pan-European reference network in [3.17]. All relevant network topologies, traffic model[3] parameters and resulting traffic matrices can be found on [3.18]. The basic reference topology is given in Figure 3.1.

[3] Note that in a first version of the model [3.15], the distance dependence was less strong. In that model voice traffic and transaction data traffic were assumed proportional to the inverse of D_{ij} and $D_{ij}^{1/2}$, respectively. In [3.16], the model of formula (3.1) was presented as an improved version of the previous.

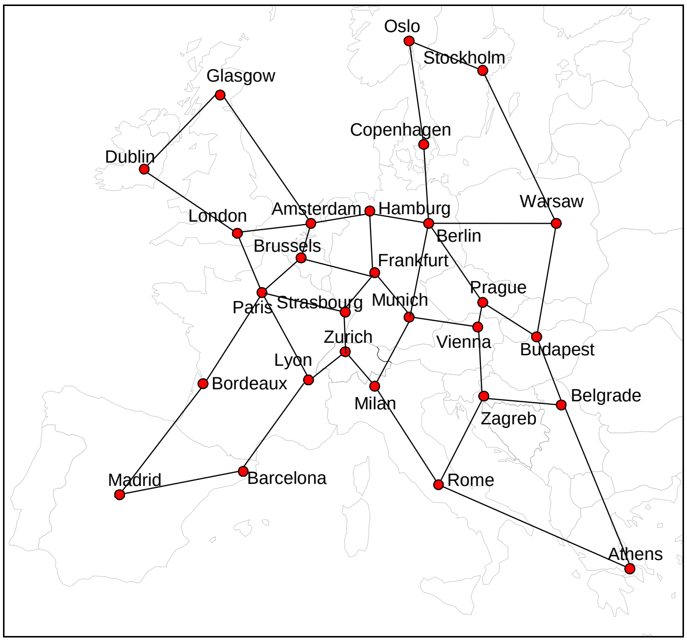

Figure 3.1: basic reference topology for pan-European network of [3.17]

3.1.2 Elasticity of Traffic Demand

Apart from the changes in the offered services and the changes in the customer preferences, which cause important traffic growth over time, other factors can also have an important impact. One of them is the price of the services offered. Its impact can be expressed using the *price elasticity of the demand*, which is defined as the percentage change in the size of the demand, resulting from a change in the price of *1%*. This is indicated in formula (3.2), with π being the price elasticity, P the price and D the demand.

$$\pi = (\frac{P}{D}) \cdot \left(\frac{\partial D}{\partial P}\right) \tag{3.2}$$

The price elasticity can directly be read from the slope of the demand curve when this curve is linear. The demand curve is a graph with the demand as its x-value and the price as its y-value. In realistic cases, the price elasticity π is between *0* and -∞. Two situations can be distinguished:

- The demand is said to be *elastic* when a price increase (decrease) results in a decrease (increase) of the demand with a bigger size, see the left part of Figure 3.2. The price elasticity has an absolute value bigger than *1* in that case. E.g. in case of a price elasticity of *-2*, reducing the price to half its value would result in doubling the demand. Elastic demand is common for luxury goods like perfumes and PC's. The demand is completely elastic if the price elasticity equals $-\infty$. The demand curve is horizontal in that case.

- The demand is *inelastic* when a price increase (decrease) results in a demand decrease (increase) of a smaller size. In this case the price elasticity has an absolute value smaller than *1*, see the right part of Figure 3.2. For example, in case of a price elasticity of *-0.5*, reducing the price to half its value would result in a demand increase of *25%*. Inelastic demand is typical for primary goods like elementary food. When the price elasticity equals *0*, the demand is completely inelastic, the demand curve is vertical and the demand is not influenced by the price.

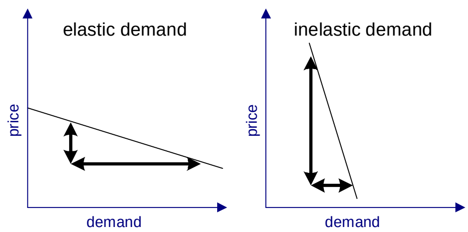

Figure 3.2: elastic versus inelastic demand

Another important factor influencing the demand for a certain asset, is the availability and price of substitute or complementary assets. The cross-price elasticity of the demand is defined as the percentage change in the demand for asset *X*, resulting from a price change for asset *Y*. It is clarified in formula (3.3), with π_{XY} being the cross-price elasticity, P_Y the price for asset *Y* and D_X the demand for asset *X*.

$$\pi_{XY} = \left(\frac{P_Y}{D_X}\right) \cdot \left(\frac{\partial D_X}{\partial P_Y}\right) \tag{3.3}$$

The concept of elasticity can be elaborated for other parameters than price. For example, the income elasticity of the demand is defined as the percentage change in the demand, resulting from an income change of *1%*.

The demand function results from a central concept of modern economics, the *equilibrium theory* [3.19]. If only a small part of the total market is considered, it is called a partial equilibrium. In the equilibrium, the demand equals the offer. When a parameter impacting demand or offer changes, both demand and offer evolve to a new equilibrium. In the demand curve, the impact of each underlying parameter is indicated by the corresponding elasticity. In order to apply this model, two steps need to be taken. First, the parameters influencing demand and offer need to be identified. Then, the corresponding elasticities need to be estimated as accurate as possible [3.20][3.21]. This model leads to the constant-elasticity demand function as suggested in formula (3.4), where D indicates the demand, A is a constant factor, the non-capital letters indicate the influencing parameters and the Greek letters denote the corresponding elasticities.

$$D = Aa^{-\alpha} b^{-\beta} c^{-\chi} d^{-\delta} \ldots \tag{3.4}$$

Note that the often used *Cobb-Douglas function* [3.22] is a special form of the general demand function indicated above. It considers the demand as a function of price and income, leading to formula (3.5).

$$D = AP^{-\pi} I^{\iota} \tag{3.5}$$

In a case study, we determined the price elasticity of the demand for broadband of residential users, based on publicly available data sources of *41* broadband providers in *25* European countries. The period under study was the year 2003. We used an econometric model considering the following parameters:

- the price of a standard broadband retail subscription P, found on the website of the different providers.
- the demand for broadband access D, expressed as the amount of subscribers. This parameter was difficult to obtain, as it is sensitive information in a competitive environment. However, companies quoted on the stock exchange include this type of information in their yearly report. As a consequence, the broadband providers considered in our study are all quoted on the stock exchange (often incumbents), so that small, start-up companies are excluded.
- the income of the potential subscribers I, estimated as the Gross Domestic Product per capita. Income clearly has an impact on the demand for broadband. People with a higher income can pay the subscription price easier and are therefore probably more interested in subscribing.
- the growth potential G, determined by the numbers of subscribers for two subsequent time periods (2002 and 2003), obtained from the yearly reports. Note that the growth potential can also be expressed by the position on Roger's S-curve, as will be explained in Section 3.2.2.
- the population density O, as reported in [3.23]. The bigger the population density, the easier to provide access to everyone.
- the price of the substitute asset S (smallband). The price for the smallband alternative could not be obtained for all broadband providers in the model, so that it is not included in the numerical results reported below.

In linear form, equation (3.6) is obtained.

$$\ln D = \ln(A) - \pi \ln P + \iota \ln I + \eta \ln G + o \ln O + \sigma \ln S + \varepsilon \tag{3.6}$$

with *ln(A)* being a constant term, π the price elasticity, ι the demand elasticity, η the growth potential elasticity, o the population density elasticity, σ the cross-price elasticity with smallband, ε is the statistical error term (reflecting the fact that we don't have perfect predictions). The elasticities together with the constant term are the parameters to be estimated. Note that the sign (+ or -) in front of the elasticities indicates the expected trend: a positive trend means that an increasing parameter leads to increasing demand, a negative trend means that an increasing variable leads to decreasing demand. The parameters are estimated using the ordinary least squares method, which calculates the best fitting curve where the sum of the quadratic deviations is minimal.

When using the model of equation (3.6), excluding smallband, we obtained both elastic price (elasticity *-2.37*) and income (elasticity *1.50*). When using the Cobb-Douglas formula, smaller elasticities were obtained (price elasticity *-1.75*, income elasticity *1.13*). The obtained results for price elasticity were compared to other studies on this topic, covering other geographic regions. The numbers we found are in line with the elasticities reported for the UK and the Australian market in [3.24] and [3.25] respectively, and only a little bit above the elasticties reported for the American market in [3.26][3.27]. However, one study covering *209* countries worldwide [3.28] reports a significantly lower price elasticity in the range *0.11-0.35*.

3.1.3 Network Demand on the Optical Layer

The traffic demand on the optical network layer originates from different applications, like plain old telephone services, voice-over-IP, videotelephony, videoconferencing, internet access, TV broadcast, movies on demand, teleworking, distance learning, file sharing, grid computing, etc. Some examples are given in Figure 3.3. Apart from the above mentioned layer 3[4] (IP/MPLS) services, also layer 2 (GbE, e.g. layer 2 VPN) and layer 1 (e.g. leased wavelength) services are sent over an optical network. The higher layer services (layer 2 and layer 3) are sent over the optical layer (layer 1) through the intermediate layer via the client-server principle explained in Chapter 2. The actual communication is made possible using the appropriate communication protocols, which are not discussed here. For the remainder of this thesis, it is only relevant to know that the traffic on the optical network layer may originate from different network services on different layers.

[4] Refer to the layered network description in Chapter 2.

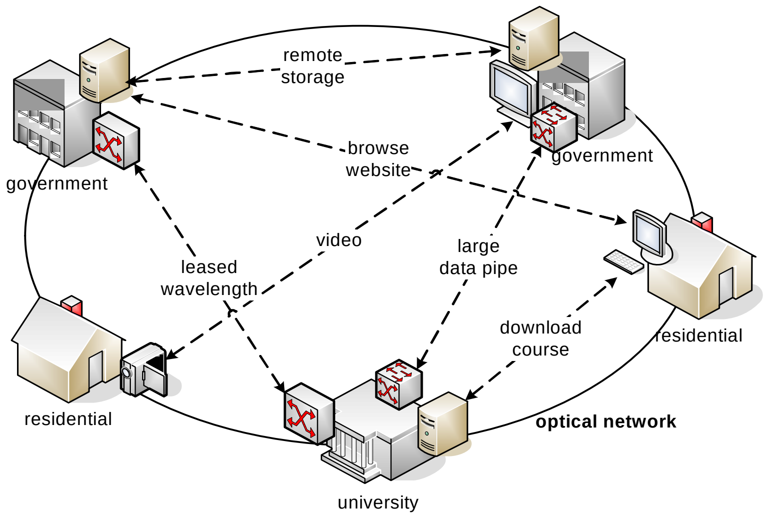

Figure 3.3: different traffic types over optical network layer

3.2 Dynamic Character of Equipment Costs

3.2.1 IP-over-Optical Equipment Cost Model

In order to estimate current and future equipment costs, an equipment cost model is required. Such a model represents the considered network equipment in its basic building blocks and defines a cost for all of those blocks. The cost figures can in principle also be obtained from vendor information. However, in practice, it is very difficult to obtain any cost figures as they are considered highly confidential information by the vendors. Therefore, within several research consortia the problem of defining a reference equipment cost model was tackled. Within our work, we refer to the cost model developed within the IST-project LION (Layers Interworking in Optical Networks). The main objective of the cost model definition is to have a reference basis to compare different network solutions from an investment cost viewpoint.

Below we discuss the simplified block models of the systems involved in an IP-over-Optical network, including their cost components.

A simplified block model for an IP router is given in Figure 3.4. This router can host up to eight slots. Each slot can be equipped with a line card. Many types of line cards can be considered: STM1/OC3 STM4/OC12, STM16/OC48, Gigabit Ethernet and Fast Ethernet, etc. Each card can be equipped with one or more ports, depending on the type of card and the speed of the interface ports. The cost of the IP router can be evaluated taking into account the following components:

- Hardware (HW) common part: processors for routing and control, buses, switching fabric, back-plane, clock and scheduling: the base system defines the system capacity in terms of bandwidth or throughput and the maximum number of interface cards that the router can handle
- Power supply, housing, conditioning
- Software (SW): Operating System and other software
- Line cards: many cards can be hosted on a single piece of equipment and the upper limit depends on the configuration of the base system

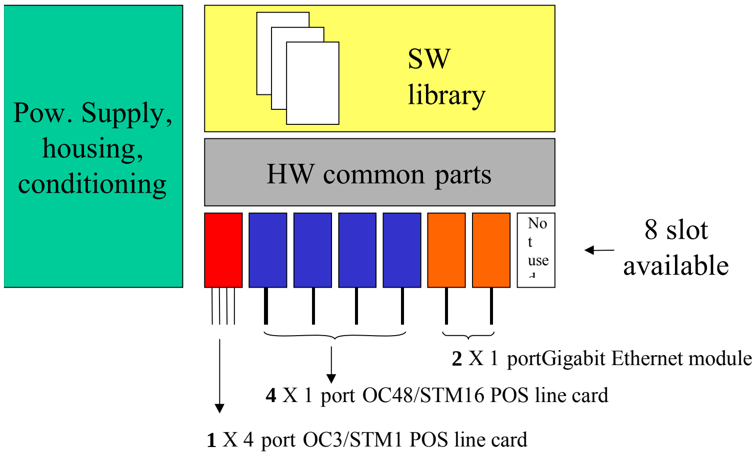

Figure 3.4: simplified block model for an IP router

Main SDH equipment families taken into account are Digital Cross-Connects (DXC), Add-Drop Multiplexers (ADM) and Multiplexers (MUX) or Line Terminators (LT). The cost of the ADM depends on the type of system (STM-1,…, STM-64) that is transmitted over the ring. Two main components influence the overall ADM cost: electrical ADM (switching matrix with tributary cards) and the LTEs (optical interfaces). The tributary cards are normally not very relevant from the cost point of view.

A simplified block model for an OXC does not refer to a particular implementation technology. The purpose of the model presented in Figure 3.5 is to give a general block model that can be adapted in a flexible way to a specific vendor or research implementation of optical switches. In particular, the model can be used for OXCs with O/E/O-conversion (i.e. switching electrical signals), as well as for OXCs that directly switch light signals (O/O/O) in their switching matrix. The following basic elements are considered in the OXC cost model:

- Input and output couples of line fibres (one couple of fibres for each line-system)

- Optical amplifiers (one for each fibre, two for each line system)
- MUX/DEMUX block (one piece for each line system)
- Transponder block with up to *W* two ways channel transponders on each block
- Switch matrix (with its own edge transponders - if present)
- Control and management supervisor block
- Input/output local (client tributary) interfaces (one interface for a couple of input and output wavelengths)

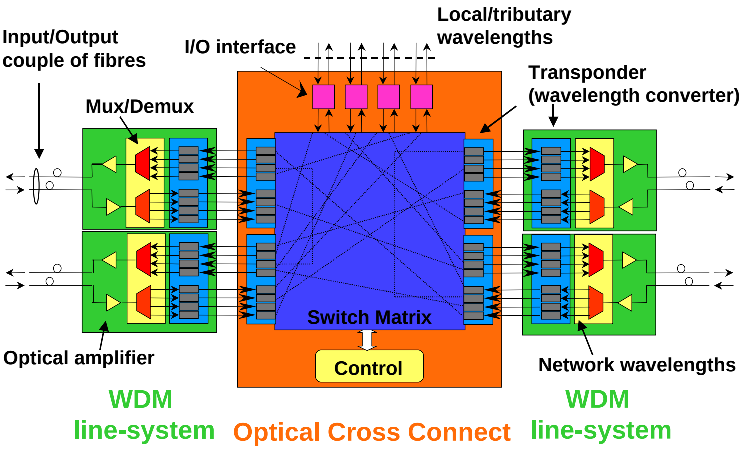

Figure 3.5: simplified block model for a generic optical cross-connect

Bi-directional line systems are assumed in the model. A couple of fibres is present on each physical link (e.g. the link connecting two OXCs). Each fibre carries a WDM signal with up to *W* wavelengths in one direction. Therefore, a couple of fibre assures a W wavelengths capacity between two switches in both directions. Wavelength conversion could be performed only on output signals, only on input signals or on both. A transponder associated to each MUX/DEMUX block is used as the necessary adapter between the line-system wavelengths and the input signal of the core matrix. The switch itself can have its own transponders. The transponders of DWDM systems are long reach transponders and the ones put at the edge of the core switch matrix are in general short reach transponders. Local/tributary signals are supposed to be available two by two, in couples of input and output wavelengths. Each couple of tributary wavelengths requires its own interface. All the wavelengths are supposed to transport the same signal at the electrical level and in this sense; the optical switch is transparent to the electrical framing format used by the client (e.g. Gbit Ethernet, STM16, etc.).

The cost model for switches with ASON capabilities is very similar to the one presented above as generic OXC model. In fact all the basic functionality at the optical and transmission layer is the same. The main difference between a generic OXC and an ASON switch is in the control plane and its cost. Switches developed for supporting ASON capabilities are more expensive because the control plane has to support routing and signaling protocols necessary to make the transmission network a full switching network via topology discovery and signaling for connection establishment.

Given the physical distance between locations, the cost of a fibre between two locations is the sum of two components: a linear component that takes into account the kilometric cost of the deployed fibre and a non-linear component that takes into account the presence of amplifiers (but not regenerators).

3.2.2 Cost Trends

As time goes by, network equipment costs will typically decrease. Several causes can be identified for that, amongst which cheaper production for bigger quantities. The *learning curve* is often used to represent the extent to which the average cost of producing an item decreases in response to increases in its cumulative total output. The learning curve model can therefore be used to predict future network equipment prices as an explanatory forecasting technique (see Section 3.1.1). The model is based on the Wright empiric law: "Each time the cumulated units production doubles, the unit cost decreases with a constant percentage", see formula (3.7). It can also be expressed by a formula where the cost C is a function of the produced output Q as in formula (3.8).

- C_Q is the cost of the Qth unit of output produced. C_0 is the cost of the first unit produced
- K is the logistic curve rate or cost reducing factor
- $b = log_2 K$ is negative, since increases in cumulative total output reduce cost. If the absolute value of b is large, cost falls faster with increases in cumulative total output than it would if the absolute value of b were small.

$$C_{2n} = KC_n \tag{3.7}$$

$$C_Q = C_0 \cdot Q^b \tag{3.8}$$

Increasing produced quantities may result from a growing market penetration of the equipment. The *logistic growth curve* is used to express the market penetration as a function of time. The logistic model was developed by Verhulst who suggested that the rate of population increase may be limited, i.e. it may depend on population density, as expressed in formula (3.9), where r_o is the maximum possible rate of population growth. In our case of the growing market penetration, the population represents the quantity of the product sold on the market. Population growth rate declines with population numbers Q and reaches

0 when $Q = Q_u$. Parameter Q_u is the upper limit of population growth and it is called carrying capacity. If population numbers exceed Q_u, then population growth rate becomes negative and population numbers decline. The dynamics of the population is described by the differential equation (3.10) which has (3.11) as a solution.

$$r = r_0 \cdot \left(1 - \frac{Q}{Q_u}\right) \tag{3.9}$$

$$\frac{dQ}{dt} = rQ = r_0 Q \cdot \left(1 - \frac{Q}{Q_u}\right) \tag{3.10}$$

$$Q(t) = \frac{Q_0 Q_u}{Q_0 + (Q_u - Q_0) \cdot \exp(-r_0 t)} \tag{3.11}$$

The logistic model has three possible outcomes, as illustrated in Figure 3.6:

- If $Q_0 < Q_u$, the population increases and reaches a plateau. This is the logistic curve, also called S-curve.
- If $Q_0 > Q_u$, the population decreases and reaches a plateau.
- If $Q_0 = Q_u$, the population does not change.

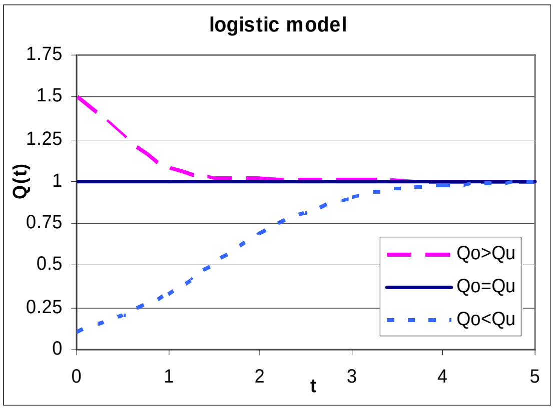

Figure 3.6: logistic model with r_0=1.5, K=1 and N_0=0.1,1,1.5 resp.

Diffusion of innovations theory was formalized by Rogers [3.29] in 1962. Rogers stated that adopters of any new innovation or idea could be categorized as innovators, early adopters, early majority, late majority and laggards, based on a bell curve. Sales as a function of time follow a bell curve. Cumulative sales as a function of time follow an S-curve[5], like the one shown in Figure 3.6. Each adopter's willingness and ability to adopt an innovation would depend on their awareness, interest, evaluation, trial, and adoption. Some of the characteristics of each category of adopter are given in Table 3.1.

adopter category	characteristics	fraction
innovators	venturesome, educated, multiple info sources, greater propensity to take risk	2.5%
early adopters	social leaders, popular, educated	13.5%
early majority	deliberate, many informal social contacts	34%
late majority	sceptical, traditional, lower socio-economic status	34%
laggards	neighbours and friends are main info sources, fear of risk	16%

Table 3.1: characteristics of different adopter categories

Note that Rogers' adoption curve is only valid in mature markets. In case of disruptive innovations, the fractions of adopters in the different categories can be completely different.

The RACE Project TITAN [3.30] proposes some evolutionary trends for network component production costs versus their technological maturity, based on a combination of the learning curve model and the logistic growth curve model, both discussed before. The trend formula is given by formula (3.12), where *t* indicates the year of the predicted cost, relative to the initial time *0*. Parameters C_0, Δt, Q_0 and K are the key input coefficients in the equation. The more reliable these input coefficients are, the more realistic the obtained cost curves can be. Most of the parameters are introduced above, but they are repeated for the sake of completeness.

- C_0 = the observed component cost at a reference time $t=0$ (reference year).
- Q_0 = the percentage of penetration volume at the reference time *0*. It is an indicator of the component maturity level reached at $t=0$. A low Q_0 value represents components with a relative short industrial life. In addition, prototype devices usually have extremely low Q_0 values.

[5] Note that the position on the S-curve indicates the growth potential for the considered product or service. This potential was one of the inputs for our econometric model to calculate price elasticity of demand for broadband access, described in Section 3.1.2.

- K = the learning curve rate or cost reducing factor (the relative decrease in the cost by the double production $C_{2n}=KC_n$). It reflects the production experience increase related with the type of component.

- Δt = the time it takes for the growth curve $Q(t)$ to go from *10%* to *90%* of the maximum penetration volume. This indicates the time the product needs to be widely commercialized. A low ΔT-value indicates a technology that will be replaced sooner or a product that will saturate the market quickly. The Δt-parameter, based on its definition, can be written as a function of the previously defined parameters r_0 and Q_u.

$$C(t) = C_0 \left[\frac{1}{Q_0} \left(1 + \exp\left[\ln\left(\frac{1}{Q_0} - 1 \right) - 2t \frac{\ln(9)}{\Delta t} \right] \right)^{-1} \right]^{\log_2 K} \tag{3.12}$$

An important advantage of this model in the current fast evolving telecom environment is that it can also be used when only a few observations are available or if historical costs are absent. In the IST-Lion project realistic values were assigned to the parameters in this model, based on market experts' opinions and vendors' information [3.1]. Those realistic equipment cost values are used in our work. As an example, in the Figure 3.7, Figure 3.8 and Figure 3.9 the cost trends valid up to year 2011 are reported, respectively for EDFA amplifiers (average cost-decrease is 10% per year), for WDM 40 channel systems, (average cost-decrease is 20% per year) and for OXC equipment (average cost-decrease is 13% per year).

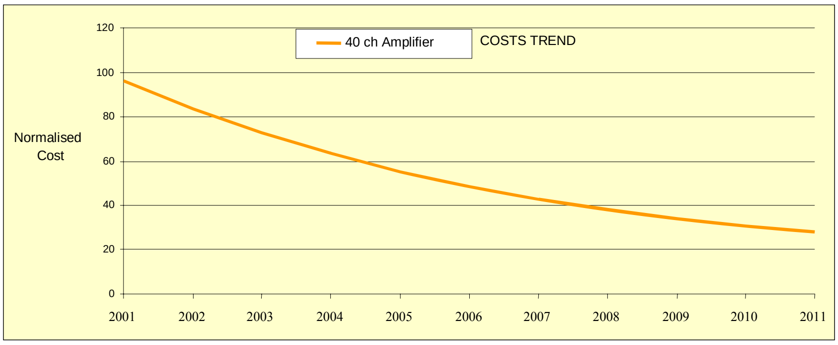

Figure 3.7: EDFA cost trend

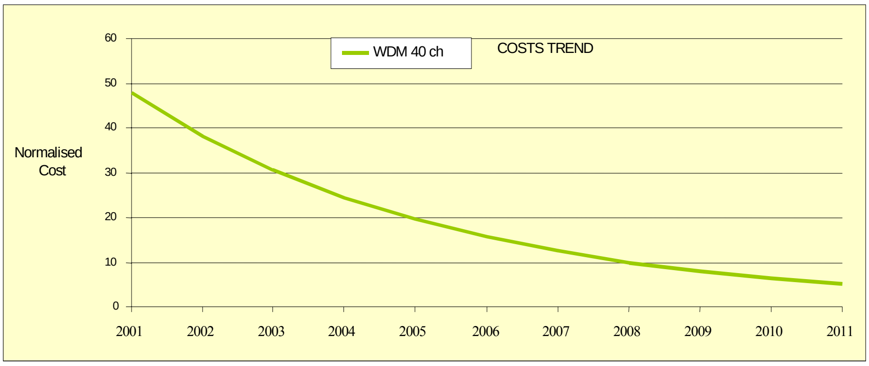

Figure 3.8: WDM cost trend

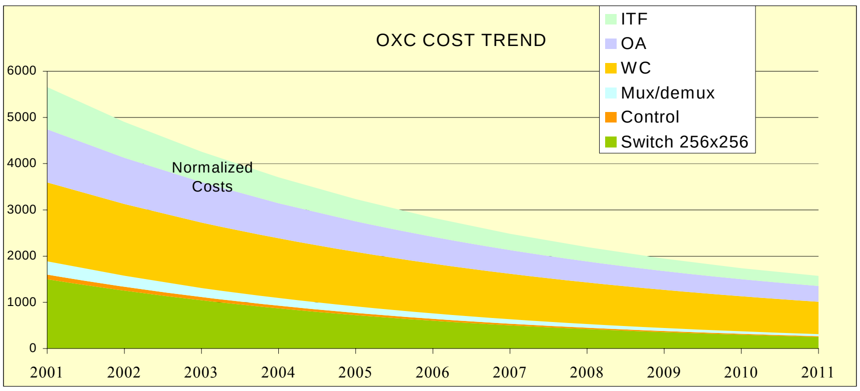

Figure 3.9: OXC cost trend

3.3 Planning Intervals and Techniques

The network planner will try to incorporate the expected evolutions for future planning inputs (network traffic, component cost, …) in his planning decisions in order to find the most cost-efficient solution. In this section, we introduce three planning methods with different levels of complexity and anticipation capability: single period planning, anticipated planning and multi-period planning.

3.3.1 Planning Intervals

We can distinguish multiple long term planning approaches, according to their capability of taking into account predictions for future evolutions and consequences of past decisions. In order to formalize them, we will start by defining some important planning intervals that will make reasoning about the methodologies easier.

The *planning horizon* is the time interval for which we want to plan the network. It is divided into several time periods.

The *augmentation interval (AI)* indicates the interval for which we have to be able to fulfil the traffic demand with the capacity we decide to install today. This is the minimum time interval during which we will not consider installing new capacity. It denotes the granularity of the planning. In our study, the augmentation interval equals the length of a single time period. In general the augmentation interval consists of the installation interval (time interval during which actual installation of new capacity happens) and the stability interval (time interval between two installation intervals, during which no changes are made to the network). We suppose that the installation interval is relative small compared to the stability interval and can therefore be neglected.

The *prediction interval (PI)* indicates the interval for which we assume to have reliable predictions for costs and demands. This is the information about future events on which we can base our investment decisions today. We can say that the prediction interval denotes 'how far we look into the future'. As network planning is about designing and dimensioning the network and augmenting capacity for the future, these predictions are of capital importance.

The *cost calculation interval (CI)* indicates how far into the future we will calculate expected costs. These costs will then be used to optimize our investment politics. It denotes to what amount we will be able to take the consequences of our planning decisions into account.

Every one of these intervals can be characterized using two parameters:

- The length of the interval: the number of planning periods.
- The fixed or moving character of the interval compared to the ongoing time. A fixed interval consisting of *N* periods begins at period *1* and ends at period

N, while the time goes from period *1* to period *N* and eventually further. A variable interval moves along with the time. The beginning of the interval always equals the current time; therefore the end is always situated in the future.

3.3.2 Planning Methodologies

By assigning several values to the parameters of the intervals defined above (prediction and cost calculation interval), we can distinguish between several planning methodologies. The three main approaches are single period planning, anticipated planning and multi-period planning.

3.3.2.1 Single Period Planning

Single period planning certainly is the most straightforward methodology. In this case augmentation and prediction interval are equal (*PI=AI*). The decision what equipment to install today is only based on the predictions for demands and costs for the current period. In every time period, the same calculations are made, not anticipating at all on any future evolution. The equipment installation decisions depend only on the expected costs for the current period (*CI=AI*). Figure 3.10 illustrates the concept of single period planning.

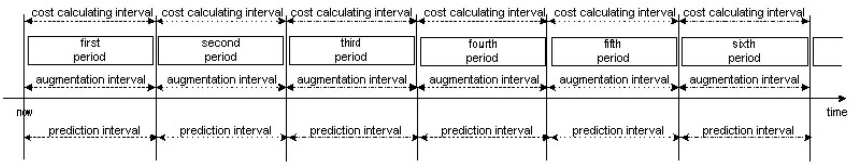

Figure 3.10: single period planning

3.3.2.1 Anticipated Planning

In *anticipated planning* the prediction interval is longer than the augmentation interval (*PI > AI*). This allows anticipating on future evolutions. Anticipated planning evaluates the situation at the end of the prediction interval for all considered scenarios and chooses the most economical one. This evaluation determines what scenario to choose. The chosen scenario is then implemented from the beginning of the prediction interval and gradually expanded according to the needs.

In this section one particular implementation of anticipated planning will be discussed. The implementation under study is using upper limits on amounts of equipment to install. In every time period, the first thing to do is to calculate what equipment we would install if we would expand the network immediately to satisfy the demands of the end of the *PI*. These calculations set an upper limit to the amount of systems to install during the whole *PI*. The decision is still based on expected costs for the current period only (*CI* = *AI*). For example, suppose we can install STM16 or STM64 line cards with a cost ratio of *2.3*. If the expected traffic in the last interval of the *PI* is *31* Gbps, the upper limits will be *3* for STM64 line card pairs (*3*10*Gbps) and *1* for STM16 line card pairs (*1*2.5* Gbps). This means that during the *PI* we will certainly need *3* STM64 cards and on the other hand we will not install more than a single STM16 line card at any point in time during the *PI*. Suppose then that the expected demand for the first time period equals *4.5* Gbps. With the cost ratio STM64/STM16 of *2.3*, this would lead to the installation of *2* STM16 line card pairs. In the case of anticipated planning, however, we have to take the upper limits for the end of the *PI* into account and therefore install a single STM64 pair instead of *2* STM16 pairs, because we know the STM64 line will become completely filled during the *PI*.

Two versions of anticipated planning can be observed, depending on the fact whether the *PI* is fixed or moving.

- *Anticipated planning with fixed predictions* presumes that new predictions are only made every *x* periods, where *x* is the length of the prediction interval. This has as a consequence that the distance over which we look into the future becomes smaller as we move to the end of the prediction interval. In this case the same upper limit is used during several time periods. Figure 3.11 illustrates the concept of anticipated planning with fixed predictions.
- In *anticipated planning with moving predictions*, we have a new prediction interval in every time period. New predictions are made for every new prediction interval. Therefore, we always have the same amount of predictions at our disposal. As a consequence the upper limit for the amount of STM16 line cards changes every period. Figure 3.12 illustrates this concept.

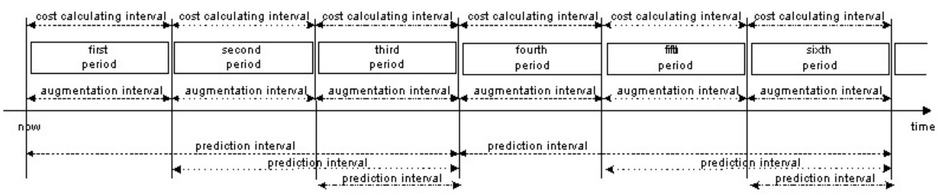

Figure 3.11: anticipated planning with fixed predictions

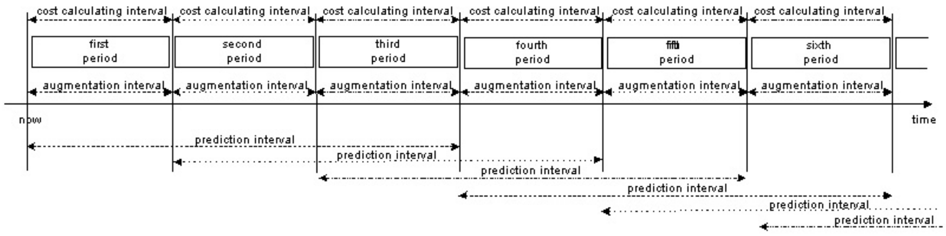

Figure 3.12: anticipated planning with moving predictions

3.3.2.1 Multi-Period Planning

In *multi-period planning* we calculate the cost of the network expansion over more than one period (*CI>AI*). In this way we are able to take into account the long term effects of a certain decision. A possible approach in this regard is to set up a decision tree by identifying several options and choosing the best of them, considering the cost of that decision over the whole *CI*. Of course for multi-period planning we need demand and cost predictions for the whole cost calculation interval (*CI=PI*).

According to the character of the *PI* we can again distinguish between two forms: using fixed predictions and using moving predictions.

- *Multi-period planning with fixed prediction interval* assumes both *PI* and *CI* to be fixed, longer than one period and equal to one another. Figure 3.13 illustrates the concept.
- In *multi-period planning with moving predictions*, we have a new prediction interval in every time period. Here we will always calculate costs over an equal amount of time intervals, making the comparison between several scenarios easier. This approach is illustrated in Figure 3.14.

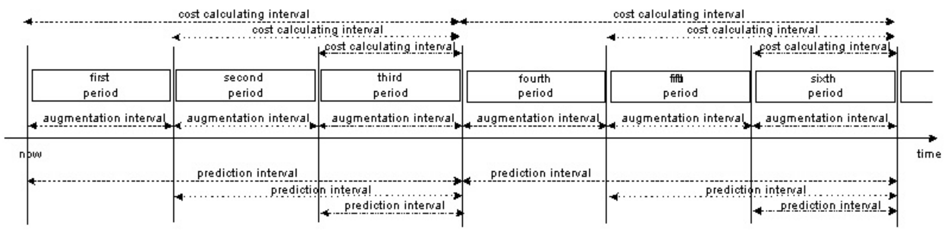

Figure 3.13: multi-period planning with fixed predictions

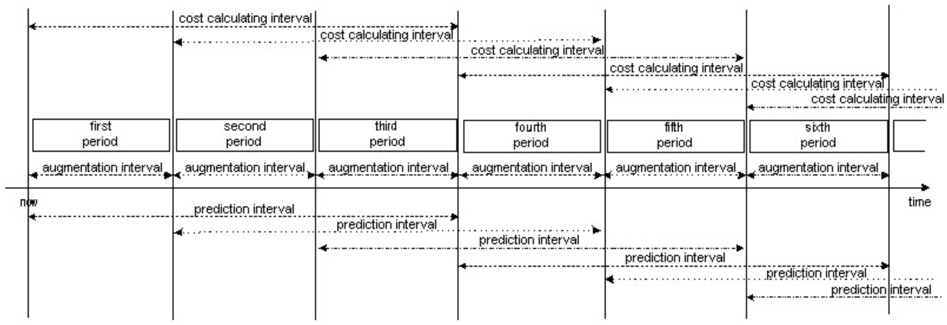

Figure 3.14: multi-period planning with moving predictions

When calculating costs over different time periods (like in multi-period planning), a basic concept to be taken into account is the *time value of money*. It is based on the observation that money that is available today cannot simply be compared to money that will become available in the future. If you receive the money sooner or spend it later, you can (in the meantime) earn some interest. The relation between a current amount of money *C* of and its future value *F* (in year *n*) is given by formula (3.13), where *i* indicates the annual interest rate. The power *n* to the term (*1+i*) indicates the principle of compound interest, i.e. when considering multiple periods (*n*) interest can be earned on interest.

$$C = \frac{F}{(1+i)^n} \tag{3.13}$$

For interest compounded a certain number of times, *m¸* per year, such as monthly or quarterly, formula (3.14) is valid, *i* still indicates the annual interest rate, so that *(i/m)* equals the interest rate per considered time period. *m* equals *12* or *4* in case of monthly or quarterly interest payments, respectively. *n* indicates the time considered in the future, expressed in years, as before. When taking the limit of *m* to infinity, the formula for continuous compounding is obtained, which is given by formula (3.15).

$$C = \frac{F}{(1+i/m)^{mn}} \tag{3.14}$$

$$C = \lim_{m\to\infty}\left(\frac{F}{(1+i/m)^{mn}}\right) = F\exp(in) \tag{3.15}$$

Therefore, when calculating total costs over a certain time frame, e.g. in a cost calculation interval longer than one period, the costs for the different time periods first need to be discounted to their present values before they can be added to find the total cost.

3.3.2.1 Summary of Methodologies

Table 3.2 summarizes the properties of the planning methodologies described above, it clearly denotes the important parameters in the long term planning process.

methodology	AI		PI		CI	
	length	character	length	character	length	character
single period	1	fixed	1	fixed	1	fixed
fixed predictions anticipated	1	fixed	>1	fixed	1	fixed
moving predictions anticipated	1	fixed	>1	moving	1	fixed
fixed predictions multi-period	1	fixed	>1	fixed	>1	fixed
moving predictions multi-period	1	fixed	>1	moving	>1	moving

Table 3.2: planning methodologies

3.3.3 Impact of Length of Prediction Interval in Anticipated Planning

In order to indicate the importance of the *PI*'s length, simulations have been performed comparing the single period planning to the anticipated planning approach. We described the following case study: we have tried to find the most suitable combination of low- and high-capacity line cards in the pan-European network of [3.17], taking into account the associated demand and cost forecasts. The planning horizon was divided into planning periods of *3* months.

Starting from the initial configuration at the beginning of *2003* we want to indicate which planning methodology results in the most cost-efficient solution, while fulfilling the expected demands for all time periods. Figure 3.15 plots the total amounts of installed pairs of STM16 and STM64 line cards over the whole network, according to single period planning and anticipated planning (with *PI*= *4*, *8*, *16* time periods). Remark that single period planning equals anticipated planning where the prediction interval is only one period long. We clearly see that the longer the prediction interval, the less STM16 line cards are installed. In the last period of our planning interval, single period planning has installed *1048* pairs of STM16 cards, whereas with anticipated planning we find *338*, *232* and *170* pairs for prediction intervals of *4*, *8* and *16* time periods respectively. Of course the required capacity has to be fulfilled, so that the opposite trend is seen when observing STM64 line cards: *11146* for single period planning and *11326*, *11352* and *11364* for growing prediction intervals.

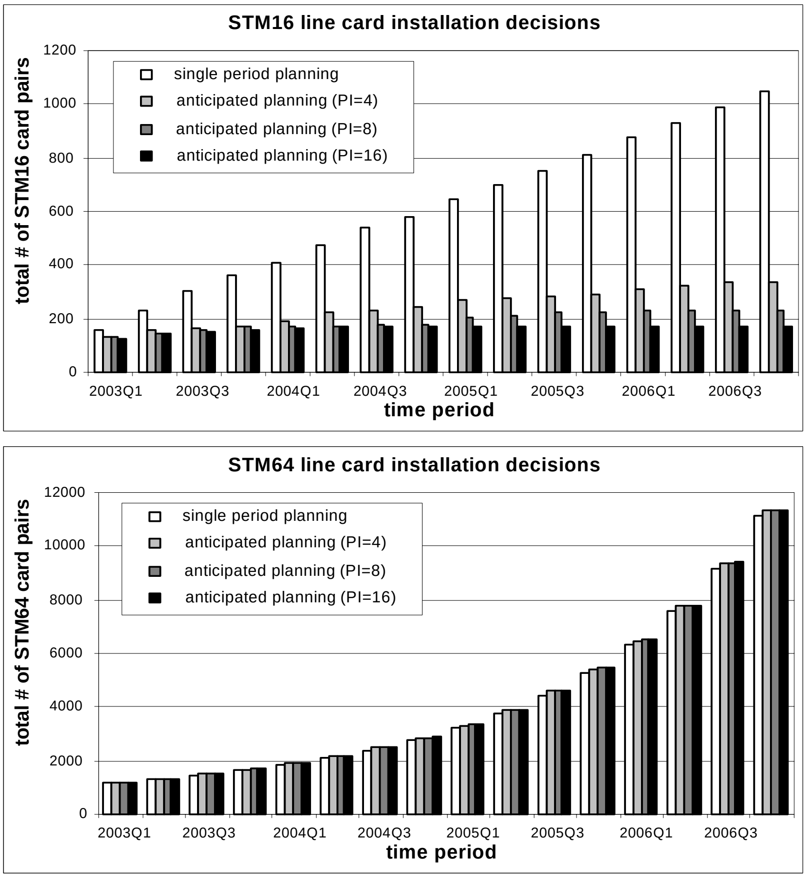

Figure 3.15: installed pairs of line cards according to different planning methodologies

Multiplying the amounts of cards needed in every time period with their costs for the corresponding period results in the total line card cost per period. Discounting the different costs per period to their present values (as explained in Section 3.3.2.1) and adding all present values leads to the total discounted costs for the period *2003-2006*. We assume a annual discount rate of *3%*, discounted quarterly in this case.

As indicated in Figure 3.16, we observe a big difference in costs between single period and anticipated planning approaches. Anticipated planning with *PI = 4* finds a solution for only *94.70%* of the cost of the solution suggested by single period planning. Enlarging the PI leads to even better results: *93.92%* for *PI = 8* and *93.45%* for *PI = 16*, but the amelioration is no longer significant. Enlarging the *PI* from *1* to *4* time periods leads to an amelioration of more than *5%*. Enlarging from *4* to *16* periods only results in a *1.25%* benefit. When we also consider the fact that long term predictions are less accurate than short term ones, it becomes clear that a *PI* of *4* time periods is the best choice in the considered case.

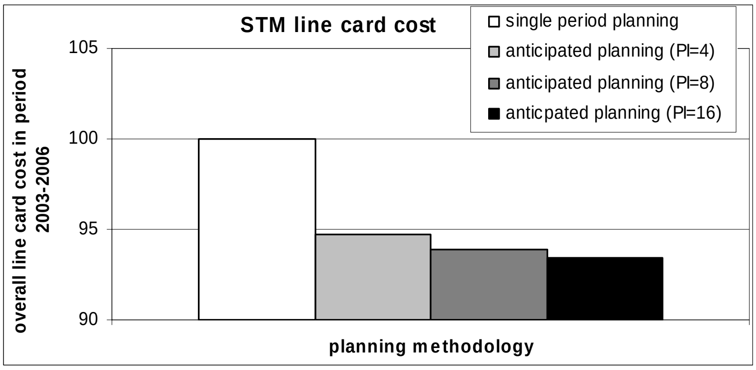

Figure 3.16: total line card costs in period 2003-2006 according to different planning methodologies

In principle anticipated planning indicates how to choose between two technological alternatives, based on the most cost efficient solution for the end of the prediction interval. The implementation of anticipated planning using the upper limit for small capacity equipment, as discussed above, was shown to be an interesting approach in case of a fixed prediction interval. In that case, we use the same upper limit during *x* periods, where *x* is the length of the prediction interval. In case of a moving prediction interval, on the other hand, this approach is not usable, as it leads to a new upper limit in every period (possibly *x* different upper limits in *x* planning periods). Other implementations of the anticipated planning techniques allowing to choose between two more fundamentally different technological solutions (e.g. deciding between fiber extension and WDM deployment), however, could be useful when using a moving prediction interval.

In conclusion we can say that anticipated planning leads to significantly better results than single period planning. Therefore a network planner should really use long term traffic predictions (*PI>AI*) while planning network expansion. It is shown here that the methodology of setting an upper limit for low-capacity cards results in line card cost savings of more than *5%*. It should be noted however that the knowledge of predictions assumes the input of an expert or a forecast model, adding an extra cost to the anticipated planning case. We strongly believe that the proposed technique would lead to important savings in the overall network planning process (not only on line card costs, but also on IP router costs, OXC costs, etc.) and that the additional cost will be small compared to the obtained benefits.

When deciding on the appropriate length for the PI, we should take into account that long term predictions are less accurate then short term ones, that the additional gain of enlarging the PI far into the future (from 4 to 16 times the AI in the example above) does not bring savings of the same order. These observations indicate that the PI should not be too long. On the other hand, it should be long enough in order to be able to really look into the future. In general, the length of the PI will probably be a small multiple of the length of the AI. In case of technological solution which is unavailable of the beginning of the planning horizon or only available at a very high cost but which is changing over time, the PI should definitely be significantly shorter than the planning horizon so that the fact that this new solution becomes available over time can indeed be taken into account.

3.4 Application of Investment Decision Techniques

The previous section indicates that network planning over a planning horizon of several years includes cost comparisons between several scenarios. *Investment decision techniques* described in economic literature [3.31] exactly have this as their goal: comparing cash flows of different projects and decide what project to choose as the most interesting one.

Figure 3.17 indicates the cash flows to be considered in a typical investment decision in an industrial environment. First there is an initial investment (e.g. buying a machine) which results in a cash out-flow. Then we obtain cash in-flows thanks to this investment (e.g. sell the produced goods) and at the end of the project there is some end value. In order to evaluate the investment decision, all the above indicated cash flows need to be taken into account. As indicated already in Section 3.3.2.1, the discounted value of all cash flows is to be considered (i.e. cash flows taking into account the time value of money when comparing cash flows for different time periods).

The cash flows used for evaluating an investment project should be *marginal or differential cash flows*, which means that they can totally be attributed to the considered project, they would not exist without the project. In case of an expansion investment, all additional incomes and expenditures that will occur during the years caused by the considered project need to be taken into account. Using *operational cash flows* means that financing costs (e.g. interests to be paid on loans) are not to be taken into account, as they are implicitly taken into account when discounting the future cash flows. Finally, cash flows are considered *after taxes*. Amortization is not directly taken into account, as it has no direct impact on the cash position, on the other hand it has an impact on profit. When amortization is higher, profit is lower. This has as a consequence that the amount of taxes to be paid decreases. More amortization therefore indirectly has a positive impact on the cash flows.

Concerning the time period to consider, several life time definitions can be distinguished: the *technical life time* ends when the machine breaks, the *fiscal life time* is the time period of the amortization and the *economic life time* is the life time during which the exploitation of the machine can be justified in an economic way. The technical life forms an upper limit for the economic life. The latter one is the relevant one in investment analysis decisions.

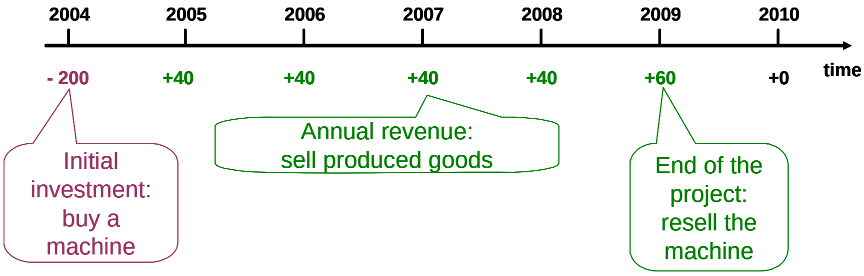

Figure 3.17: typical investment decision

The following sections list several well-known investment decision rules with their advantages and disadvantage and indicate how they can be applied for long term telecom network investment decisions.

3.4.1 Traditional Investment Decision Rules

A very straightforward investment decision technique is the *payback time*. The payback time indicates the time needed to pay back the initial investment. According to this rule, a project should be carried out if the payback time is smaller than or equal to some maximum acceptable payback time. Figure 3.18 illustrates this rule for the example of Figure 3.17. The advantages of this rule are that it gives an indication about the project risk "The shorter the payback time, the smaller risk" and that it is easy to use. The disadvantages are that it does not take into account any cash flows after the payback period and that it does not take into account the timing of cash flows or the time value of money. As an improvement the *discounted payback time* could be considered.

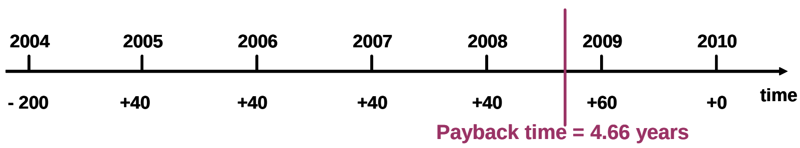

Figure 3.18: payback time

The *return on investment* of a project is given by the average future cash flow, divided by the initial investment (average over the economic lifetime of the project). According to this rule, the project should be carried out if its return on investment exceeds a certain minimum return on investment, e.g. set by company management. The advantage of this decision rule is it also takes into account cash flows after the payback time. A disadvantage is that it does not take into account the timing of the cash flows or the time value of money.

The *net present value (NPV)* of an investment project is defined as the present value of all cash flows in the project, discounted using the minimum required return on investment. It is given by formula (3.16), where r indicates the minimum required return for the considered project, which grows with the project risk. For riskless projects, the interest earned on a bank account could be used. According to this rule, an investment project needs to be carried out if the NPV is positive. The advantages of this rule are that it takes into account all cash flows, it takes into account the timing of the cash flows, using the time value of money and it takes into account the size of the project (size of the cash flows). On the downside, it should be noted that the NPV is not always easy to interpret.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{3.16}$$

The *internal rate of return (IRR)* of a project is the discount rate for which the present value of the expenses equals the present value of revenues. It is given in formula (3.17). According to this rule, an investment project should be carried out if its internal rate of return exceeds a certain minimum, e.g. set by company management. The advantages of this rule are that it takes into account all cash flows and it takes into account the timing of cash flows, using the time value of money. It is a disadvantage that it does not take into account the actual size of the cash flows. Moreover, in case the sign of the cash flows changes multiple times over the life time or in case of mutual exclusive projects, IRR no longer leads to reliable results whereas NPV does.

$$\sum_{t=0}^{n} \frac{CF_t}{(1+IRR)^t} = 0 \tag{3.17}$$

In general, investment techniques taking into account the time value of money (and especially NPV) are to be preferred. Investment decisions in telecom network planning can, like in other disciplines, have strategic, operational as well as financial consequences. The above described investment techniques give a good insight in the financial consequences of the investment. However, in most cases several types of consequences will be taken into account in the decision process. E.g. when choosing between two projects where the first has a slightly lower NPV value then the second, the first might still be considered more promising if it leads to a strategic advantage. Of course, strategic advantages are very difficult to quantify.

As telecom projects are considered to be very risky, the acceptable payback time will be small, the expected return on investment, or the internal rate of return high. Telecom companies often cite payback times of about 5 years and an expected internal rate of return of *10* till *15%*. This is also the discount rate often used when calculating NPV.

3.4.2 Trade-off between Traffic Grooming and OXC Introduction in a pan-European Network

Traffic grooming means making efficient use of the available resources. This may include traffic multiplexing as well as traffic bundling. In case of optical networks, the wavelengths are the resources we want to use efficiently. Grooming in SDH-frames over an Optical Transport Network (OTN) network is clarified using the example of Figure 3.19 and Figure 3.20. In case of *link-by-link grooming*, the traffic between the different node pairs is packed as efficiently as possible on a single wavelength. *End-to-end grooming* reserves a dedicated wavelength for each source-destination pair and no special efforts are taken to fill the wavelengths efficiently. We consider four different traffic streams, resp. between the nodes *A* and *B* (*2* Gbps), *A* and *C* (*2* Gbps), *A* and *D* (*3* Gbps) and *A* and *E* (*3* Gbps). In Figure 3.19 four wavelengths are required between *A* and *B* in case of end-to-end grooming. In case of link-by-link grooming in Figure 3.20, however, the traffic is bundled in a single STM-64 frame between nodes *A* and *B* (together *10* Gbps), so that only one wavelength is needed.

End-to-end grooming requires a lot of wavelengths, causing an important cost on the optical layer. Link-by-link grooming reduces the number of wavelengths and does not require the ability to switch traffic on the optical layer. Therefore, the use of optical cross-connects is not required in the latter case. If they are present anyway, in general, a smaller size of OXCs will suffice in case of link-by-link grooming than in case of end-to-end grooming, because of the more efficient usage of the wavelengths in the former case[6]. On the other hand, link-by-link grooming requires bigger IP routers, because all traffic is also sent back to the IP layer in the intermediate nodes. The choice between end-to-end and link-by-link grooming is also to be based on a cost trade-off between the optical and the IP layer.

[6]Note that a trade-off needs to be made between the reduction in OXC port expenses because of efficient use of wavelengths and additional OXC ports used in case transit traffic in passing through the IP router in case of link-by-link grooming.

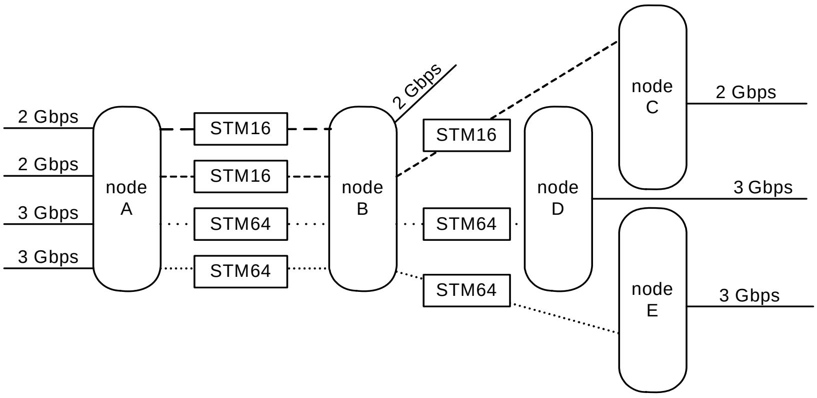

Figure 3.19: end-to-end grooming

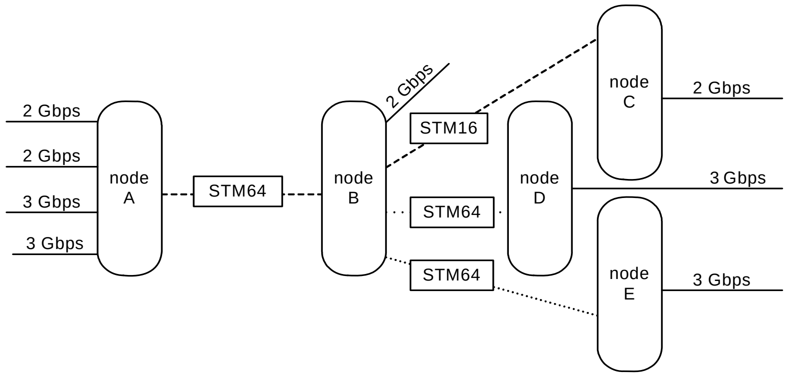

Figure 3.20: link-by-link grooming

In [3.6], added to this thesis as Appendix A, we compare both grooming approaches for the pan-European reference IP-over-Optical network and the corresponding traffic matrices of [3.17], based on expected CapEx to dimension and expand the network. We assume that the network operator under consideration attracts *30%* of the market share (i.e. *30%* of the traffic forecasted by the model). For small traffic demands, the link-by-link grooming approach (efficiently filling SDH frames) is shown to be most interesting. As traffic increases, however, we reach a point where the savings in IP layer expenses realized by end-to-end grooming compensate the extra expenses of introducing the needed optical cross-connects.

For the traffic growth considered over the time period *2004-2014*, the total costs to dimension the network according to the two extreme grooming approaches (link-by-link versus end-to-end), are shown in Figure 3.21 (only plotted till *2012*). We see that until *2008* the link-by-link grooming approach is most economical. As the demand is fairly small compared to the capacity of the considered SDH frames, efficiently filling those frames leads to an important gain. As the demand increases, the capacity of an SDH frame is better approximated by the demand for a single source-destination pair. The intersection point of the graphs is situated around late *2008*. Note that we have plotted the total cost to build the network from scratch in every time period. The intersection point of Figure 3.21 indicates that, for a new operator entering the market, it would be interesting to set up a network with OXCs and use end-to-end grooming right away from that time onwards. After *2009*, end-to-end grooming is cheaper than link-by-link grooming, which means that the gain in IP layer expenses obtained by applying end-to-end grooming is able to compensate the additional expenses for introducing OXCs in all network nodes.

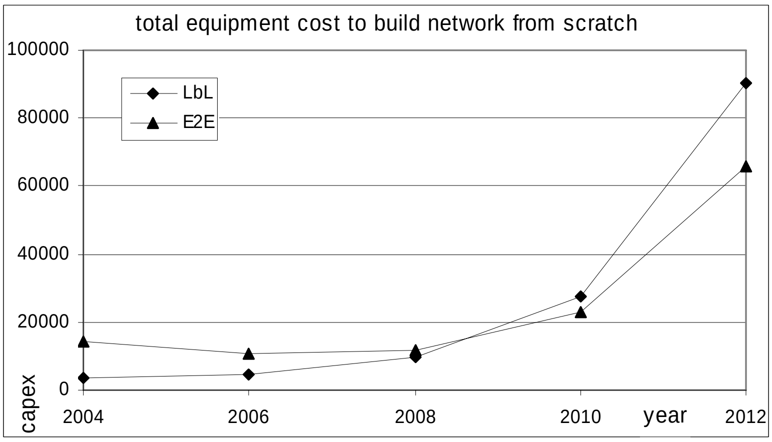

Figure 3.21: CapEx comparison for different grooming approaches, green field situation

Figure 3.22 considers an operator with an existing link-by-link grooming network (dimensioned for the traffic of *2002*) and indicates the incremental costs to expand this network, either using link-by-link grooming or using end-to-end grooming (and thus introducing OXCs in all nodes in *2004*). The important investment of introducing the needed OXCs, can clearly be observed in *2004* in the curve for end-to-end grooming in Figure 3.22. In subsequent time intervals, the incremental costs denote the cost of the additional equipment needed because of the observed traffic growth. These costs are lower in case of end-to-end grooming, because less expensive SDH line cards need to be installed in this case.

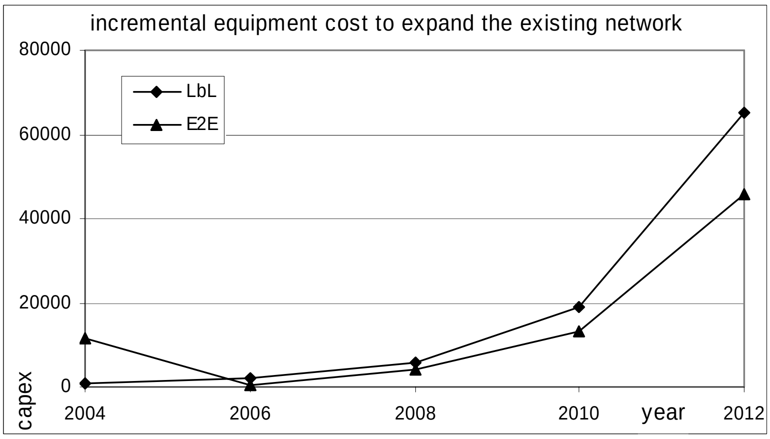

Figure 3.22: CapEx comparison for different grooming approaches, situation for incumbent

Considering the network-wide migration from link-by-link towards end-to-end grooming, the optimal migration time can be determined using the NPV technique, i.e. by comparing the sum of the discounted costs, as the revenues are equal for all scenarios and therefore not taken into account. We consider the incremental costs over the time period *2004-2014* to expand the network according to the growing traffic demand. We consider several possible timings to perform the network-wide migration from link-by-link towards end-to-end grooming, as an extension to the study of Figure 3.22, where the migration in *2004* was already studied for the incumbent operator. Figure 3.23 indicates the NPV as the sum of those incremental expenses, discounted using a discount rate of *10%*. We observe that *2010* would be the best migration time from link-by-link towards end-to-end grooming (lowest NPV).

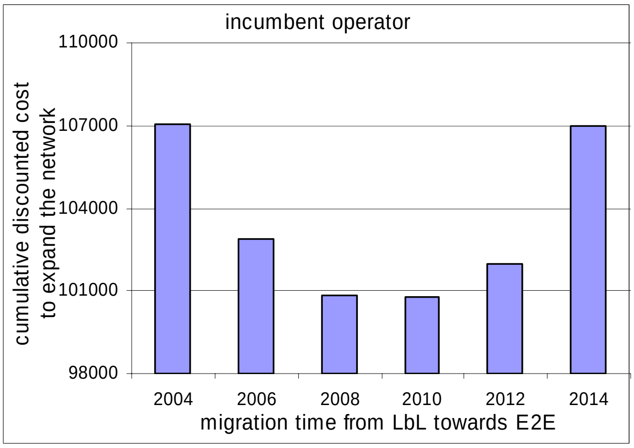

Figure 3.23: determination of optimal migration time from link-by-link towards end-to-end grooming, for incumbent operator

In practice, it is very unlikely that the migration from link-by-link towards end-to-end grooming happens at a single point in time. Therefore, we also study a possible migration path, where OXCs are introduced gradually in so-called *end-to-end grooming islands*. The position of those islands is based on a local cost comparison between the situation with and without OXCs in the node. Simulations have shown that this island based grooming approach can lead to important savings in CapEx. This type of gradual migration leads to an intermediate situation between link-by-link and end-to-end grooming, avoiding the high costs for OXCs in case of small traffic demand as well as the high costs for SDH line cards in case of big traffic demands.

Note that island based grooming tries to find the best solution over the entire planning interval, whereas optimized grooming algorithms or heuristics [3.32][3.33][3.34] aim at finding the best solution for a certain point in time (with a certain traffic). Those techniques consider a static situation. Our island based grooming approach considers growing traffic demand as well as changing component costs and studies the expected expenses over an entire planning interval.

An important parameter in the NPV formula is the considered life time of the project *N*. In case of long term network planning, this corresponds to the planning interval. In Figure 3.23 the planning period was set to ten years, *2004-2014*. In Figure 3.24 the impact of a smaller planning interval is studied. We see that, for *N* up to four years (considered interval *2004-2008* or smaller), three of the considered options have similar NPV: *expansion using link-by-link grooming*, *island based migration* and *network-wide migration in 2010* (which is actually equal to link-by-link grooming in the considered interval). *Network-wide* *migration in 2004*, leads to significantly higher NPV and therefore needs to be avoided. When considering a planning interval of six years (*2004-2010*), it becomes clear that network-wide migration in the year *2010* is a better option than continuing to keep expanding the network using link-by-link grooming. Island based grooming is clearly the best solution. Enlarging the planning interval even further makes clear that migration towards end-to-end grooming definitely is to be preferred over the continued use of link-by-link grooming. With a planning interval of eight years (*2004-2012*), network expansion based on link-by-link grooming is the worst option. Even immediate migration towards end-to-end grooming (in *2004*) is better.

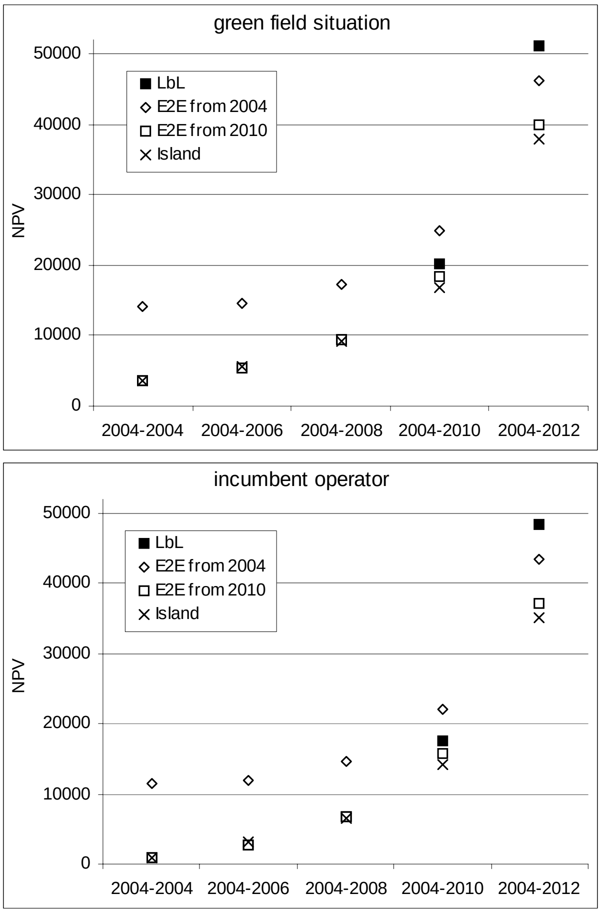

Figure 3.24: CapEx comparison between grooming approaches, based on cumulative equipment costs

Note that the use of link-by-link grooming can be seen as an implementation of single period planning, the use of end-to-end grooming from 2004 can be seen as implementation of anticipated planning (immediately choosing the solution which is best for the end of the prediction interval), whereas the use of end-to-end grooming from 2010 as well as the island based grooming approach are two different implementations of multi-period planning. When considering a planning horizon which is long enough (8 years in the considered case study), we see that single period planning leads to the most expensive solution, followed by anticipated planning and finally multi-period planning. The island based grooming approach is the most flexible of the two multi-period planning solutions and therefore is the cheapest.

Finally, also the importance of a sensitivity analysis of the obtained results is indicated in Appendix A, as it can give a good insight in the cost factors with the highest impact in the overall project. Especially the costs of SDH line cards, SR and LR transponders have an important impact on the cost comparison between the different grooming approaches.

3.5 Conclusions

After describing several existing models for estimating and representing dynamic traffic demand and network equipment costs, this chapter has focused on the application of long term planning approaches for optical network planning problems. We worked with a normative traffic forecast model and a reference IP-over-Optical equipment cost model, where cost erosion is taken into account based on a learning curve model as an explanatory forecasting technique. Single period planning, anticipated planning and multi-period planning are introduced as the three main long term planning approaches. Single-period planning is inappropriate for making long term planning decisions, as it bases its decision and cost calculations on short term forecasts. Multi-period planning is the most complex, but also the most powerful technique, working with long term forecasts and comparing costs for several network scenarios over multiple planning periods. Anticipated planning works with long term predictions, but simplifies the cost calculation step. With a smart choice for the length of the prediction interval, it can lead to valuable results. As long term network planning techniques aim at judging investment decisions in network equipment, the application of investment decision techniques to compare several possible future network scenarios is very useful. We applied the Net Present Value technique to study the trade-off between traffic grooming and OXC introduction in a pan-European network. Island-based OXC introduction was shown to allow a gradual, cost-efficient migration from link-by-link towards end-to-end grooming, in case of growing traffic demand.

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4
Handling Uncertainty of Planning Inputs

“Doubt is not a pleasant condition, but certainty is absurd”- Voltaire

This chapter deals with forecast uncertainties, one of the important challenges that network operators face today. Networks are planned over a horizon of *5* to *10* years, while it is impossible to exactly predict the future evolutions in terms of traffic growth and traffic distribution, available technologies and market shares in a competitive environment. Section 4.1 indicates how the uncertain character of input data can be categorized into four uncertainty levels. Section 4.2 evaluates a straightforward approach to handle uncertainty via the use of safety margins. In Section 4.3 we discuss several steps in taking into account uncertainty in planning decisions describing some uncertainty handling techniques from literature. Section 4.4 makes a risk analysis for an optical network operator, indicating the most important threats originating from uncertain traffic and equipment cost forecasts. Section 4.5 introduces the ideas Real Options thinking to deal with flexibility in uncertain planning problems. In Section 4.6, this technique is applied to several possible network migration approaches using dark fibre or wavelength lease. Finally, Section 4.7 attaches a broader meaning to the value for a network operator, taking into account immaterial factors, like attitude towards risk. Our research results in these fields directly contributed to the publications [4.1][4.2][4.3][4.4][4.5][4.6].

4.1 Uncertain Character of Traffic Demand and Equipment Costs

Available strategically relevant information, e.g. concerning inputs for the network planning process, tends to fall into 2 categories [4.7]. First, it is often possible to identify clear trends, such as market demographies, that can help define potential demand for a company's future products or services. Second, if the right analyses are performed, many factors that are currently unknown are in fact knowable, e.g. performance characteristics for current technologies, the elasticity of demand for certain stable categories of products, and competitor's plans to expand capacity.

The uncertainty that remains after the best possible analysis has been undertaken is what we call *residual uncertainty*, e.g. the outcome of an ongoing regulatory debate or the performance characteristics of a technology still under development. An important aspect of planning under uncertainty is to define the scope of this residual uncertainty, since that is a crucial input to determine the most suitable technique for the support of the decision making. The general framework of [4.7] is widely adopted and classifies the notion of uncertainty into four different levels, as illustrated in Figure 4.1:

- **Level I: A Clear-Enough Future.** In circumstances with a limited uncertainty, some experts can make forecasts that are accurate enough to base decisions on. In that case, the residual uncertainty can be considered irrelevant for the decision under consideration and deterministic techniques can be applied. In the past, where telephony was dominant in transport networks and was subject to a virtually certain 3 or 4% annual growth, we could assume a clear enough future.
- **Level II: Alternative Futures.** On the second level of uncertainty, experts are able to identify a number of discrete scenarios for the future. However, it is impossible to indicate which of those will turn into reality. This level of uncertainty can occur e.g. in case of changes in the legislation. There might be different ideas from different parties, in which case it is unclear which will become law.
- **Level III: A Range of Futures.** A range of plausible futures can be identified as a near continuum of finely differentiated discrete future scenarios. The range is determined by a limited set of key variables, for which the actual future value is somewhere within the predefined range. Concerning voice traffic again, which is relatively easy to forecast, we can see an example of a range of futures in the fraction of this voice traffic that will be delivered by voice-over-IP instead of traditional telephony: the future fraction of voice-over-IP traffic is somewhere in the range between 0 and 100% of the total voice traffic. At this uncertainty level, it is useful to

characterize the uncertainty using random variables with some (continuous) probability distributions.

- **Level IV: True Ambiguity.** Multiple dimensions of uncertainty interact, what causes an environment that is virtually impossible to predict. At this level, experts don't even succeed in identifying a range of future evolutions. There is simply no basis to forecast the future at the time of decision making.

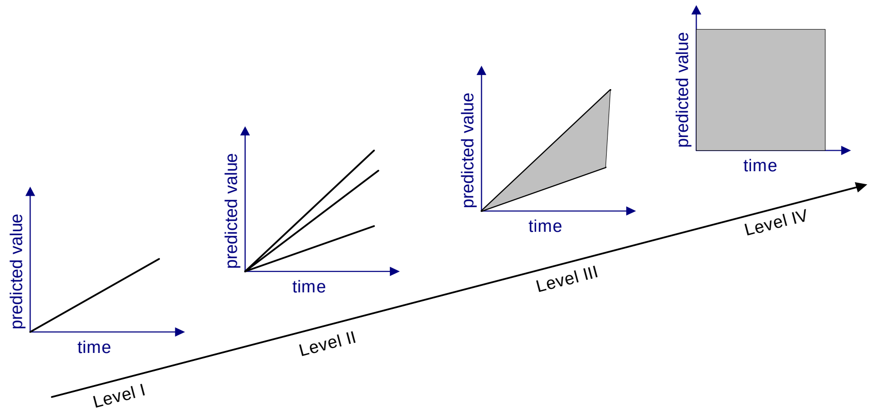

Figure 4.1: uncertainty levels

Problems of the first uncertainty level are very rare in strategic network planning. In case of medium term planning, the uncertainty of the demand forecast can often be classified in level II. For long term planning problems, we are confronted with problems in level III. In practice, however, although level III might give a better description with the continuum of future demand scenarios, some planners assume level II uncertainty even in long term planning in order to be able to work with a smaller number of characteristically different scenarios [4.7][4.8][4.9]. In any case, if one is able to postpone capacity planning decisions for a while and wait for more information so that some discrete scenarios are revealed, level III problems will naturally evolve to level II. At level IV uncertainty often prohibits us from planning, however, level IV situations are rather rare and tend to migrate to level II or III situations over time. Our work focuses on network planning problems facing uncertainty of level II or III.

4.2 Straightforward Approach: Making Use of a Safety Margin

Knowing the important risk associated with traffic uncertainty for a network operator, it is clear that the design of the network should be sufficiently robust to errors made in the forecast [4.10]. In this regard, a straightforward extension of deterministic planning approaches, as described in Chapter 3, is to add some safety margin to the deterministically calculated capacity requirements.

We distinguish two planning approaches using safety margins to incorporate the effects of uncertainty: a priori and a posteriori adjustment. Both models are widely used in practice today. Their popularity can be explained by their conceptual as well as computational simplicity.

- In case of *a priori adjustment*, the safety margin is added to the inputs of the planning problem. Therefore, a different safety margin value can be used for every input variable.
- In case of *a posteriori adjustment*, the margin is added to the sharply calculated result after all calculations are performed, so that only one safety margin value can be used.

Table 4.1 indicates the sum, maximum and product of two uncertain planning inputs with *v1* and *v2* as their expected value, *m1* and *m2* as the applied a priori adjustment safety margins for the two inputs resp. and *m* as the a posteriori adjustment margin.

	a priori adjustment	a posteriori adjustment
sum	$v_1 \frac{(100+m_1)}{100} + v_2 \frac{(100+m_2)}{100}$	$(v_1 + v_2)\frac{(100+m)}{100}$
maximum	$MAX\left[v_1 \frac{(100+m_1)}{100}, v_2 \frac{(100+m_2)}{100}\right]$	$MAX[v_1, v_2]\frac{(100+m)}{100}$
product	$v_1 \frac{(100+m_1)}{100} \cdot v_2 \frac{(100+m_2)}{100}$	$(v_1 \cdot v_2)\frac{(100+m)}{100}$

Table 4.1: a priori and a posteriori adjustment methods

In [4.1], attached to this thesis as Appendix B, we compare the use of a fixed safety margin to the case where the static traffic matrix is replaced by a matrix of random variables whose expected value is equal to the predicted traffic (the former matrix). This approach is similar to the one described in [4.11]. Depending on the actual planning input we are modelling, the appropriate probability distribution can be different. In circuit-switched network, for instance, it is natural to use a discrete distribution for the number of connections between a node pair. In our study, we modelled expected inputs to the reference traffic model of Chapter 3 (population *P*, number of non-production business employees *E*, number of Internet hosts *I*) as well as traffic matrix entries (Gbps) as continuous random variables. Note that normal distributions are most widely used to model uncertain planning inputs, sometimes motivated by the central limit theorem stating that the sum of several independent random variables approaches a normal distribution. In [4.5], we indicate that also the use of uniform and triangular distributions may lead to good results.

Figure 4.2 illustrates the use of the safety margin (added a priori or a posteriori) and the use of random variables with probability distributions for the dimensioning problem under traffic uncertainty.

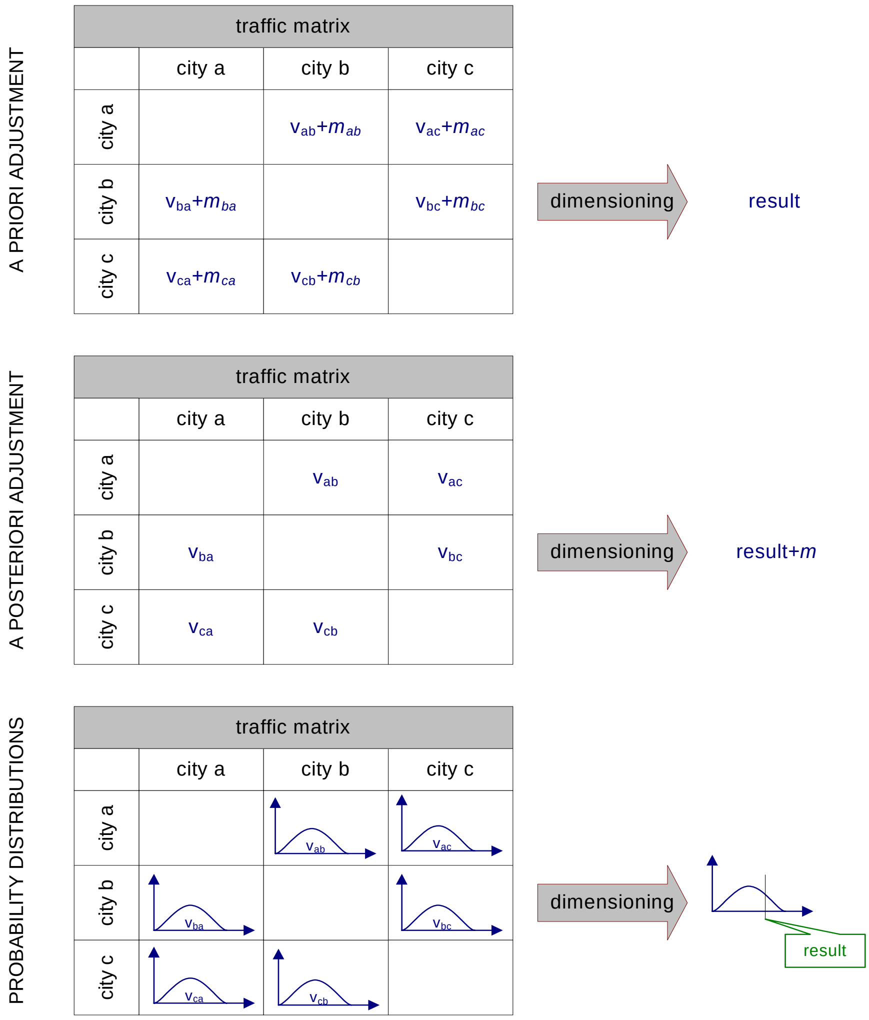

Figure 4.2: taking into account traffic uncertainty in dimensioning calculations

We assume that, in order to model an uncertain planning input, three essential parameters are needed: the *predicted value* expressing for instance an expert's view, the *uncertainty level* indicating the doubt there is about the presented predicted value, e.g. estimated by the standard deviation on the associated probability distribution, and the *confidence parameter* indicating how often the real value of the calculated output parameters would be in the confidence level (e.g. *95%*).

Appendix B relates the predicted value, uncertainty level and confidence parameter of the a priori and a posteriori adjustment approaches to those of the approach based on probability distributions. This allows to indicate that, under some conditions, it is possible to determine a safety margin value which allows a priori or a posteriori adjustment to approximate the case where the uncertain variables are represented using probability distributions. This appropriate value is a function of the confidence parameter, the ratio of the predicted values, and the number of operands.

The expression for the safety margin for the addition of two uncertain planning inputs *x1* and *x2*, represented by normally distributed variables, with *v1* and *v2* as mean values, respectively and percentual standard deviation p for both of them is given in formula (4.1). m represents the safety margin, $r=v_1/v_2$ is the relative magnitude of the predicted values and c is the confidence parameter.

$$m(p, r, c = 84\%) = p\sqrt{r^2 + 1}\,/(r + 1) \tag{4.1}$$

In practice, however, it is often infeasible to determine a useful safety margin value before the start of the planning calculations. This can for instance be the case when the shape of the distribution of the result is not known in advance, because of the skewness of the input distributions, the considered operations, etc. Some general observations concerning the safety margin are given below.

- Leaving all the rest unchanged, a growing ratio of the predicted values of the operands causes the appropriate safety margin to decrease (for small values of the ratio), as could be expected by the obtained formulae for *m(p, r, c)*. In Figure 4.3, which plots the limit value y_{limit} for the sum found by a priori adjustment relative to the analytical value (analytical value is shown by the 100%-line in the figure), this difference is indicated by the decreasing trend of the curves from the value for *v1/v2=1* towards the value for *v1/v2=10000*.
- The difference between the appropriate safety margins for operands in the same order of magnitude and in a completely different order of magnitude, grows with an increasing confidence parameter (when the uncertainty level is fixed). This is also illustrated by Figure 4.3 for confidence parameters of *84%* and *97.5%*. An intelligent choice (taking into account the ratio of the parameters) for the safety margin is thus even more important when the confidence parameter grows. Remark in this context that confidence

parameters in the range of *95%* (or higher) are common in realistic planning problems.

- The appropriate safety margin value decreases with the number of operands. It is expected to increase, however, with the correlation of the operators. Correlated variables[7] will have a bigger standard deviation on their sum, leading to a bigger appropriate safety margin.

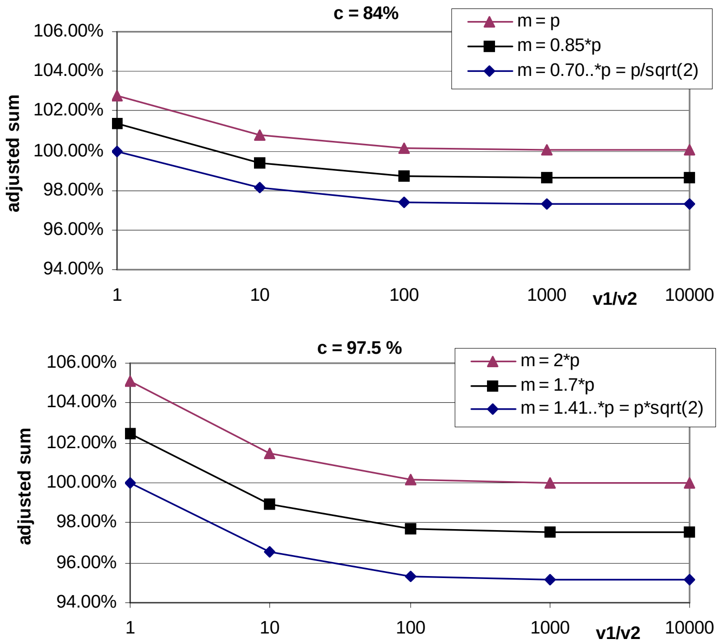

Figure 4.3: influence of the predicted values ratio (r)

As a consequence of the difficulties to define a correct safety margin as a function of the parameters mentioned above, network planners often use a fixed safety margin value. Based on a realistic planning problem for a reference pan-European core network, including forecasting future network traffic from uncertain inputs and dimensioning a network to accommodate an uncertain traffic demand, we have shown that the use of a fixed safety margin value may lead to incorrect planning decisions, such as underestimation of the impact of the

[7] In a lot of studies statistical independence between traffic matrix inputs is assumed. However, in practice some correlations definitely exist. Their strength might depend on the specific situation: short term versus long term predictions, traffic in access versus core networks, traffic matrix entries which have source or destination node in common versus completely distinct node pairs.

input uncertainty and overdimensioning in case of inaccurately modelled dimensioning problems. For instance, naively setting the safety margin to $p \cdot \sqrt{2}$ when adding uncertain future traffic demands in a dimensioning problem where the confidence parameter equals *97.5%*, may result in serious capacity shortage if the actual ratio of the predicted values turns out to be *100* or more (which might be the demand ratio between a busy and a quiet link). A priori adjustment is to be preferred over a posteriori adjustment, especially in cases where multiplicative operations are involved.

4.3 Different Steps in Taking into Account Uncertainty in Planning Decisions

It is a common misunderstanding that experts and powerful tools can forecast future evolution sufficiently accurate. This is impossible, planning under uncertainty will always remain a difficult task. No technique or model can completely remove the uncertainty. Tools and techniques can only help the planners to reduce the level of uncertainty they are confronted with correctly and adapt their planning decisions accordingly. In this Section, we discuss several uncertainty handling techniques and indicate what kind of problems they can deal with.

- **Risk adjustment technique.** A common approach to deal with uncertainty is to adapt the discount rate of the cash flows in the NPV calculation, in order to adjust for the risk of the project [4.12]. The base principle of adjusting the discount rate is that investment projects need to have a return which is high enough to compensate the investors in a correct way. When the associated cost is expressed as the return required by the financers, it is called the *cost of capital*. Cost of capital can be defined per project or for the entire company. The latter is called the WACC, the *weighted average cost of capital*.[8] The WACC provides an appropriate means by which to calculate the discount rate if the project under consideration is small relative to the company as a whole, the entire project has the same level of risk, the financing of the new project does not lead to a significant change in the capital structure of the firm. For projects that are riskier or safer, the required project return can be different, although very difficult to determine. The

[8] The WACC is defined as the weighted sum of the costs of equity and liabilities, weighted in proportion to the share both of them contribute to the company's capital structure. The cost of liabilities and debt can easily be determined by the interest rate to be paid. The cost of equity can be determined by the security market line (SML) of the Capital Asset Pricing Model (CAPM) [4.13], which expresses the cost of equitiy c_e as a function of the risk free interest rate r_f, the average interest rate on the market r_m and the factor β which indicates the systematic (non-diversifiable) risk: $c_e = r_f + \beta\,(r_m - r_f)$.

concept of adjusting the discount rate for risk has led to a commonly used discount rate of 10 to 15% for telecom projects.

- **Scenario analysis.** This technique is suitable for uncertain variables that can be classified in level II. In its most simple form, scenario analysis takes a pessimistic and an optimistic view on the uncertain variables and performs a deterministic analysis for both of them. In general, the different unique scenarios are planned for, each of which is associated with a probability measure (often difficult to quantify). Various approaches to quantify characteristically different demand patterns for the evaluation of robustness of a survivable network are discussed in [4.14].
- **Decision trees analysis (DTA).** Some large projects present a wide variety of alternatives with varying degrees of uncertainty. In contrast to the previous technique, this technique does not only consider the scenario itself, but also the decision you can make during the course of the scenario.
- **Simulation analysis.** This method allows to imitate a real life situation. It considers all possible combinations of all variables, after you specify the probability distributions of each of the input variables. *Monte-Carlo simulation* randomly generates values for the uncertain variables over and over again in order to simulate the model. Simulation analysis can be seen as an extension of scenario analysis or decision tree analysis, which allows to consider an enormous amount of scenarios, in order to simulate a continuous range of possible future values.
- **Stochastic programming.** This technique allows to take into account uncertainty while solving an optimization problem [4.15]. A two-step approach is suggested (two stage formulation with recourse). In a first step a certain decision is taken. In the second step, the expected cost based on this decision is minimized. Therefore, an additional objective is added to the problem. Moreover, extra boundary conditions are added in order to indicate the relation between the decision in the first step and the consequences in the second.

A technique also often mentioned in the context of uncertainty is *sensitivity analysis*. Sensitivity analysis can be used to determine how sensitive the evaluation parameter (e.g. the profitability of the project) is when a single factor, or specific group of factors, changes by a given amount. It is useful in identifying what are the key drivers in a project. It can indicate how large a forecast error on a key driver can be tolerated, before the project becomes unacceptable. Sensitivity analysis helps to get a better insight in the uncertainty inherent to the planning problem, but it does not indicate how to take it into account in the planning decisions.

4.4 Risk Analysis for Optical Network Operator

In this Section a sensitivity analysis is performed for an optical network operator, in order to find the impact of the most important uncertain input parameters.

4.4.1 Cost-Benefit Analysis

We have used the reference pan-European network topology and the corresponding estimated traffic demand predicted by the traffic growth model of [4.16][4.17], also described in Chapter 3. The dimensioning of the optical network layer was performed using OPNET's WDMguru [4.18]. We assumed unprotected shortest path routing. The resulting Bill Of Material (BOM) was used as an input for the cost-benefit analysis described below. A planning interval of 5 years was considered, where the network was built from scratch in the first planning period and incrementally extended in the following periods to cope with the growing traffic demand.

Capital Expenditures (CapEx) resulted directly from the BOM, taking into account the equipment unit costs of Table 4.2. Cost erosion over time was assumed, following an exponential curve. The yearly cost reduction factors assumed for the different equipment types are also specified in Table 4.2 (based on [4.19]).

Operational Expenditures (OpEx) were estimated to be proportional to the CapEx, we assumed a 50% OpEx/CapEx ratio in this case. This is in the range of the ratio found in [4.20].

Revenues were assumed to be proportional to the amount of traffic over the network. We applied a revenue per routed STM1 leading to a break-even point after 2 years and taking into account an annual decrease in revenue per STM1 of 25%.

		equipment type			unit cost	yearly cost reduction
link	fiber	WDM TM			100	20%
		OA			75	10%
		REG			100	20%
	channel	REG Card			60	20%
		LR transponder			30	20%
node	electrical	DXC	type1	64 ports	300	20%
			type2	128 ports	600	
			type3	512 ports	1000	
			type4	1024 ports	2000	
			type5	2048 ports	3500	
			type6	4192 ports	6000	
		tributary port STM1			1	20%
		trunk port STM16			5	20%
	optical	OXC	type1	64 ports	600	13%
			type2	128 ports	1600	
			type3	512 ports	4000	
			type4	1024 ports	10000	
			type5	2048 ports	40000	
			type6	4192 ports	100000	
		tributary port STM16			10	13%
		trunk port STM16			10	13%

Table 4.2: equipment unit costs and cost reduction rates

In a first phase, we have performed a static cost-benefit analysis. Undiscounted, incremental costs and revenues for the considered European network are indicated in Figure 4.4. The NPV calculated by summing all discounted cash flows (using a discount rate of 15%) over the life time of the project (the 5 year planning interval) is positive (1 933 070 units), so that the project will indeed be profitable under the considered assumptions. This static case is used as the base case for the risk analysis in the following sections.

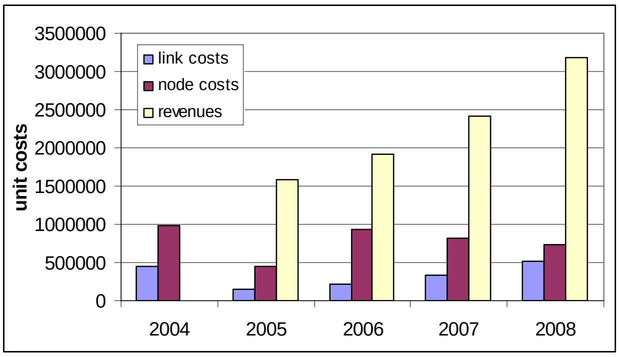

Figure 4.4: project costs and revenues

4.4.2 Uncertain Equipment Costs

As explained above, we assume exponentially decreasing equipment costs. However, even then, future equipment costs are only assumptions and exact future costs are difficult to predict. Therefore, in this section, we study the impact of the uncertain character of the actual equipment costs on the overall situation for the network operator, more specifically, on the NPV.

We evaluated the risk by performing Monte Carlo simulations in our static model, using Crystal Ball [4.21]. The different equipment unit costs of Table 4.2 were assumed to be the uncertain assumptions and they were modelled using Gaussian distributions with the estimated unit cost (indicated in Table 4.2) as their mean value and a 10% standard deviation for all uncertain parameters. We studied different scenarios:

- scenario 1: link costs are uncertain, uncorrelated, node costs are fixed
- scenario 2: node costs are uncertain, uncorrelated, link costs are fixed
- scenario 3: all costs uncertain, uncorrelated
- scenario 4: all costs uncertain, all fully correlated
- scenario 5: all costs uncertain, link costs fully correlated, node costs fully correlated (2 independent groups)

The impact of the different scenarios on the standard deviation of the obtained NPV is shown in Figure 4.5. In the scenarios without any correlation between the uncertain input costs (scenarios 1 till 3), the obtained standard deviation is below 10%, which was assumed as the standard deviation on the uncertain equipment costs. This can be explained by the observation that the percentage standard deviation on a sum of independent uncertain variables (with positive mean values and equal percentage standard deviation) will always be smaller than the percentage standard deviation on the input variables. The NPV calculation is a summation of cash flow, a lot of them being uncertain values (*dimensioning * uncertain equipment costs*) so that the previous applies here.

On the other hand, if we consider scenarios 4 and 5 where the uncertain costs are fully correlated (in one group and two groups respectively), we note that the standard deviations are high above the defined *10%* value. This is clear by the fact that the (positive) co-variance between the input values must be taken into account to calculate the variance of their sum or difference.

The observations concerning the impact on NPV of correlated input values are very relevant for a network operator, as it is a realistic assumption that different equipment costs (e.g. on a single network layer) will be correlated, to some extent. This implies a risk for the operator, as correlated input values have a bigger impact on the overall NPV value. When applying the common practice of using a safety margin as discussed in Section 4.2, e.g. during the network dimensioning phase (adding a percentage margin to the calculated value for the case the actual value would be bigger than the forecasted one), there is an additional importance of knowing the correlation between the uncertain parameters, as this may effect the choice of the margin. In case of correlated input variables, the appropriate safety margin is larger.

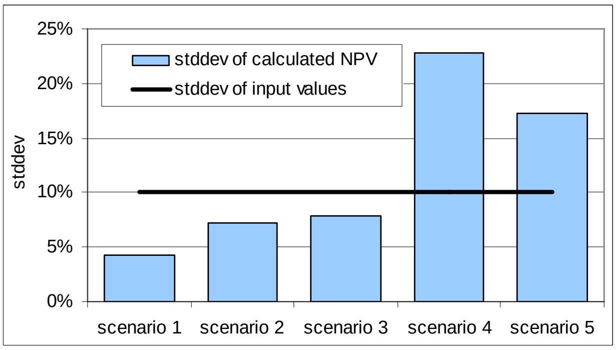

Figure 4.5: impact of correlation

We performed a sensitivity analysis[9] to find out how important the uncertainty on the inputs (traffic and costs) is to the output value (NPV). In scenario 1, the NPV is most sensible to changes in the LR transponder costs. They contribute to *85%* of the variance of the total NPV value, whereas the other link costs have a far smaller impact. Despite the relatively small unit costs for LR transponders (compared to other link costs), this is caused by the big amount of LR transponders required in the network.

In scenario 2 the biggest OXCs (type5 with *1024* ports and type6 with *4096* ports) have the biggest impact, followed by the STM16 ports in the OXC. DXCs and their cards have a smaller impact.

When both link and node costs are considered uncertain, as is the case in scenario 3, we see that NPV is most sensible to changes in OXCs with *4096* ports, followed by LR transponders and OXCs with *1024* ports, as illustrated in Figure 4.6.

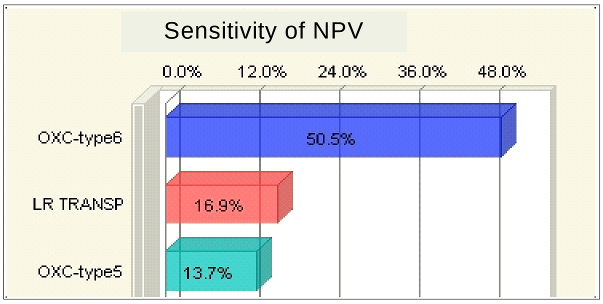

Figure 4.6: sensitivity of project value to equipment costs

When all equipment costs are fully correlated, as is the case in scenario 4, changes to all of them have the same impact to the variance of the overall NPV.

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[9] Crystal Ball calculates sensitivity in the following way. It calculates the Pearson correlation coefficient for each pair of an uncertain input value and the obtained output value, averaged over all trails in a simulation run. The sensitivities reported in this section (including those in Figure 4.6) are expressed as Contribution To Variance, which is the normalized square of the sensitivity coefficient (obtained by adding all squares, dividing the squares by the sum of all squares to ensure a sum of 1 and converting the normalized values to a percentage). The Pearson correlation coefficient is obtained by dividing the covariance of the two variables by the product of their standard deviations. For two random variables X, Y with mean values, μ_X, μ_Y and standard deviation σ_X, σ_Y respectively, it is given by formula (4.2).

$$\rho_{XY} = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y} \qquad (4.2)$$

Finally, when they are correlated in two groups (link and node costs separately), as in scenario 5, we note that the node costs have the biggest impact. This was also clear from Figure 4.4 where we see that node costs constitute the biggest part of the overall network cost.

When considering all scenarios, we find the following overall top 5 of equipment types with a high impact on the NPV: OXC-type6, LR Transponders, OXC-type5, optical tributary and trunk ports and OXC-type4.

4.4.3 Uncertain Traffic Demands and Equipment Costs

Uncertain traffic has received more attention in the literature so far than uncertain equipment costs. Also joint analysis of the impact of uncertain traffic and costs are rare. Again, we have performed some simulations on our model using Monte Carlo simulations. If we assume traffic to be more volatile (50% standard deviation) than costs (10% standard deviation), we find a sensitivity of about 3% to the equipment costs (equipment costs account for 3% of the variance of the NPV) and about 97% to the changes in the traffic. If we assume a standard deviation of 10% on both traffic and costs, we find a sensitivity of 8% to the equipment costs and 92% to the changes in the traffic. Taking into account that we made some simplifications concerning the costs of big DXCs and OXCs (more ports than the ones in Table 4.2), the real sensitivity to costs could probably be even a bit higher. Also assuming a correlation between the different cost inputs would lead to a higher impact on the output value.

4.4.4 Most Important Findings

This section considers the incremental planning of an optical network with growing traffic demands, over a 5 year planning interval. We have performed a sensitivity analysis concerning uncertain future equipment costs and traffic demands. The following guidelines can be drawn from this study:

- Sensitivity analysis using Monte Carlo simulations is a useful and straightforward approach to estimate the risks following from uncertain planning inputs.
- Correlation between uncertain input parameters to the planning process has an important and often underestimated impact of the project value.
- Although they are of second order importance, uncertain equipment costs can still have an important impact on the overall value for a network operator.
- The following equipment types were shown to have the biggest impact on the NPV: OXCs, LR transponders, and optical tributary and trunk ports.

We therefore believe that paying insufficient attention to cost or traffic uncertainty, correlation between input parameters or sensitivity analysis during the planning phase can cause serious risks to the network operator.

4.5 Real Options Valuation

In Chapter 3 we discussed several investment decision techniques and how they can be applied for long term network planning. Net Present Value came out as the most interesting solution. However, this technique completely fails to incorporate input uncertainty. We already mentioned in Section 4.3 that adjusting the discount rate to be used in NPV is an attempt to cope with risk. However, it is very difficult to come up with the correct discount rate. Moreover, NPV, even with adjusted discount rate, is unable to take into account flexibility in the project. In economic literature, Real Options were suggested as an extension to NPV, overcoming some of its shortcomings. It is based on an analogy between investment projects and stock options.

4.5.1 Some Option Terminology

An *option* can be defined as the right for a limited time, to buy or sell the underlying value for a predetermined exercise price. Exercising the option (i.e. buying or selling the underlying value) is always optional; it is a right, not an obligation. This right holds for a predetermined time, till the so-called *exercise date*. The underlying value is the asset which the option concerns; this may be assets, real estate, precious metals, etc. The *exercise price* is the price for which the option can be exercised by its holder.

Some additional terminology is introduced below:

- *Option price = option premium*: price to acquire the option, price to acquire the right
- *Exercise price = strike price*: price for which option holder can exercise the option (fixed)
- *European option*: can only be exercised on the exercise date
- *American option*: can be exercised till the exercise date
- *Call option*: option holder has right to buy the asset
- *Put option*: option holder has right to sell the asset

4.5.2 Option Valuation

Let's start by considering the *end value of an option* (value on exercise date). Assume e.g. a call option, the right to buy a stock for a predetermined exercise price X. Assume that the market value of the stock on exercise date is S.

- If $S < X$, the option is useless. Everyone interested in the stock will directly buy it on the market instead of using the option.
- If $S > X$, the option is valuable. It is more interesting to use the option than to just buy the stock on the market. The value of the option is $S - X$

In summary, we can say that the value of a call option on exercise date equals *MAX (0, S-X)*, as illustrated in Figure 4.7. It is clear that the option always has a positive value.

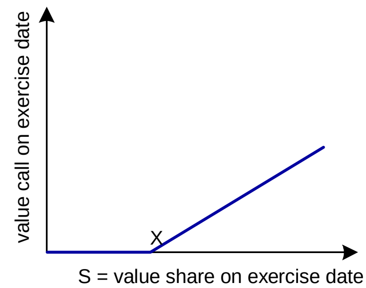

Figure 4.7: value of call option on exercise date

The total value of an option consists of the end value (value the option would have if today was the exercise date, see above) and the time value. The properties of the *time value of an option* are listed below.

- It grows with a growing time to maturity: Over a longer time, the chance is bigger that good changes will occur.
- It grows with volatility of share value: Big volatility, big chance the value will change a lot before exercise date, bigger option value. Remark that this is the opposite of what we see in case of traditional valuation techniques (e.g NPV), where the volatility has a negative impact on the value.
- It is small when the difference between S and X is big: A big |S-X| means that the value of the option (+ or -) not likely to change, there is a small time value. A small |S-X| means a big chance that the option value will change, this means a big time value.

In economic literature, there exist several option valuation techniques (techniques to indicate the value of an option). The *binomial tree* method is a straightforward method that assumes *2* possible end values for the stock value. It can be extended for more time periods, if software is used. A popular (European) stock option pricing formula was suggested by *Black and Scholes (B&S)* [4.22]. It determines the option value *C*, based on the exercise price of the option *X*, the value of the underlying stock *S*, the variance of the return on the stock σ^2, the risk-free interest rate *r* and the time until the expiration of the option. Black-Scholes assumes arbitrage-free pricing (financial transactions that make immediate profit without any risk do not exist) and it assumes that stock prices S follows a Brownian motion. Option valuation eliminates the need to adjust the discount ratio for risk, the risk-free interest is used, e.g. in Black&Scholes. [4.23] states that the uncertainty is accounted for with the estimation of the variance, thus determination of a risk-adjusted discount rate is not necessary.

4.5.3 Financial versus Real Options

Using the translations of Figure 4.8, real options can be translated into stock options and the above introduced options valuation techniques can also be used for real options. In this way, e.g. B&S formula is often used in the literature to valuate real options. When doing this, however, we should be aware that some assumptions for stock options might not always hold for real options. First of all, stock option valuation is based on arbitrage-free pricing. This is difficult to prove for real options, as those are not traded. Secondly, B&S assumes that stock prices *S* follow a Brownian motion, considering real options we should prove that the NPV of the cash flows generated by the project follow a Brownian motion. Also binomial tree and option valuation techniques based on simulation can be extended from the financial towards the options world, whereas they allow a more intuitive use than B&S.

	stock option	**real option**
X	exercise price of the option	investments required to carry out the project
S	value of the underlying stock	NPV of the cash flows generated by the investment project
σ	volatility of the stock	risk grade of the project
r	risk- free interest rate	risk-free interest rate
t	life time of the option	time period where company has the opportunity to invest in the project

Figure 4.8: real options compared to stock options

4.5.4 Real Options as an Extension of Net Present Value

Real Options theory allows to attach a value to the options that become apparent during the life time of an investment project, like expanding, reducing or stopping the project. It can be considered as an extension of the Net Present Value (NPV) rule. NPV discounts the cash flows using a fixed discount rate and evaluates a now-or-never investment decision. For risky projects, it is very difficult to determine an appropriate discount rate. Real Options theory, on the other hand, includes the options that may be present in an investment project with uncertain parameters. It therefore includes flexibility in the decision process and avoids the need to determine an adjusted discount rate for valuating the options. The value of a project can therefore be extended by the value of the options [4.24], as indicated in formula (4.3)

$$\begin{gathered}\textit{expanded (strategic) NPV} = \\ \textit{passive NPV of expected cash flows} + \textit{value of options}\end{gathered} \tag{4.3}$$

Real Options valuation is especially useful for two-phase investment decisions, with an optional second phase (e.g. only performed if market situation is favourable). This explains the suitability of real options for uncertain investment problems. By the time of the second phase of the investment, the market situation is already more clear, so that a well-advised decision can be taken.

The term Real Options was introduced in 1977 [4.25]. It referred to the application of option pricing theory to the valuation of investments in real assets where a large part of the value is attributable to flexibility and learning over time. After some academic attention in the 1980s, interest in real options from industry rose considerably since mid 1990s. [4.26] provides a comprehensive introduction to Real Options theory, with a lot of practical examples.

4.5.5 Applications of Real Options

Real Options theory can be applied on several types of investment problems under uncertainty where flexibility is present. The 7S framework [4.27] distinguishes 7 types of real options, see Figure 4.9.

real option category	real option type	description	examples
Invest/ grow	*Scale up*	Well positioned business can scale up later through cost-effective sequential investments as market grows	• high technology • R&D intensive • multinational • strategic acquisition
	Switch up	A flexibility option to switch products or processes given a shift in underlying price or demand of inputs or outputs	• small batch good producers
	Scope up	Investments in proprietary assets in one industry enables company to enter another industry cost-effectively	• companies with lock-in
Defer/ learn	*Study/start*	Delay investment until more information or skill is acquired	• natural resource companies • real estate development
Disinvest/ shrink	*Scale down*	Shrink or shut down a project if new information changes the expected payoffs.	• capital intensive industries • financial services • new product introduction
	Switch down	Switch to more cost-effective and flexible assets as new information is obtained	• small batch good producers
	Scope down	Limit the scope (or abandon) operations in a related industry when there is no further potential for business opportunity	• conglomerates

Figure 4.9: types of real options – the 7S framework

Real Options theory has been successfully applied in modular plant expansion, [4.28], R&D for new drug development [4.29][4.30], mine exploration [4.31] and other fields. In the telecom sector, it has been applied to value telecom companies (e.g. amazon.com, see [4.32] during the dotcom-boom, explaining why it was handled sceptical afterwards. [4.33] describes a theoretical model to find the optimal time to open a new segment in an already existing network (not necessarily a telecom network). [4.34] studies the application of the problem of optimal timing of investment into new capacity in a telecom network, presenting a mathematical model. [4.35] values lighting decision on dark fiber based on Real Options tree valuation.

In [4.4] we study the introduction of an OXC in an existing network with growing traffic demand as a two-phase decision. First we need to decide on the introduction of the OXC itself (only including interface cards needed to switch the current traffic). Afterwards we have the option to expand the OXC with extra interface cards if needed. The Black&Scholes valuation formula is used. OXC introduction was beneficial in those nodes where the expected overall traffic demand exceeds the router capacity within the next 2 years and the fraction of transit traffic surpasses *60%*. Real Options thinking also allowed us to determine the most suitable timing for the introduction, implicitly making the trade-off between postponing the investment till the additional initial investment of the OXC is compensated by additional revenues from the additionally routed traffic and advancing the introduction to avoid revenue loss because of insufficient node capacity.

4.6 Uncertainty in Dark Fibre Deployment

The presence of multiple telecommunication providers and their past investments in optical layer capacity, have led to a wide availability of dark fibre throughout Europe. Therefore, for a new network operator planning to deploy a new network, there is no need to acquire all physical capacity himself.

Starting from a *fully procured* network, where the new operator lays out all cable and ducts himself, towards a situation where capacity is leased in a form ready to use, several ownership models to deploy a network can be distinguished. The CapEx costs for the operator willing to deploy a network are constituted of the costs for buying the required equipment (lease costs are considered OpEx). The amount and type of equipment the operator needs to procure differs for the different considered scenarios and is indicated in Figure 4.10. In case the operator obtains a *dark fibre* network, besides the network node equipment, also some transmission equipment needs to be bought, whereas this transmission equipment is owned by the external service provider in case of a *leased wavelength* network. In case the considered operator leases a *managed SDH* or *managed Ethernet* network, in principle all equipment is owned by the external provider. Only an IP router can be added by the new operator.

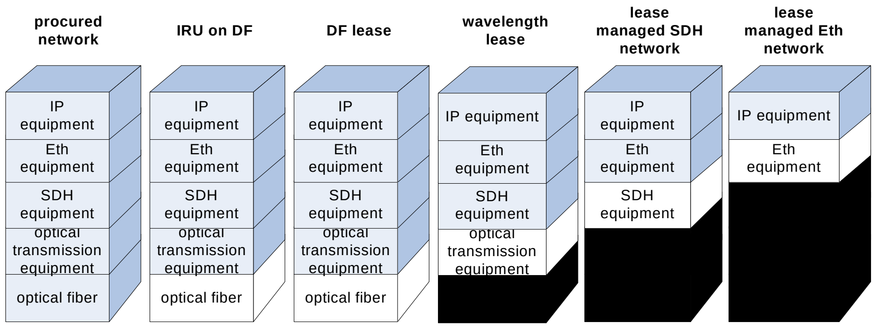

Figure 4.10: several ownership models to deploy a network

In [4.6], attached to this thesis as Appendix C, we carried out a case study considering a Belgian network, where we compare several network deployment scenarios over a *15* years planning horizon, using Real Options thinking to model the ability to respond to uncertain changes in the traffic during the course of the planning horizon. Real Options theory can be seen as a way to quantify Decision Tree Analysis. Monte Carlo simulation is applied to valuate the real options, as this approach is very intuitive and flexible. We prefer it over Black&Scholes to get a better insight in the problem. We distinguish the following network deployment scenarios:

- acquisition of an Indefeasible Right of Use on dark fibre (IRU on DF)
- leasing of dark fibre (DF lease)
- leasing of wavelengths (lambda lease)

An IRU can be seen as a lease with a longer contract term, we assume *15* years in our study. The contract terms for DF and lambda lease were *5* and *1* year, respectively. We assume that we can only switch to another network deployment scenario at the end of the contract term, this means that we don't consider the possibility to prematurely end the contract. In order to keep the problem comprehensible, we split the planning horizon in two parts. We assume the predictions for the first *5* years to be more or less reliable and therefore consider the case where the network is deployed for the traffic forecasted for the first *5* years and has an uncertain evolution during the last *10* years. In the case study described, we consider year *5* to be the only point which allows flexibility to change to another network scenario, which is a simplification of the realistic situation. This is illustrated in Figure 4.11. We assume information concerning the traffic evolutions for the last *10* years is unknown upfront, but becomes available in year *5*. The lease contract size (number of fibres or wavelengths) is determined at the beginning of the contract term, based on the traffic forecasts available. All equipment costs and lease contract costs figures assumed are given in Appendix C.

The problem to be solved is which network scenario (IRU on DF, DF lease of lambda lease) to start deploying in year *0*, taking into account the uncertain future traffic evolutions as well as the flexibility to respond to them during the course of the planning horizon, namely in year *5*.

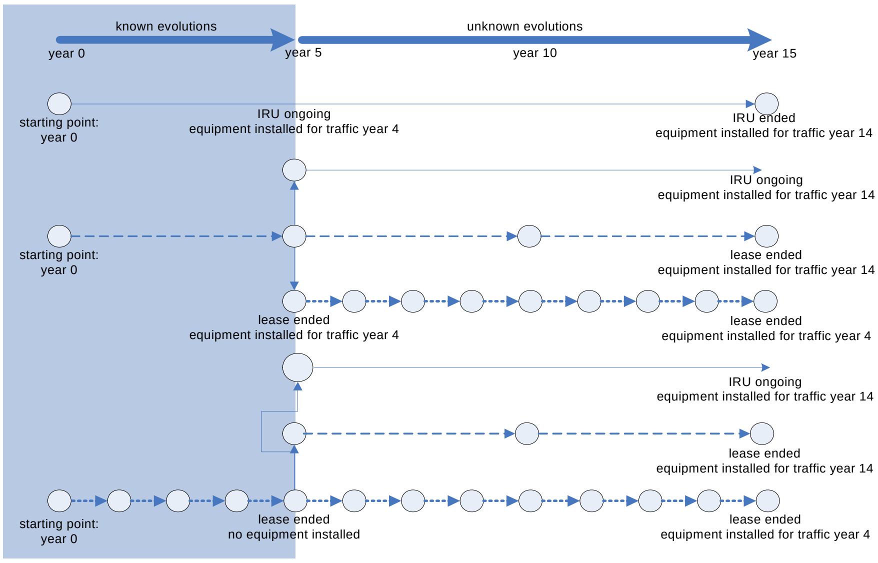

Figure 4.11: considered flexibility to switch between scenarios

The information of Figure 4.11 is mapped to the network migration tree of Figure 4.12, which gives more information. The nodes in the top part of Figure 4.12 indicate what equipment has been installed in the network by that time as well as the status of the lease contract. We see that the edges *a*, *c* and *f* have a common destination node and the same holds for the edges *b* and *e*. In both cases, a dark fibre scenario was followed in the last *10* years to that optical layer transmission equipment has been installed for the traffic of the end of the planning horizon in both nodes. In case a lambda lease scenario is followed during the entire planning horizon or a part of it, less transmission equipment will be installed. Although the actual path followed differs between edge *b* and *e* for example (no transmission equipment installed in the five years preceding edge *e*) and the actual configuration of the equipment may be different, the available equipment will be dimensioned to cope with the traffic of the end of the planning horizon. We also see on the figure that starting to deploy a network based on an IRU on DF in year *0* gives no flexibility in year *5* as we assume the IRU cannot be ended in year *5*. On the other hand, both the DF lease and lambda lease scenarios provide the flexibility to switch to either one of the three scenarios in year *5*. The end of contract times where we didn't assume any flexibility in the case study are not shown in Figure 4.12.

As indicated before, we assume the traffic does not necessarily evolve as forecasted during the last *10* years of the planning horizon. We consider several sets of future traffic evolutions, which are simulated using Monte Carlo simulation:

- *traffic deviations from the expected value:* the estimated yearly traffic growth of *60%* is considered uncertain and it is modelled as a random variable with uniform distribution between *0* and *60%*.
- *abrupt traffic change in year 6*: the traffic is supposed to follow the forecasted traffic growth of *60%* a year, except from an abrupt change in that trend in year *6* (beginning of second planning period). The abrupt change is modelled as a traffic increase or decrease somewhere between *0.01* times its current size and *10* times is current size. A continuous variable with uniform distribution is assumed.
- *abrupt traffic decrease at unknown time*: the traffic change is supposed to be a decrease to a fraction of *0.05* till *1* of its current size, modelled as a continuous uniform random variable. The timing of the occurrence of the abrupt change is modelled as a discrete variable with uniform distribution over the second part of the planning horizon (year *6* till *15*).
- *abrupt traffic increase at unknown time*: similar to abrupt traffic decrease at unknown time, but with a traffic increase of *1* till *10* times its current size.

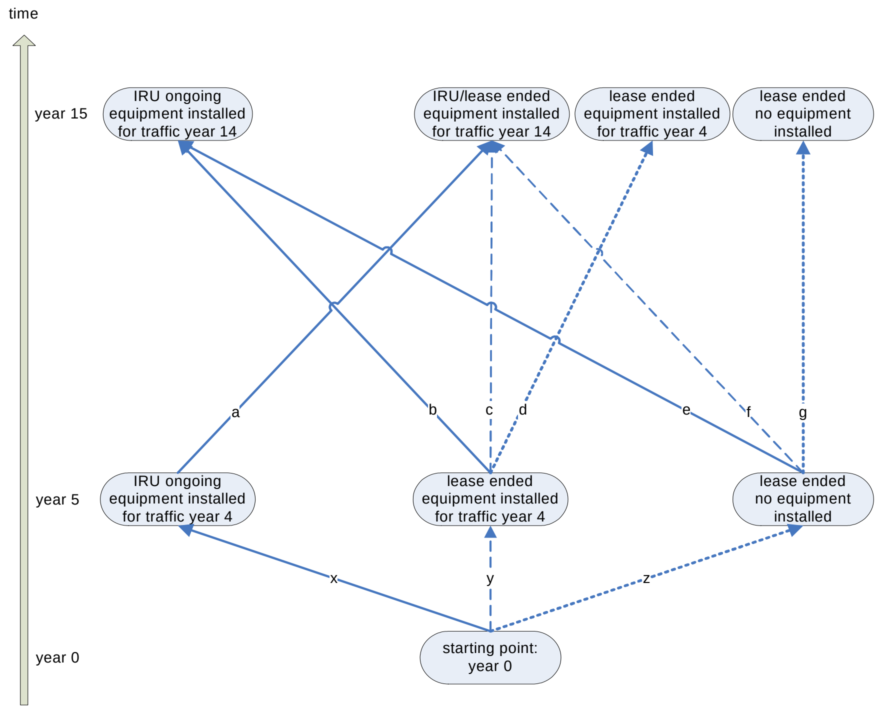

Figure 4.12: network migration tree

The costs (cash out-flows) for the network deployment strategies starting with one of the three network scenarios in year 0 is calculated by formula (4.4). This formula takes into account the observation that only one of the three possible edges out of the nodes “lease ended, equipment installed for year 4” or “lease ended, no equipment installed” will be chosen, dependent on the actual traffic situation by that time. This is fundamentally different from considering the average of all possible future evolutions, without recognizing that the actual network deployment strategy will be changed during the course of the project, as explained in appendix C.

$$\begin{aligned} &\textit{cost IRU on DF} = x + a \\ &\textit{cost DF lease} = y + E[\min(b,c,d)] \\ &\textit{cost lambda lease} = z + E[\min(e,f,g)] \end{aligned} \tag{4.4}$$

The results obtained for the costs in the last 10 years of the planning interval (top part of Figure 4.12) are given in Table 4.3. The rows in grey indicate the costs for the second phase according to the Real Options theory (second term behind the equal sign in equations (4.4)), whereas the rows below those indicate the average expected costs. The expected total costs for the different scenarios calculated using formula (4.4) is given in Table 4.4. Investment decision techniques, including Real Options valuation, prescribe to choose the solution with the highest value. In our study, the cash in-flows for all scenarios are equal (as all scenarios are dimensioned to be able to cope with the actual traffic), so that we need to choose the scenario with the lowest cash out-flows. From Table 4.4 we learn that this is the DF lease scenario for all sets of uncertain traffic evolutions considered.

		traffic deviation from expected	abrupt traffic change in year 6	abrupt traffic decrease at unknown time	abrupt traffic increase at unknown time
IRU ongoing, equipment installed for traffic year 4	E[a]	2.89E+01	5.70E+02	8.73E+01	6.80E+02
lease ended, equipment installed for traffic year 4	E[b]	4.47E+02	8.09E+02	5.06E+02	9.02E+02
	E[c]	2.82E+02	1.87E+03	2.95E+02	1.20E+03
	E[d]	1.38E+03	6.92E+03	9.37E+02	6.38E+03
	E(min[b,c,d])	2.82E+02	*7.80E+02*	2.95E+02	*6.98E+02*
	min (E[b,c,d])	2.82E+02	*8.09E+02*	2.95E+02	*9.02E+02*
lease ended, no equipment installed	E[e]	4.54E+02	8.16E+02	5.13E+02	9.09E+02
	E[f]	2.89E+02	1.88E+03	3.02E+02	1.21E+03
	E[g]	1.38E+03	6.92E+03	9.37E+02	6.38E+03
	E[min(e,f,g)]	2.89E+02	*7.87E+02*	3.02E+02	*7.05E+02*
	min (E[e,f,g])	2.89E+02	*8.16E+02*	3.02E+02	*9.09E+02*

Table 4.3: costs for second planning interval in the graph of Figure 4.12, in case of uncertain traffic evolution

	traffic deviation from expected	abrupt traffic change in year 6	abrupt traffic decrease at unknown time	abrupt traffic increase at unknown time
Start with IRU on DF in year 0	9.73E+02	1.51E+03	1.03E+03	1.62E+03
Start with DF lease in year 0	3.10E+02	8.08E+02	3.23E+02	7.26E+02
Start with lambda lease in year 0	4.02E+02	9.00E+02	4.15E+02	8.18E+02

Table 4.4: total costs for different network scenarios taking into account option values

Whereas IRU on DF allows to cope with growing traffic without the need to update the contract immediately, the flexibility of the DF lease scenario is twofold: shorter contract allow to respond to traffic decrease sooner and the end of the contract time always to easily switch to another network scenario. This flexibility is rewarded by the ideas of Real Options, so that DF lease comes out best in our study.

In Chapter 3, we mentioned that strategic advantages (like the flexibility to respond to uncertain changes during the course of the planning horizon) are difficult to quantify, however, Real Options theory allows to solve this problem to some extent.

4.7 Broader Meaning of Value for the Network Operator

Network planning aims, in general, at optimizing the value of the network operator. This can be seen as maximizing the profit, i.e. revenues – costs. The techniques described in the current and the previous chapter for planning a network taking into account dynamic and uncertain input parameters can be seen in this respect. However, the value for the operator or the network planner can also be formulated in a broader sense.

Immaterial or intangible influencing factors like knowledge, trust relationships, intellectual property, leadership, etc. are taken into account more and more in business models [4.36]. If we want to take them also into account in the planning process using one of the techniques described above, a value should be awarded to them.

One intangible asset that can be taken into account in network planning, is the operator's attitude towards risk. Several future solutions with an equal expected value and a different risk associated to them, might be valuated differently by different operators. Three types of decision makers can be distinguished according to the extent to which they are willing to accept risk:

- A *risk neutral* decision maker evaluates alternatives according to their expected values. For example, such a decision maker would be indifferent between receiving *10* euro for certain and an alternative with equal chances of yielding *0* euro and *20* euro, since this is the average amount that the alternative would yield.
- A *risk averse* decision maker values alternatives at less than their expected values. A risk averse decision maker might prefer an alternative yielding *5* euro over an alternative with equal chances of yielding *0* and *20* euro, even though the expected value for this alternative is *10* euro just because the *5* euro alternative suits his attitude towards risk.
- In contrast to the risk averse investor, a *risk attracted* investor values alternatives at more than their expected values.

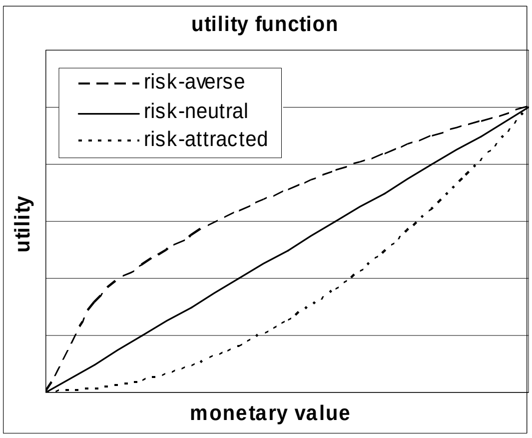

Figure 4.13: utility function for different risk attitudes

The *utility function* is a means to quantify this attitude towards risk [4.37]. It relates the decision maker's satisfaction with the outcome (or *utility* associated with the outcome) with the monetary value of the outcome. According to the classification of risk behaviour outlined above, the utility function has to be linear for a risk neutral decision maker, concave for a risk averse decision maker and convex for a risk attracted decision maker, as illustrated in Figure 4.13.

4.8 Conclusions

This chapter describes how input uncertainty can complicate the network planning process and how the network planning techniques described in Chapter 3 can be extended to take this into account. A classification of the residual uncertainty of the input data into four uncertainty levels was described. The straightforward approach to handle uncertainty via the use of an a priori or a posteriori applied safety margin is evaluated. We have shown that it may lead to incorrect planning decisions, the situation is even worse for a posteriori adjustment than it is for a priori adjustment. We have discussed several steps in taking into account uncertainty in planning decisions and focused on simulation analysis. Based on a risk analysis for an optical network operator, we indicated that correlation between uncertain input parameters to the planning process has an important and often underestimated impact of the project value. Although traffic demand uncertainty is most important for a network operator, uncertain equipment costs can have an important impact on the situation of the network operator. We have described the Real Options technique, a technique originating from the financial world of stock options allowing to deal with flexibility in uncertain planning problems. This technique was applied to evaluate several possible network migration approaches using dark fibre or wavelength lease, with different contract durations. We have shown that, in case the duration of the lease contract is longer than the planning interval, the end value of this ongoing contract is to be taken into account in the analysis. Indefeasible Right of Use on dark fibre and dark fibre lease were shown to be competitive in terms of costs. Real Options Valuation allowed to model some flexibilities in this problem: IRU on DF allows to cope with growing traffic without the need to update the contract immediately, whereas the flexibility of the DF lease scenario is twofold: shorter contract terms allow to respond to traffic decrease sooner and the end of the contract time allows to easily switch to another network scenario. Finally, we indicated that network planning techniques can also take into account some immaterial factors that might be relevant to the network planner, like attitude towards risk.

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5 Modelling Network Operator Costs

“You'd be surprised how much it costs to look this cheap” - Dolly Parton

The availability requirements for today’s networks are very high. However, higher availability often comes with a higher cost. This chapter describes several steps required to estimate the costs for realistic network scenarios. Section 5.1 defines the total costs for a telecom operator. Sections 5.2 and 5.3 make a classification of capital and operational expenditures, respectively. Section 5.4 describes several cost modelling approaches. In Section 5.5, an activity based approach is followed to quantify the cost of the event-driven operational processes like repair and service provisioning. Sections 5.6 and 5.7 discuss activity duration and availability parameters as required input data in order to calculate the processes’ costs for realistic network scenarios. The relevant availability measures for an IP-over-Optical network are described using a triplet-representation with optimistic, nominal and conservative values. In Section 5.8 the suggested methodology to calculate the total cost for the network operator is summarized. The model is applied to a reference German network scenario in Section 5.9. Our research results in these fields directly contributed to the publications [5.1][5.2][5.3][5.4][5.5][5.6].

5.1 Total Costs for a Telecom Network Operator

The total expenditures of a company such as a telecom operator can be split generally in two parts: the capital expenditures and the operational expenditures. Some obscurity exists in literature concerning their exact definitions. Below we highlight our view and how it relates to the different literature sources. *Capital expenditures (CapEx)* contribute to the fixed infrastructure of the company and they are depreciated over time [5.7]. For a network operator, they include the purchase of land and buildings (e.g. to house the personnel), network infrastructure (e.g. optical fiber, IP routers) and software (e.g. network management system). *Operational expenditures (OpEx)* do not contribute to the infrastructure itself, they represent the cost to keep the company operational and include costs for technical and commercial operations, administration, etc. They are often referred to as OAM costs: Operation, Administration and Maintenance. For a network operator, OpEx is mainly constituted of rented and leased infrastructure (land, building, network equipment, fiber,…) and personnel wages. This approach is consistent with [5.8]. However, other sources, like [5.9] and [5.10] believe all infrastructure (no matter whether it is bought or leased) is to be counted as CapEx.

5.1.1 Impact of Legislation

The main difference between CapEx and OpEx is that the former are subject to depreciation, whereas the latter are not. Depreciation is considered on formation expenses and on tangible and intangible fixed assets with a finite useful life. As depreciation has a positive impact on the taxes to be paid[10], this has an important impact on the accounting situation of the network operator. Therefore, for an operator, it is more interesting to have a bigger CapEx/OpEx ratio. In this respect, the concept of the *Produced Fixed Assets (PFA)* is important. They are defined as internal activities valorised as fixed assets and classified as revenues [5.11]. Their production cost consists of the acquisition cost for the acquired material, the associated direct cost for wages and a suitable part of the indirect production costs [5.12]. An interesting example for a telecom operator is the cost for network equipment installation. Apart from the acquisition cost of the network equipment itself, also the costs for the installation of the equipment (often carried out by the equipment vendor) can be considered as CapEx.

Depreciation of an asset commences when the asset is ready for its intended use. Depreciation periods are not prescribed in legislation, economic (useful) or technical life times are to be used (see also the discussion on different life times in Chapter 3). The useful lives assumed in the annual report of the Belgian incumbent operator Belgacom [5.13] for some tangible assets are indicated in Table 5.1. Those numbers are in line with the numbers cited in other sources. Intangible assets are assumed to have a useful life of *15* to *20* years in case of licence fees, e.g. for GSM or UMTS and *3* to *20* years in other cases, incl.

[10] Here regional differences may occur, based on specific legislation. The situation described in this chapter corresponds to the Belgian case.

software. Note that the technical life times form an upper limit for the useful life times.

asset	useful life (years)
land and buildings	
land	indefinite
building and constructions	5 to 33
technical and network equipment	
switches	3 to 10
cables and operational support systems	4 to 20
transmission	4 to 10
equipment installed at client premises	2 to 5
equipment for data transfer business	3 to 5
mobile antennas	6
furniture and vehicles	
furniture and office equipment	3 to 10
vehicles	5
other tangible assets	**3 to 33**

Table 5.1: useful lives from [5.13]

5.1.2 OpEx/CapEx Ratio in Practice

Capital and operational expenditures are interconnected issues. A network technology allowing to perform a lot of maintenance and provisioning tasks automatically, will probably have higher acquisition cost (CapEx), but will be cheaper to operate (OpEx). To estimate the capital expenditure costs for a network operator, equipment cost models are available in literature, e.g. the model specified in Chapter 3. For operational expenses, however, very little work has been done and quantitative results are rare. We want to make a contribution to that field.

A questionnaire carried out in the framework of the IST-project NOBEL indicates that field experts (network operators, equipment vendors and telecom consultants) don't have a clear view on the realistic OpEx/CapEx ratio. They indicate an OpEx/CapEx ratio between *1.6* and *4*. In the mentioned questionnaire, the equipment vendor had the most optimistic view concerning OpEx, while the operator had the most pessimistic view. Annual reports of some incumbent operators like Belgacom and France Telecom show that the OpEx/CapEx ratio for the total company is of the order *5* to *7*. The ratio is probably smaller for the backbone network part than it is for the total telco.

5.2 Classification of Capital Expenditures

For a network operator or network service provider, capital expenditures are constituted of 3 categories, as illustrated in Figure 5.1.

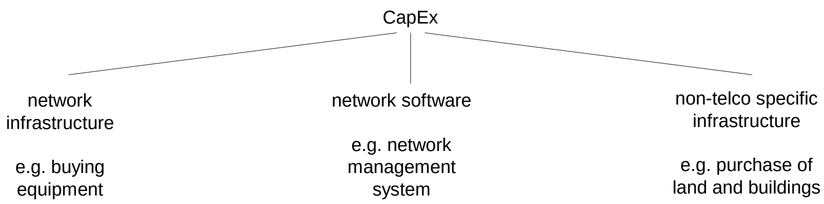


Figure 5.1: classification of CapEx costs for telco

First, there is the purchase of network infrastructure, starting from the outside plant infrastructure (when it is bought and not leased), over the big network equipment parts like IP routers, Optical Cross-Connects etc. Remark that buying equipment always contributes to CapEx, independent from the fact whether the payment is made in one time or spread over time when paying back debt systematically (for financing reasons). Infrastructure (building, network equipment, etc.) being leased does not constitute to CapEx in our model, it is counted as OpEx. Another part is the software that needs to be bought. This includes all assets needed to build the network, such as the network management system. This also includes the software to implement a distributed control plane in case of GMPLS deployment. The third part is the non-telco specific infrastructure, which means general assets, not specific for a telecom operator. This includes purchase of land and buildings, e.g. to house the personnel.

5.3 Classification of Operational Expenditures

The major contributors to the operational expenditures for a telecom operator can be classified in the following three sub-categories: OpEx parts directly related to operate an existing network (which has already been set up), OpEx for equipment installation and some more general OpEx aspects (not specific to a network operator). They are classified in Figure 5.2.

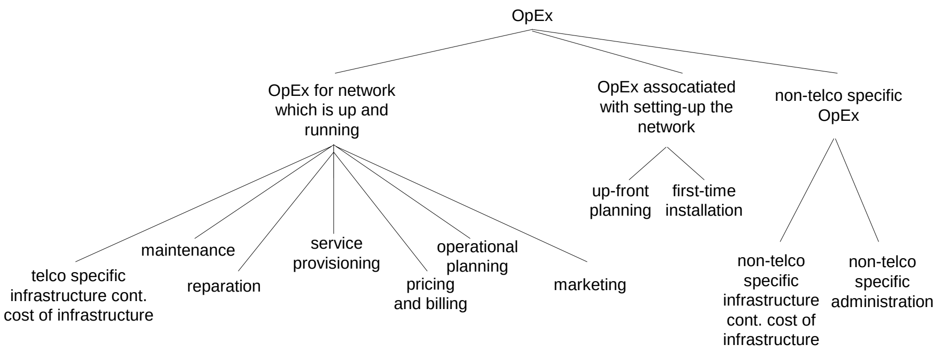


Figure 5.2: classification of OpEx costs for telco

The left most category is formed by the *expenditures to operate an existing network (network which is up and running)*. This includes the activities corresponding to the 5 traditional management areas (FCAPS): fault, configuration, accounting, performance and security.

- First, there is the cost to keep the network operational in a failure free situation, we call this the *telco specific continuous cost of infrastructure*. It includes the costs for paying (floor) space, power and cooling energy and leasing network equipment (e.g. fiber rental). Also right-of-ways, i.e. the privilege to put fiber on the property of someone else (e.g. along railways) is part of this cost.
- Secondly, the traditional *maintenance cost* can be seen as the cost to maintain the network or to operate the network in case a failure may occur. The main actions performed here aim at monitoring the network and its services. Therefore, the actions involved include direct as well as indirect (requested by an alarm) polling of a component, logging status information, etc. Also stock management (keeping track of the available resources and order equipment if needed), software management (keeping track of software versions, and install updates), security management (keeping track of people trying to violate the system and blocking resources if needed), change management (keeping track of changes in the network, e.g. whether a certain component goes down) and preventive replacement are included. Furthermore, cleaning of equipment can be taken into account as well.
- Third, *repair* means actually repairing the failure in the network, if this cannot happen in routine operation. Repair may lead to actual service interrupts, dependent on the used protection scheme. The actions involved in the repair process are diagnosis and analysis, the technicians travelling to the place of the failure, the actual fixing of the failure and performing the needed tests to verify that the failure has been repaired.

- The fourth important part of the OpEx cost is given by the process of *provisioning and service management*. This follows the service request by the potential customer and includes the entire process from order entrance by the administration to performing the needed tests; service provisioning, service move or change and service cessation.
- The cost to operate the network includes the cost of *pricing and billing* as a fifth part. This means sending bills to the customers and making sure they pay. It includes actions like collecting information on service usage per customer, calculating cost per customer as well as sending bills and checking payments. Calculating penalties to be paid by the operator for not fulfilling the Service Level Agreement (SLA) is another task here.
- As the sixth OpEx cost part, we distinguish the ongoing network planning activity which we call *operational network planning*. It includes all planning performed in an existing network which is up and running, including day-to-day planning, re-optimization, planning upgrades.
- Finally, there is the cost for *marketing*. With marketing we mean acquiring new customers for a specific service of the telco. The actions involved are promoting a new service, providing information concerning pricing etc. Possibly, new technologies enable new services.

The middle category of operational expenditures we distinguish in Figure 5.2 is the *OpEx associated with equipment installation*. This represents all the costs to be made before connecting the first customer in case of a green field scenario, or the migration costs before the network becomes operational again in case of a major network extension[11]. In some cost models this OpEx category is taken together with CapEx as 'first installed costs' [5.14]. A simple modelling approach could estimate the OpEx for equipment installation as some fraction of the CapEx cost.

- It includes the costs for *up-front planning*, which denotes all planning done before the decision "let's go for this approach" is taken: planning studies to evaluate the building of a new network, changing the network topology, introducing a new technology or a new service platform, etc.
- The second part of the OpEx category on equipment installation is constituted by the operational aspects of *first-time installation of new network equipment*. All costs related to installing the equipment (after buying it) is counted here. This includes the actual connecting and installation of the new component into the network, as well as the necessary testing of the component and its installation. This first-time installation is usually carried

[11] Also costs for out-phasing old equipment and gracefully terminating the operation of the old network can be included here.

out by the equipment vendor. In this case, the costs for the operator are included in the contract with the vendor. The costs for first-time installation can to a large extent be capitalised, as described above. For the costs for up-front planning (first part of the OpEx for equipment installation category), on the other hand, this is not possible.

The right-most category in Figure 5.2 indicates OpEx subparts that are present in every company; they are *not specific for a telecom operator*.

- *Non-telco specific continuous cost of infrastructure* denotes the cost of leasing infrastructure, not related to the network itself. This includes buildings to house the personnel, energy for desktop PCs, heating, cleaning of buildings, etc.
- *Non-telco specific administration* includes the administration every company has, such as the payment administration for employees, the secretary, the human resources department etc. 'Non-telco specific administration' and 'non-telco specific cost of infrastructure' can jointly be seen as 'overhead' costs.

The *enhanced Telecom Operations Map (eTOM)* [5.15], a business process framework developed by the TeleManagement Forum (TMF) describes several operational processes and subprocesses, grouped in 3 so-called *level 0 processes*:

- *Operations (OPS)* includes fulfilment, assurance and billing as well as operations support and readiness and corresponds to the process based costs in our OpEx for a network which is up and running (i.e. without the continuous cost of infrastructure).
- *Strategy, Infrastructure and Product (SIP)* relates to our OpEx category for equipment installation and includes strategy and commit, infrastructure lifecycle management and product lifecycle management.
- *Enterprise Management (EPM)* can be seen as non-telco specific process-based OpEx (i.e. again not considering the continuous cost of infrastructure).

The eTOM framework has been standarized by the ITU in [5.16].

We represent the three main OpEx categories (OpEx for a network which is up and running, OpEx for equipment installation and non-telco specific OpEx) in a matrix structure (Figure 5.3) in order to clarifiy our belief that personnel costs (wages) should not be considered as a subpart of OpEx on itself (as suggested in [5.17]), but rather as a kind of expenses present in several OpEx subparts. In our matrix representation this is indicated by having personnel costs as a row in the matrix, which intersects with all OpEx subparts representing actual operational processes (columns in the matrix). Other expenses apparent in several OpEx subparts are (floor) space, energy and rental. They are therefore also indicated as matrix rows, whereas the OpEx categories are indicated as matrix columns. Note that, apart from the wages themselves and the expenses related to training, there are other costs related to personnel, namely the expenses for tools and transport. Here also the cost to actually buy the necessary tools is included: [5.18] believes these tools are bought and therefore CapEx. [5.10] and [5.19] on the other hand, believe they should be considered OpEx because they can be seen as a part of the personnel cost for the considered technician, the technician cannot operate without those tools. We adopt the latter assumption. Examples of such tools are measurement equipment, screw drivers, mobile phones to name only a few. Unlike the big investment of buying assets like buildings, network equipment and inherent instrumentation equipment (which is CapEx), the small investment to buy those tools is counted as OpEx.

In the matrix of Figure 5.3 the inapplicable entries are shaded. From this perspective, it is clear that continuous cost of infrastructure is constituted of (floor)space, energy and rental and leasing, whereas the costs for the other categories are mainly constituted of personnel and associated costs. The matrix entries ‘transport’ and ‘travel time’ are marked inapplicable for the cost part pricing and billing, operational network planning and up-front planning, as we believe that displacement is not required for these processes, whereas it is for the others like maintenance and repair.

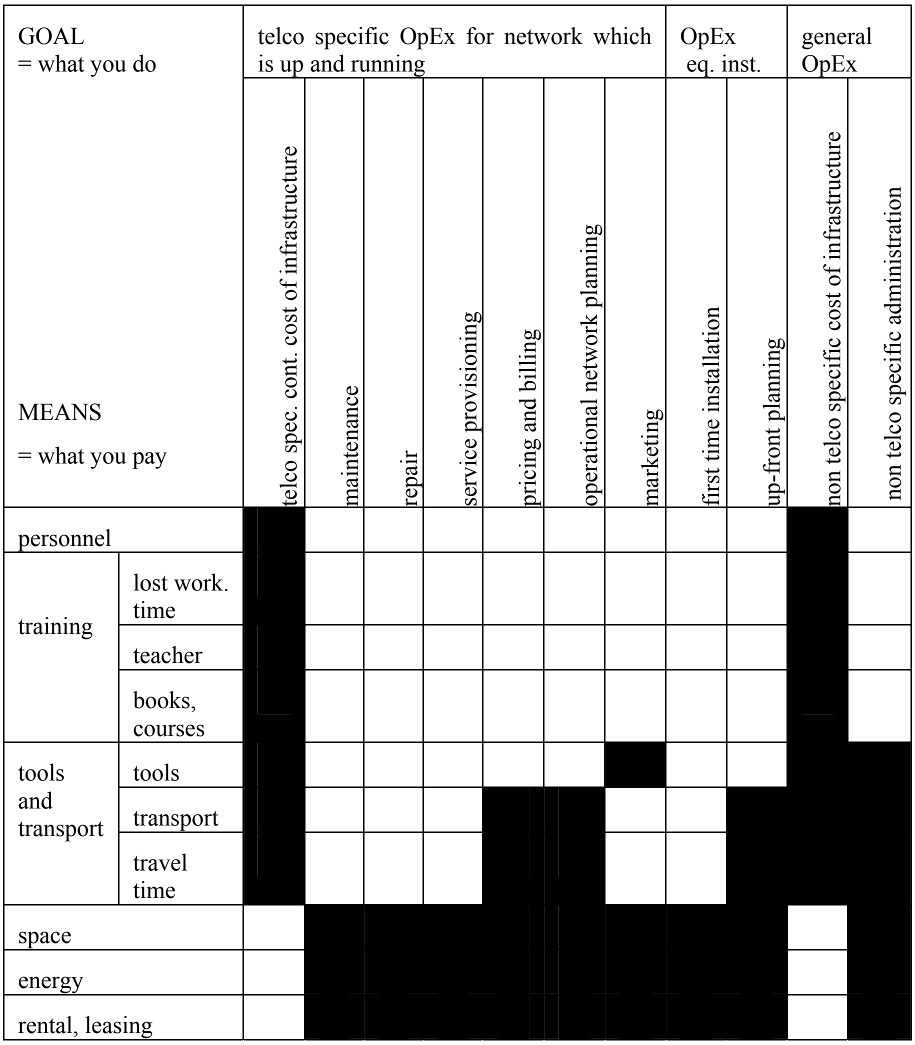


Figure 5.3: matrix description of operational expenses for telecom operator

5.4 Cost Modelling Approaches

5.4.1 Top-Down versus Bottom-Up Cost Modelling

Two approaches can be followed for network cost modelling. They differ in their starting point for the modelling process: top-down versus bottom-up.

The first approach, the *top-down* method, starts from the existing network infrastructure. In this case, the actual network dimensioning is a result from fluctuations in historic and current demand, e.g. a growing number of customers and increasing traffic volume for several services, but also a declining service demand for other services (e.g. fixed telephone lines). The network is therefore less efficient than a new network (specifically designed for the current traffic demand). The total installed equipment is observed from the existing network, which allows to calculate the total current CapEx cost as well as the current service/resource usage. Similarly to installed equipment, also the current situation with respect to available manpower (what we call *operational dimensioning*) can be observed, as an input to calculate the total OpEx cost. Two important cost bases can be distinguished for the top-down valuation of equipment. *Historical Cost Accounting (HCA)* uses the asset purchase costs as book value, taking depreciation into account. Since this method counts all historical costs, it can not be used for network optimization. *Current Cost Accounting (CCA)* values assets at the current market price. This cost base represents the replacement cost of an asset, i.e. how much it would cost today to purchase that asset. However, as a result of the continuous evolution of technology, it is not always possible to find the same equipment on the market as what has been installed in the network previously. A possible solution to this problem is given by the *Modern Equivalent Asset (MEA)* cost base, where the costs of equipment is valuated using the cost of a new technology offering the same (or more) functionality as the one that is currently installed.

The second approach, the *bottom-up* method, requires as a starting point the demand for the services. The network is dimensioned in such a way that it is optimal for the current situation: it can serve all customers with the requested services at the proposed quality of service. Also the operational dimensioning (required amount of manpower to operate the network) is defined in an optimal way. The bottom-up method can be used for different studies. It can be used for calculating the costs when designing a completely new network-architecture. It can also be used for making the comparison of the costs in an existing network considering an optimized (bottom-up calculated) network architecture providing the same services. In the bottom-up method, the company’s properties and goods will be evaluated following the *forward looking cost (FLC)*. When considering a new network this means that only new and efficient technology will be used. When modelling an existing network, on the other hand, it might mean that less expensive technology is used in the study. This implies that the current network must be reconsidered and remodelled. Two approaches[12] are distinguished in the literature for doing so, the *scorched earth* (green field) and *scorched node* (path dependent) approach. In the former approach, the network is redesigned with as few constraints as possible: a different number of nodes, a changed topology and other technological solutions can be taken into account. On the other hand, the latter approach makes a more fair compromise between efficiency of new technologies and networks and the existing network structure. The topology stays the same, whereas all equipment can be changed [5.20].

The last step in both approaches, determining the cost per service, is called the *cost allocation* step. In case of bottom-up cost modelling, it can follow naturally from the network dimensioning phase. In case of top-down modelling, the use of appropriate *cost drivers* is required, which are often very difficult to define. Cost allocation will be discussed in more detail in Chapter 6. In this chapter, we will focus on the calculation of the total cost for the network operator, without detailing this cost per service.

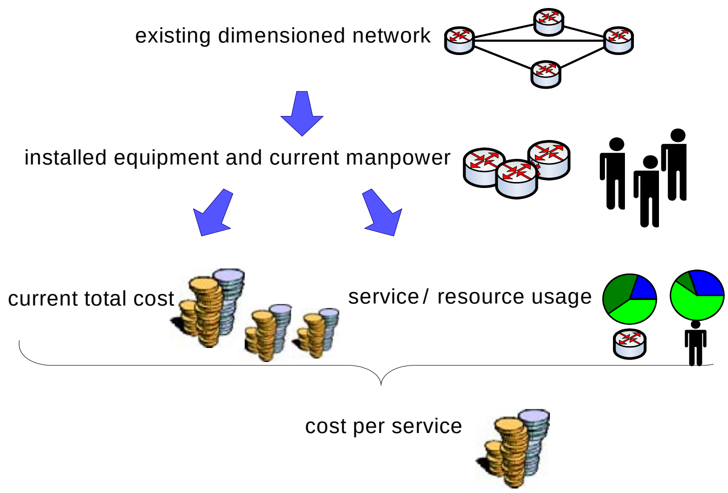


Figure 5.4: top-down cost modelling approach

[12] Remark that, apart from scorched node and scorched earth, also an incremental approach (starting from the existing situation and only modeling the network capacity in an optimal way for the additional service demand) can be useful in some cases. However, this is not a bottom-up approach in the strict sense. As it starts from the existing network as well as the service demand for a new service, it is a combination of top-down and bottom-up cost modeling.

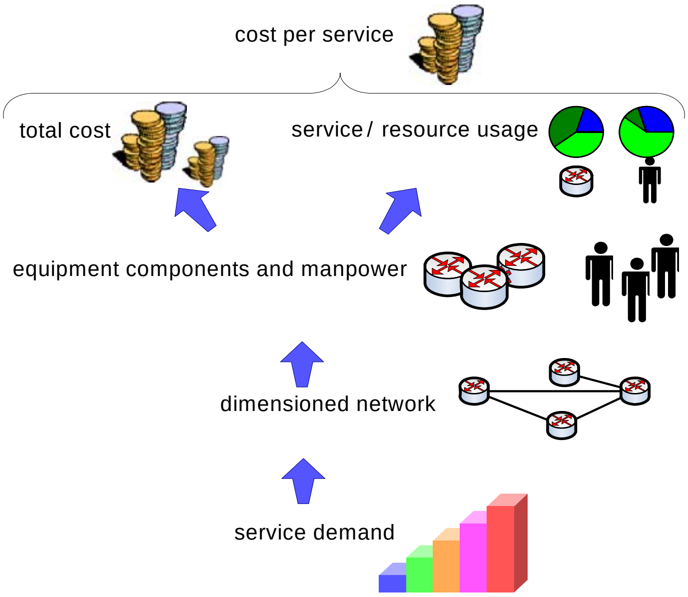


Figure 5.5: bottom-up cost modelling approach

5.4.2 Suitable Modelling Approaches for a Network Operator's CapEx and OpEx

For calculating total equipment costs of existing networks, the top-down approach is the logical choice. In case of planning studies for future networks, the bottom-up approach is more suitable. This approach has been used in our planning studies in the previous chapters.

When considering OpEx costs, on the other hand, the situation is a bit different. Exactly calculating the OpEx costs based on the existing dimensioned network is a very difficult task, as it is often unclear where the actual operational expenses originate from. Therefore, the bottom-up approach is preferable over the top-down approach for OpEx cost modelling, in case of an existing network as well as for planning future networks [5.8]. In the following sections, we will focus on a bottom-up cost model to determine the network operator's total operational expenditures.

5.5 Activity-based Description of Operational Processes

The general framework for OpEx costs of a network which is up and running is defined by the continuous cost of infrastructure (left most column in the matrix of Figure 5.3), i.e. the costs that need to be paid in any case to keep the network operational (also in the failure free case). The other columns in the OpEx for an existing network indicate the actual operational processes that interact with each other, as illustrated in Figure 5.6. The maintenance (routine operation) process is the central process. An important task of the routine operation process is to monitor the status of the network and its components. Network utilization info will serve as an input to the pricing and billing process. There is also a constant interaction between the planning process and the routine operation process. The first determines which parameters to be monitored by the latter and takes the monitoring results as an input to analyze the network behaviour and suggest improvements for the future. In case of a failure alarm, the repair process is triggered. The service provisioning process is another central process which sets up the service requested by a customer. There is an interaction with the pricing and billing process in order to calculate the price of the provisioned service and another one with the repair process that indicates the downtime caused by a failure and therefore the associated penalties to be paid to the customer. The marketing process can be seen as a background process trying to attract new customers, it therefore influences the service provisioning process. The planning process interacts with all other processes as a steering process.

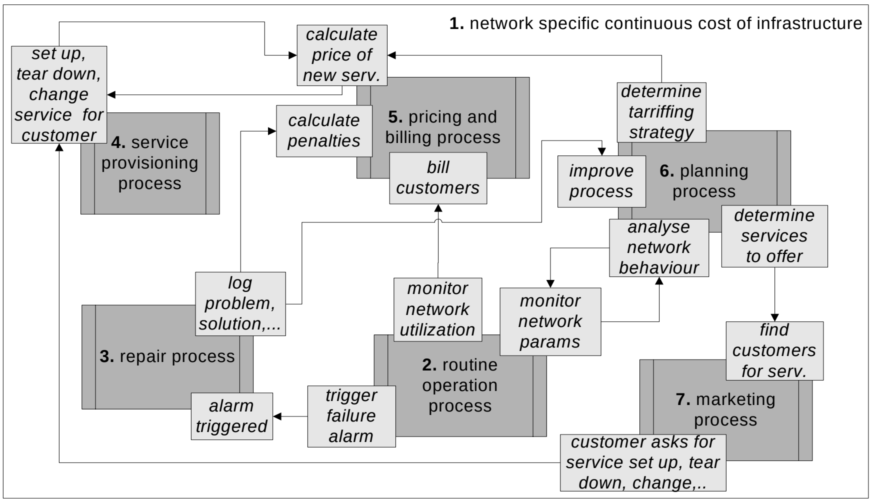


Figure 5.6: interaction between different operational processes for network which is up and running

In order to calculate or estimate the costs of the different OpEx subparts, again a distinction has to be made between the continuous cost of infrastructure and the costs for the operational processes. The former can easily be calculated by summing the operational costs for all used network components, when all required network characteristics such as power consumption and footprint are known. On the other hand, the costs for the operational processes can be analyzed using an activity-based approach. Therefore, diagrams have been developed describing all processes under study, indicating the different steps in the considered process (on the horizontal axis in the diagram) as well as the departments involved (on the vertical axis in the diagram). On the following pages, some activity-based descriptions of the identified processes for a network which is up and running are illustrated. Figure 5.7 illustrates the repair process, the maintenance process is given in Figure 5.8, Figure 5.9 describes the service provisioning process and, finally, Figure 5.10 deals with the pricing and billing process. The arrows in the diagrams denote the flow of the process, the rectangles denote actions, the diamonds denote questions or splits in the process flow. For more information concerning the interpretation of the process diagrams, we refer to [5.3].

For illustrative purposes, we explain how the repair process can be interpreted below. The explanation can easily be followed on the process diagram of Figure 5.7 itself. The repair process can either be triggered by a failure alarm coming from the routine operation process or by a helpdesk call from a customer. After this fault detection phase, the important task of fault diagnosis is started. In the diagnosis phase, we distinguish between a fault at the customer premises equipment (CPE), a problem that can be solved from the network operations center (software (SW) fault or misconfiguration), a cable cut, any other hardware failure (HW) and an external failure. An external failure might be a power interrupt, a failing external component on which the network relies, etc. Diagnosis is performed in several steps. If the problem turns out to be a CPE problem, it is only considered further if this is required by the contract. For network problems, a trouble ticket is created. In the trouble ticket database similar tickets are searched for. If the problem has already been reported, it is marked like this and the solution of the problem is awaited. For unreported problems, the initial diagnosis is performed, which means that it is checked whether this is a standard problem (with known procedures). If it is not, an expert will be needed to perform further diagnosis. In case of an external problem at the interconnect of two domains (two domains of the considered operator, or one local and one external domain), the diagnosis (as well as the repair) becomes more complex. Then the actual repair phase can start. This might be a lengthy process. If required by the contract, the customers are informed on the expected downtime. We distinguish four subactivities in repairing a failure. First the failure is isolated. In case of a SW failure leading to a memory leak or a failing HW component using too much power, this may mean shutting down this part of the system so that the rest can stay operational. In case of a cable cut, the exact location of the cut needs to be determined before isolation can start. Once the failure has been isolated, recovery is performed if needed. If, for some reason, the traffic affected by the failure is unprotected, it will be rerouted by some form of restoration. If the network is protected against single failures by a 1+1 protection scheme, on the other hand, only very little work has to be done (traffic was sent via both paths anyway). If the problem cannot be solved from the network operations center (NOC), a technician needs to go on site. In some cases also spare equipment needs to be transported to replace a failing component. After the actual reparation step, the component is tested and also an end-to-end test is performed. Finally, the entire repair process is logged (reported problem, found problem cause, performed solution, experienced downtime) so that this info is available for future fault diagnosis. If required by the contract the customer is informed on the solution of the problem (network is back up again) and, finally, the trouble ticket is closed.

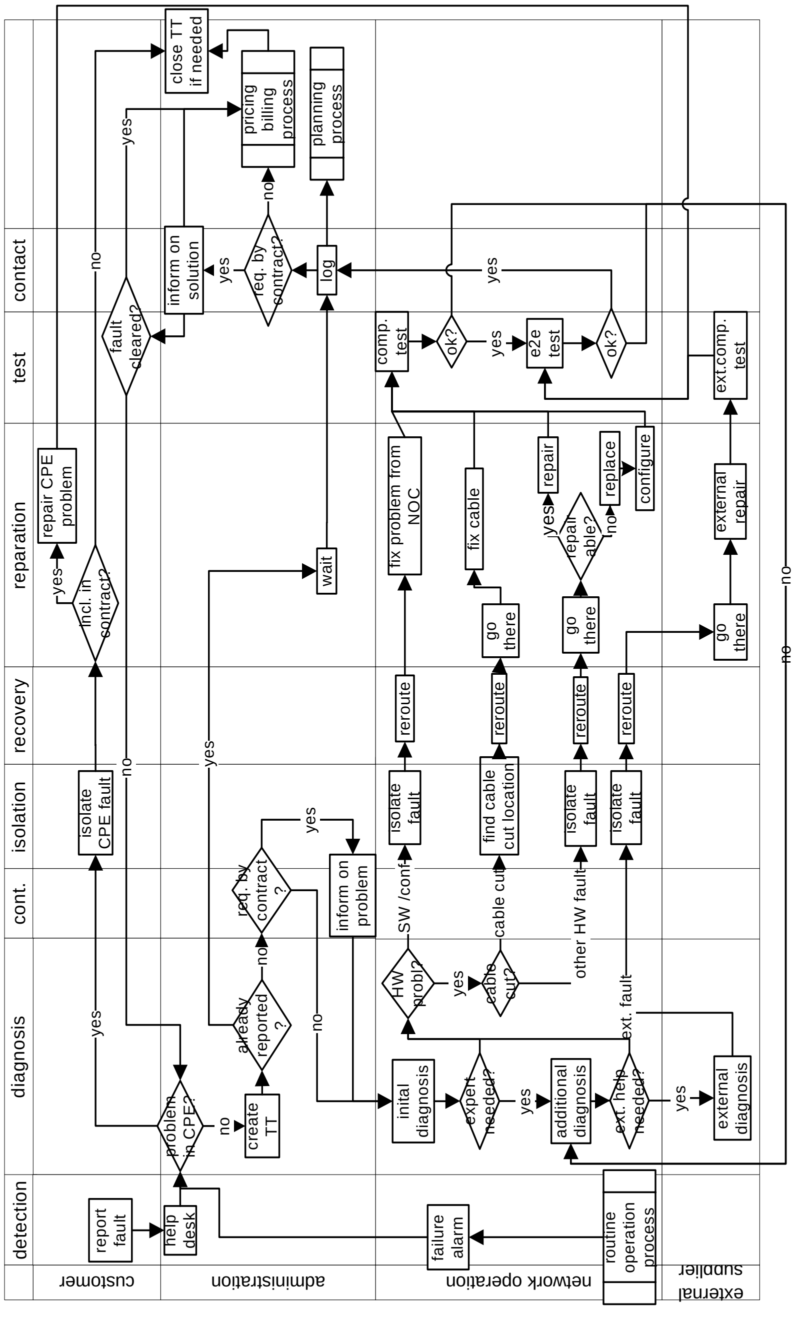


Figure 5.7: activity-based description of repair process

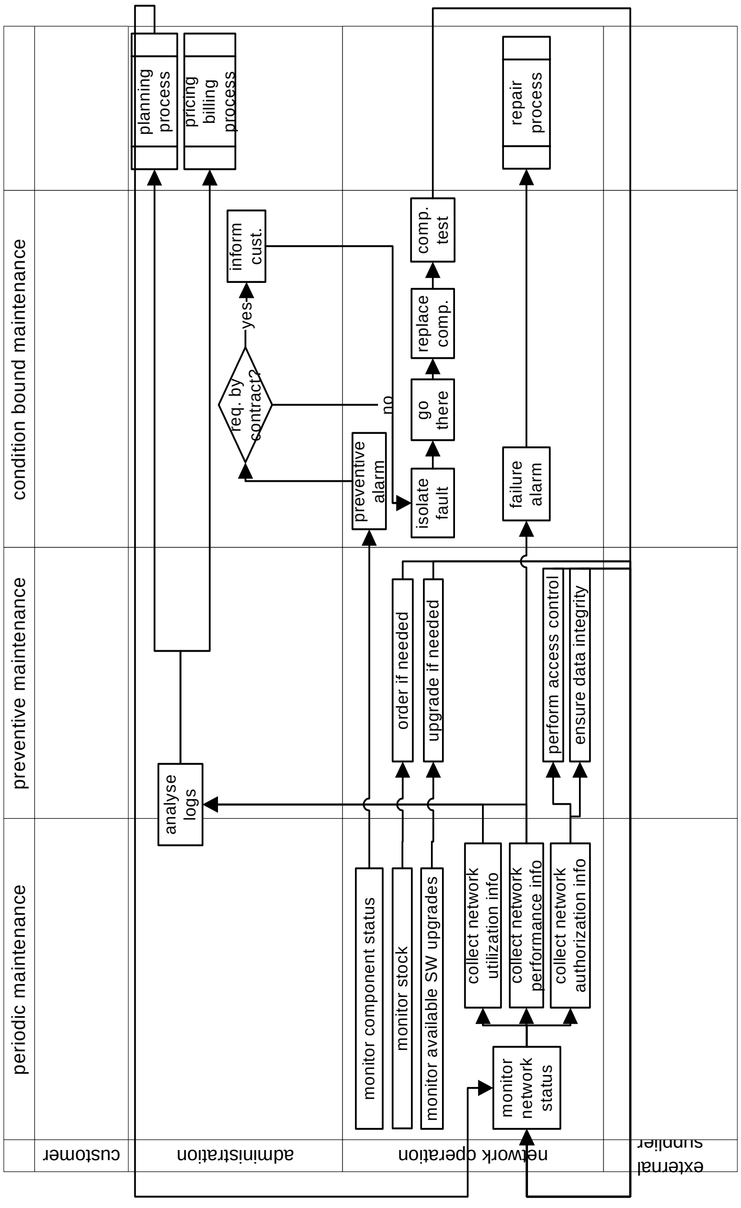


Figure 5.8: activity-based description of maintenance process

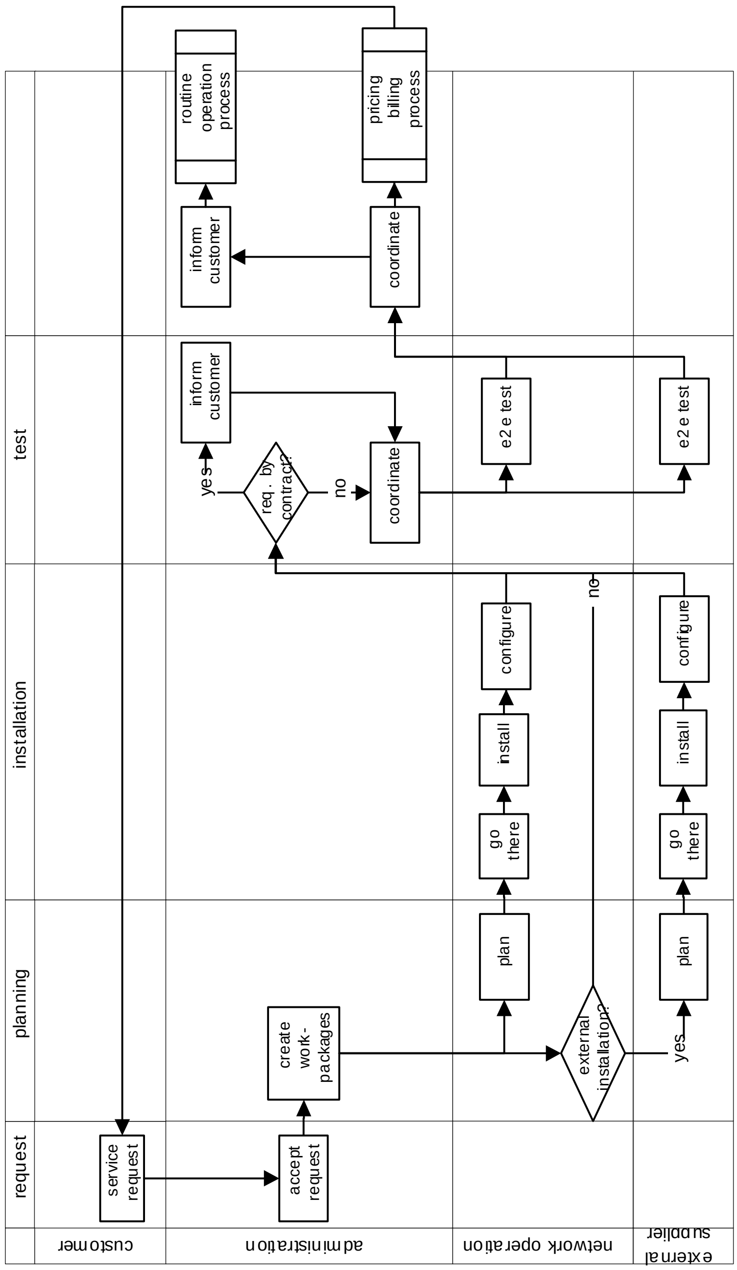


Figure 5.9: activity-based description of service provisioning process

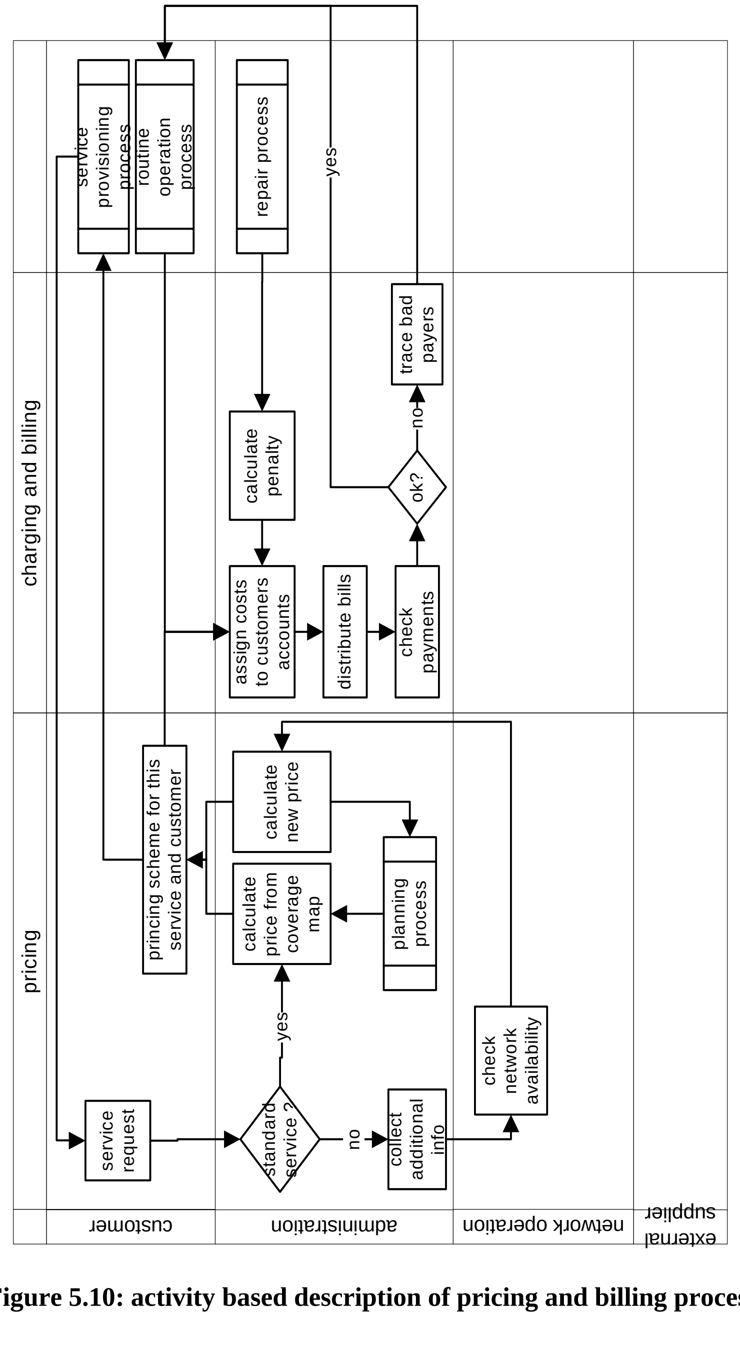


Figure 5.10: activity based description of pricing and billing process

5.6 Activity Duration and Relation with Process Cost

Starting from the process diagrams and attaching costs to the rectangles (denoting actions) and probabilities to the branches out of the diamonds (denoting answers to the diamonds' questions), we can easily determine the formula for the cost of an entire process. This is calculated by summing up the cost of all sequential actions and the weighted costs of the conditional actions. Considering the example of Figure 5.11, including four actions *A1*, *A2*, *A3* and *A4* and one question *Q1* with probability *p* for the answer *yes* and probability *(1-p)* for the answer *no*, the cost of this represented process is given by formula (5.1). Remark that, in case the yes and no branches of the questions do not join after a single action, the entire branch (possibly including new questions) needs to be weighted by the probability for the appropriate answer.

$$cost_{A1} + p \cdot cost_{A2} + (1\text{-}p) \cdot cost_{A3} + cost_{A4} \tag{5.1}$$

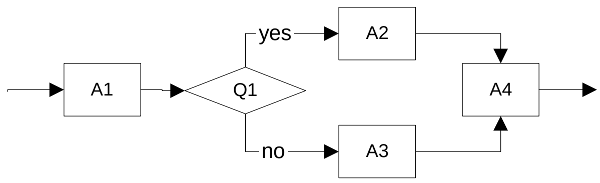


Figure 5.11: methodology to calculate OpEx formulae from process descriptions

Note that in some process descriptions, a loop can be detected. This is, for example, the case in the repair process described above, where an arrow is coming back from the testing phase to the diagnosis phase (forming a loop) when the test after the actual repair phase is unsuccessful. This loop could in principle be executed an infinite amount of times. In order to solve this problem and handle the process as described before, the loop can be broken if the outgoing probability of the joining node is adjusted, as shown in Figure 5.12 and the corresponding formula (5.2).

$$p_x = p_1(1 + p_2 + p_2^{\ 2} + p_2^{\ 3} + ...) = p_1 \sum_{i=0}^{\infty} p_2^{\ i} = \frac{p_1}{1 - p_2} \tag{5.2}$$

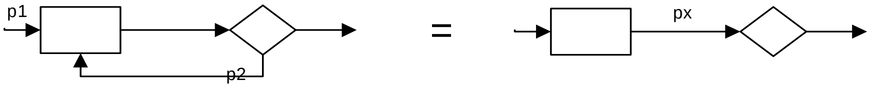


Figure 5.12: breaking the loop in the process descriptions

Finally, we sum the cost of all continuous processes (routine operation, planning, marketing, continuous cost of infrastructure) and the product of the event driven processes (repair, service provisioning, pricing and billing) with their number of occurrences over the considered time frame to find the total OpEx cost for the considered network scenario. The number of occurrences of the repair process is determined by the availability characteristics of the considered equipment, for the service provisioning processes it is determined by the number of service requests and for the pricing and billing processes by the number of customer contracts.

As we described the operational processes in a general way, for some network scenarios some actions can be superficial. Setting the corresponding cost to zero in this case, allows to use the same process description and e.g. also the same spreadsheet containing the associated formulae for all scenarios.

A straightforward way to attach a cost to an action in an operational process is to estimate the time needed to perform this action and multiply it by the wages of the person taking care of it. This approach is also suggested in [5.21]. We should take into account that several types of employees are involved in the operation of a network and several classes of wages should be used for them. Personnel wages could be estimated from company internal information or from public sources like information from trade unions, e.g. for the Belgian case [5.22]. However, it appears that the additional personnel costs for training and for tools and transport (second and third row in the matrix of Figure 5.3) are not covered by the model in this way. Exactly calculating the amount of training and the tools needed for each of the considered actions is probably impossible. On the other hand, some general trends can easily be detected (e.g. technicians will need more tools than administrative personnel), so that we can identify a weight factor for all considered personnel categories what the personnel cost needs to be multiplied by. The use of the weight factor is similar to what is described in [5.19]. A possible way to estimate the weight factor is by dividing the total expenses of a certain company department by the actual cost of the personnel, as suggested in ABC-costing [5.23]. Apart from the personnel wages, also the activity duration is required to calculate the cost of the actions. This activity duration could be estimated from company internal information. However, some company independent estimations obtained from a survey with different network operators can be found in [5.4], added to this thesis as Appendix D.

Calculation of OpEx costs using the suggested process-based approach allows to study the impact of the business organization of the considered carrier, i.e. more efficient workflows are reflected in the processes directly, where more efficient organization (e.g. smaller departments) are reflected in the weight factor. This approach is far more flexible and more realistic than the traditional approach where OpEx is estimated to be proportional to the CapEx cost.

5.7 Availability Measures in Relation with Routine Operation and Repair Costs

5.7.1 Reference Availability Numbers

The repair process is event-driven. In order to determine its number of occurrences, availability information concerning the considered network equipment is required. Within the IST-project NOBEL, we took the initiative to define a general availability model and collect general, vendor independent availability numbers for IP, SDH and WDM equipment as well as optical fiber. Using a questionnaire, consortium partners were asked to express their opinion on equipment reliability for the components in our model. Only in some cases, the initial estimation could be based on literature sources like [5.24][5.25][5.26] [5.27][5.28][5.29]. After bringing all received data together, a reliability interval was obtained for all components and harmonized between all partners to obtain a consensus. Finally, we ended up with a triplet-representation for each of the availability measures: *[optimistic value, nominal value, conservative value]*. The conservative value indicates a pessimistic view on the availability of the system, the nominal value represents the average of the values from different information sources and the optimistic value represents a best-case scenario.

Table 5.2 lists the collected availability numbers: *Mean Time Between Failures (MTBF)*, its alternative *Failures in Time (FIT)* and *Mean Time To Repair (MTTR)*. The relation between MTBF and FIT is given by formula (5.3).

$$MTBF[h] = 10E09/FIT \tag{5.3}$$

More information concerning the rationale behind the numbers can be found in [5.6]. Link failure probability values for optical fibre should take into consideration both the type of the physical link and the geographical distribution of network segments. For buried cable, we assume a nominal MTBF of *2.63E06* hours or about 300 years for *1* km (corresponding to a *Cable-Cuts (CC)* value of *3E02* km, indicating the average cable length suffering from *1* cable-cut per year [5.30]) and a MTTR of *12* hours.

	equipment part	MTBF (hours) *(years)*	FIT	MTTR (hours)
IP layer equipment	IP router: route processor	[1E06, 2E05, 4E03] *[114.2, 22.8, 0.5]*	[1E03, 5E03, 2.5E05]	[1.8,4,10]
	IP router:	[3.5E05, 8.5E04, 1E04] *[40.0,9.7,1.1]*	[2.86E03, 1.18E04, 1E05]	[2,4,5]
	IP router: SW	[1E05,3E04,5E03] *[11.4,3.4,0.6]*	[1E04,3.33E04,2E05]	[4E-04,2E-02,2.5E-01]
SDH equipment	SDH DXC or ADM	[1E06,5E05,1E05] *[114.2,57.1,11.4]*	[1E03,2E03,1E04]	[2,4,9]
WDM equipment	bidir OA	[5E05,2.5E05,1E05] *[57.1,28.5,11.4]*	[2E03,4E03,1E04]	[2,6,9]
	bidir mux/demux	[1E06,1.67E05,1E05] *[114.2,19.1,11.4]*	[1E03,6E03,1E04]	[2,6,9]
	transponder 2.5 Gbps	[5E05,4E05, 2.94E05] *[57.1,45.7,33.6]*	[2E03,2.5E03,3.4E03]	[2,6,9]
	transponder 10 Gbps	[9.6E05,3.5E05, 2.94E05] *[109.6,40.0,33.6]*	[1.04E03, 2.86E03,3.4E03	[2,6,9]
OXC equipment	WDM OXC (OEO) or OADM	[-,1E05,-] *[-,11.4,-]*	[-,1E04,-]	[-,6,-]
	ODXC redundant: 1+1 protected	[-, 2E06,-] *[-,228.3,-]*	[-,5E02,-]	[-,4,-]

Table 5.2: collected availability numbers in the triplet representation [optimistic, nominal, conservative]

5.7.2 Impact of Availability Numbers on Cost of Operational Processes

There is a direct relation between availability numbers and the repair as well as the routine operation (maintenance) process. The MTBF-value indicates the average time between two failures of a component. This can allow to estimate the frequency of occurrence of the repair process. The MTTR-value, on the other hand, is an important input for the activity duration in the repair process.

Note that, knowing the availability numbers, for some components, also preventive replacement (in the service window, and therefore during routine operation) could be planned for. Preventive replacements increase the cost of the routine operation processes, while decreasing the repair process cost.

5.8 Calculation of Overall Cost for a Network Scenario

After describing several building blocks for cost calculation in the previous sections, in this section, we want to summarize the overall methodology to calculate the total cost, CapEx as well as OpEx, for a certain network scenario. We distinguish several steps:

- *Collecting equipment information.* Knowing the technology for the network scenario under study, some information about the considered equipment needs to be collected, such as equipment price and availability information, power consumption and footprint. In case a real network scenario is considered, this can be found in the datasheets provided by the equipment vendor. In case a theoretical study is performed, without reference to a specific vendor, the assumptions need to be based on public sources like the collected availability numbers of Section 5.7 or some educated guesses for equipment costs, footprint and power consumption.
- *Dimensioning the network.* From the estimated number of customers and their expected demand pattern, the capacity requirements for the network can be determined. Dimensioning the network for this amount of capacity learns the required number of components of each equipment type.
- *Calculating total CapEx cost.* Multiplying the number of components of each equipment type by the corresponding component price, and summing this over all components in the network, results in the total CapEx cost.
- *Calculating OpEx for equipment installation.* The OpEx costs associated with equipment installation are to be determined together with the CapEx costs as ‘first installed costs’. For a real network scenario this information comes from the contract with the equipment vendor. For a theoretic study, it can be estimated as a fraction of the CapEx costs, e.g. *30%*.

- *Calculating OpEx for a network which is up and running.* Using the activity-based approach of Section 3, the costs of all identified operational processes can be estimated, based on the input information concerning personnel wages and activity duration. This information suffices to calculate the cost for the continuous processes like routine operation, operational network planning and marketing. For the recurring processes, the number of occurrence over the considered time frame (e.g. one year) is required. For the repair process, this follows from the availability information. For the service provisioning process it is determined by the number of service requests and for the pricing and billing process by the number of customer contracts.
- *Calculating the cost distribution over time*. Given the results for CapEx and OpEx costs, the distribution of the costs over the considered planning interval can be determined. CapEx and OpEx for equipment installation are one-time costs in the beginning of the planning interval. OpEx for the network which is up and running is to be counted for every time period (e.g. every year). The knowledge of the cost distribution over time is important in order to evaluate investment decision criteria like Net Present Value, as described in Chapter 3 or apply Real Options valuation, as described in Chapter 4.

5.9 OpEx Impact of Resilience Scheme and Control Plane

5.9.1 Impact of Resilience Scheme

[5.4], attached as Appendix D, presents a quantitative study on the total expenditures for a transport network operator in a German reference network scenario. A WDM network carrying *2.5* Gbps leased lines is considered. The topology is the reference German network [5.31] with *17* nodes and *26* links and the associated traffic demand matrix for *2004*. This traffic leads to *1214* services for one year, *80%* of which we assume to be standard services. We also assume that there is no service cessation or move during this period. All assumptions concerning equipment charachteristics, cost parameters, activity duration, personnel cost and failure probabilities can be found in the appendix. The CapEx and OpEx costs for the optical layer of the network are compared for an unprotected network, a network with shared path protection and 1+1 protection.

The first, obvious impact of the considered resilience scheme on the overall network costs is observed in the dimensioning results. This has a direct effect on the CapEx costs and the OpEx part which is directly related to continuous costs of infrastructure (floorspace, energy,…). Those costs are smallest for the unprotected network and grow with the needed required amount of backup capacity, as shown in Figure 5.13 and the left part of Figure 5.14(a).

The right part of Figure 5.14(a) as well as Figure 5.14(b) show the impact of the resilience scheme on the process-based OpEx costs. The costs of service provisioning, which is most expensive in case of 1+1 protection (more connections need to be set up). Also planning costs grow with the amount and complexity of failure scenarios that need to be planned for. Finally, the cost of the repair process is smaller for a protected network. Although more equipment leads to more possible failures, on the other hand and more important, the availability of backup capacity strongly reduces the time to get the network operational after the occurrence of a failure (both because the actual repair action should not effect the network availability as well of because traffic is not to be rerouted) so that he repair costs is lower for protected networks. Note that the penalties to be paid to the customer will be smaller in case backup paths are available (service is not interrupted). However, this effect is not modelled in the case study described.

Considering the overall picture, we note significant differences between the resilience schemes. The network using shared path protection is the cheapest to operate. When taking into account the considered life time of the equipment, we can compare the total CapEx and OpEx over this time frame. With the considered assumptions, we see that CapEx exceeds OpEx costs in all cases. The ratio OpEx/CapEx is *60%* for an unprotected network, *43%* for shared path protection and *42%* for 1+1 protection. Part of the explanation for the fact that OpEx is smaller than CapEx can come from the observation that the operational expenses for first-time installation as well as the general expenses for non-telco specific administration and infrastructure are not counted in this study.

Furthermore, in this study only the backbone network was taken into account. A higher OpEx/CapEx can be expected for access networks, because of the larger number of nodes, the variety of equipment, the larger impact of the individual customer, etc.

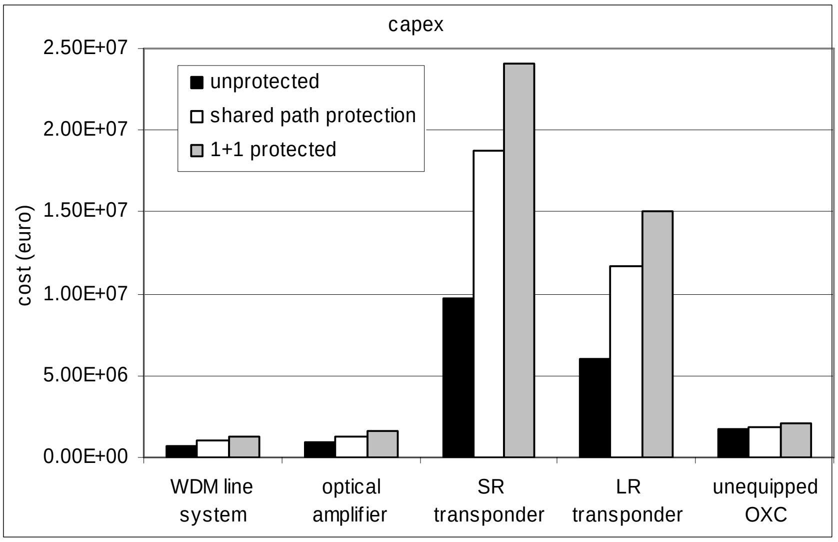
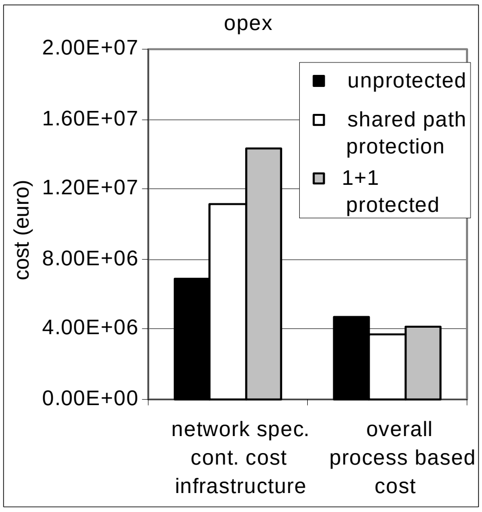
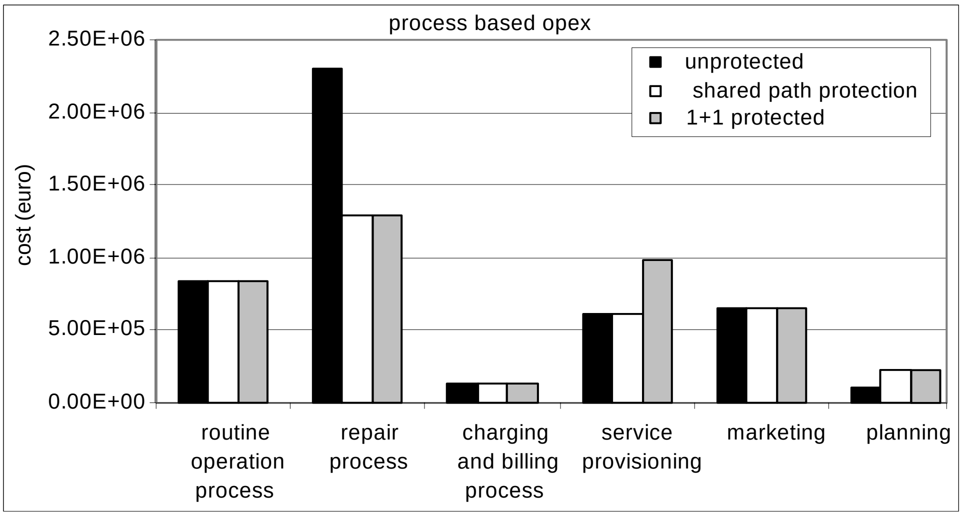


Figure 5.13: impact of resilience schemes on CapEx



(a) impact on continuous cost of infrastructure versus process based cost



(b) impact on process based OpEx

Figure 5.14: impact of resilience schemes on OpEx

5.9.2 Impact of Control Plane

[5.2], attached as Appendix E, studies the operational expenses for a Generalized Multiprotocol Label Switching (GMPLS)-enabled network i.e. a network with control plane functions such as routing and signalling for automated connection control. Note that, in this study, we do not distinguish the details of the approaches described by ITU, OIF and IETF, but generally assume a control plane supporting automation of network operations. We use the term GMPLS to refer to any kind of control plane according to one or several of these standards.

Concerning the cost of the operational processes, we started from the OpEx model of Section 5.4 and defined the operational processes for the traditional as well as for a GMPLS-enabled network. We evaluated how GMPLS technologies impact the costs of the operations as well as the probabilities of the process branches.

The main difference in OpEx costs was observed in two subprocesses, namely *service offer* and *actual service provisioning*, as explained in the appendix. In case of a GMPLS-enabled network, signalling can be done via standardized interfaces (User-Network Interface UNI and Network-Network Interface NNI), without requiring manual intervention. This means that the cost for setting up a new connection (actual service provisioning) decreases strongly. Since the service delivery will now be automated and executed on the pure machine level, correct agreements and regulations have to be negotiated by the sales department, and implemented well before in the form of Service Level Agreements (SLAs) leading to a higher cost for negotiations (service offer). The use of GMPLS technologies and the possibility to offer dynamic services are strongly interconnected issues.

Focusing on the cost for a single service request, the study also considers the major differences between incumbent operators and new entrants. New entrants have much lighter business processes but also more complex technical processes since they have to resort to external partners more often[13]. Incumbents, on the contrary, often have lean technical processes that allow providing standard services more easily. On average over the considered subprocesses, the costs for service provisioning are about *25%* lower for the new entrant than for the incumbent. For both types of operators, OpEx effort and cost reductions of nearly 50% compared to traditional operations can be identified when introducing GMPLS, as shown in Figure 5.15 and Figure 5.16.

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[13] This is also the reason why new entrants are very often focusing on large customers and project business, where customized solutions with more technical efforts are required anyway.

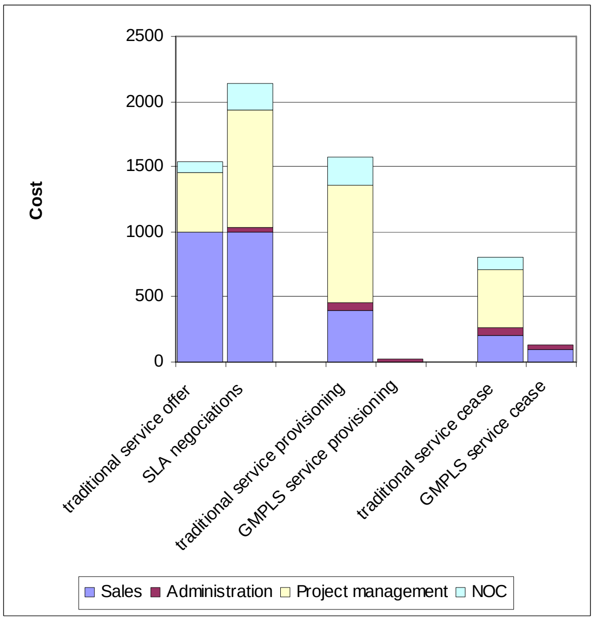

Figure 5.15: cost comparison for incumbent

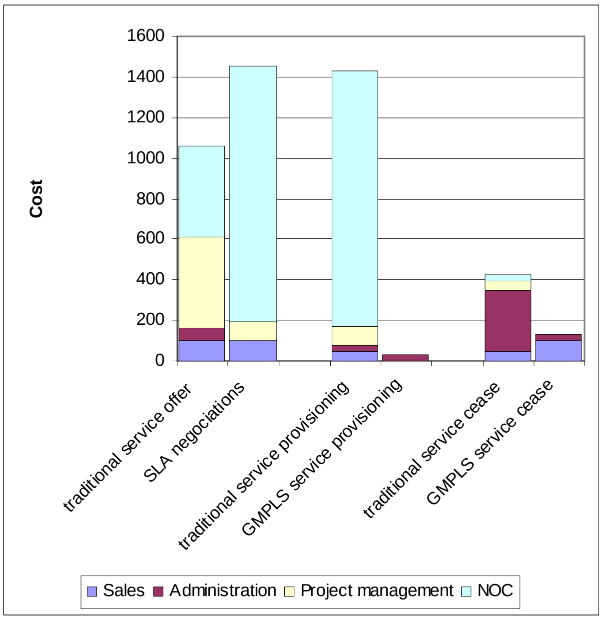

Figure 5.16: cost comparison for new entrant

5.10 Conclusion

In the rapidly changing telecom market, an accurate planning of different network deployment plans is important. Often a trade-off needs to be made between network availability and cost. In this chapter, we have described a general methodology to calculate the costs for a telecom operator. CapEx and OpEx were classified. We have represented the identified OpEx subparts in a matrix structure and starting from this, we have discussed the most important operational processes, using a bottom-up approach. We have indicated how attaching costs to the individual actions in those processes allows to calculate the operational expenditures for a certain network scenario. We have shown that most network operators' processes are similar and can be modelled quite generically. We discussed the required input data in order to calculate the processes' costs for realistic network scenarios. They include activity duration and availability parameters. In a case study, we study the impact of different resilience schemes and the introduction of GMPLS on the operational expenditures.

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6

Network Costs in a Liberalised Market

“Competition is a painful thing, but it produces great results” - Jerry Flint

The liberalization of the telecom market has fundamentally changed the situation of the telecom operator. The regulator imposes a lot of reporting on interconnection costs. On the other hand, also a good insight in the internal cost structure is very important to obtain a stronger position in the market. We describe the different situations where costing can be useful in a competitive environment in Section 6.1. In Section 6.2, we focus on cost allocation schemes and indicate how the different CapEx and OpEx cost parts can be mapped to the different service cost classes. In Section 6.3, we briefly describe CapEx and OpEx cost allocation for regulatory purposes. Finally, in Section 6.4 we indicate how cost models can serve as a basis for pricing decisions. Our research results in these fields directly contributed to the publications [6.1][6.2][6.3][6.4].

6.1 Costing in a Competitive Environment

Until the eighties most European telecom network operators were owned by their government. A monopolistic situation was created over the years, which had to be liberalized. This belief was mainly caused by the understanding that regulated monopolies lead to high prices and excessive cross subsidization of profitable towards lossy segments [6.5].

The telecom market was transformed from a regulated monopoly into a private competition. In this regard, an open competitive market had to appear. However, the transition from a regulated monopoly into a free market is subject to a strong re-regulation [6.6][6.7][6.8][6.9][6.10]. Interconnection between network operators in a liberalised market is essential for delivering services to end users. As the incumbent has a strong advantage compared to the new entrants (e.g. he can use interconnection tariffs for protecting his market shares), regulation is necessary to ensure that a competitive market can be established.

In a liberalised market, cost modelling provides input information to support several kinds of decisions. For a network operator, it serves multiple purposes:

- *Costing for strategic planning* provides useful information concerning the total network operator’s costs. It includes cost calculations to decide on the introduction of a new technology, the migration to a new platform, etc.
- *Costing for internal monitoring and management* provides cost information split per service. It allows the network operator internally to perform some benchmarking, perform a profitability analyses for different services, etc. It may also form a starting point for service pricing decisions.
- *Costing for regulatory reporting* allows an operator with a Strong Market Position (SMP) to report to the National Regulatory Instance (NRI) and indicate the true costs made for offering these services.

For the purpose of strategic planning (e.g. technology introduction), total costs are the most important input. Therefore, the concepts discussed in Chapter 5 to calculate CapEx and OpEx costs will in most cases provide sufficient information.

However, in order to calculate costs for internal or regulatory reporting, it is essential to be able to split the total costs according to the services causing these costs, i.e. to allocate the costs to the services. In a fully converged network environment in which all services are running over a single network architecture, the bandwidth provisioned in the network is available to all services. This leads to lower bandwidth requirements and lower costs per unit (as a result of the positive effects of economy of scale and scope). However, it leads to a far more complex *cost allocation problem*. Since the equipment in a converged network is used by all services, the cost of installation and maintenance of the converged network is a shared cost among the different services. In order to make well-informed business decisions, one has to be able to calculate the economic drivers for each service correctly. This implies that a fair proportion of the shared network cost should be allocated to each service.

6.2 Cost Allocation to Services

6.2.1 Service Cost Categorization

There are different service cost categories that need to be taken into account, as illustrated in Figure 6.1.

- The *direct costs* are expenses which would not have been made if the product/service was not produced.
- *Shared costs*[14] are defined as costs of the usage of resources which are shared amongst several processes/services. They can be divided in a fair way, e.g. according to bandwidth usage.
- *Common costs* are defined as joint costs for which the resources are not directly associated to the product or services sold. They are mainly seen as overhead.

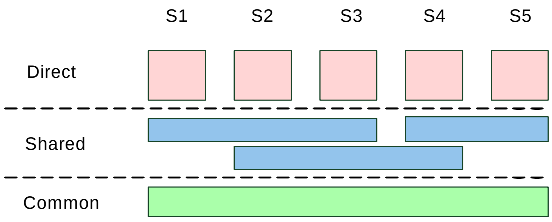

Figure 6.1: service cost categorization

Different types of costs per service can be calculated through different methodologies, see Figure 6.2.

- The first method is the *Stand Alone Cost (SAC)*. It considers the cost per service as if there was only one service offered. All shared costs and common costs are added to the direct costs of the considered service and are allocated to that service. The SAC is the highest cost level the service can reach. This method is only used in a top-down approach to determine an upper bound for the cost of a service.
- The *Fully Allocated Cost (FAC)* method allocates all costs to all services. Direct costs are directly attributed to each cost consuming service, shared and common costs through cost drivers. This method can be used for top-down as well as bottom-up approach. The hardest part when using this cost base is to find the right driver for each of the costs.

[14] Note that there is no consensus in the literature concerning the precise definition of shared and joint costs [6.11][6.12]. In this thesis, we only consider shared costs.

- The *Incremental Cost (IC)* method only measures the change in total costs when a substantial and discrete increment or decrement in output is generated. This increment can be a newly offered service, but also an increase in output of one service. A well known methodology to measure incremental costs is through *Long Run Incremental Costing (LRIC)*. Long run implies that when a large increment occurs, capacity can be expanded. Economies of scale will be playing an important role in the allocation of shared cost, resulting in a smaller part of attributed costs than in FAC. The LRIC method is mainly used in the bottom-up approach.

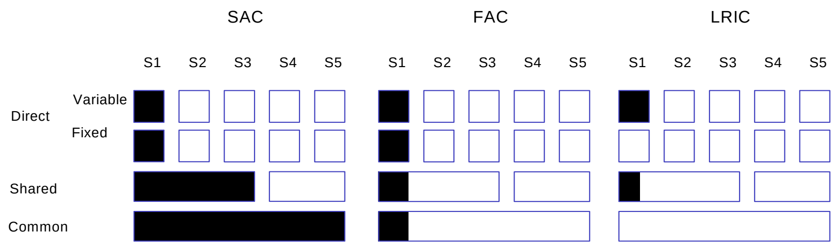

Figure 6.2: different methodologies for calculating cost per service

6.2.2 CapEx and OpEx Parts Mapped into Service Cost Categories

In the previous chapter, several CapEx and OpEx cost parts have been distinguished. A typical mapping of these costs on direct, shared and common service cost categories is given in Figure 6.3.

Some cost parts can directly be attributed towards a certain service. It concerns the costs for service provisioning, pricing and billing and marketing. Those costs can therefore be seen as direct costs. For service provisioning, the entire process from ordering entrance by the administration till performing the needed tests is specific for a certain service. It includes planning, installing and configuring the equipment in order to be able to provide the considered service. If the considered service would not be offered, this cost would not exist. For pricing and billing, the cost of pricing (defining the price for a certain service) can definitely be seen as a direct cost as well. This activity is specific per service. Also, the cost of charging (calculating the price to be paid by a certain customer over e.g. one month) can be considered a direct cost. In case of billing, it is possible that a common bill is made for a certain customer, who uses different services. In that case the cost for billing is to be seen as a shared cost. If none of the services would be offered, this cost would completely disappear. In case the bill only concerns one service, the cost of billing can be considered a direct cost. If marketing is performed for individual services, then it is to be considered as a direct cost as well.

Further, there are some general costs, the non-telco specific CapEx (e.g. the buildings to house the Human Resources (HR) department, the PCs for the administration etc.), together with the non-telco specific OpEx costs (e.g. heating of the buildings to house the personnel, wages of the HR personnel, etc.) which are not specific to a certain network service. Those costs can therefore be considered as common costs. For the telecom operator or service provider, they can be seen as overhead costs.

Finally, the costs for the network infrastructure should be considered as shared costs, as the same network infrastructure is used to offer all network services in case of a converged network. Note that the network infrastructure cost does not only include the cost for the capacity required by the dimensioning process, but also the additional capacity in the network induced by a granularity of the equipment, equipment bottlenecks and backup capacity to provide protection and restoration. Some other cost parts are very closely related to the infrastructure cost and are therefore also considered as shared costs. They are to be allocated in the same way as the infrastructure cost. First there is the cost of the network software (CapEx part), e.g. the NMS is used for several services. The telco-specific cost of infrastructure (e.g. floor space, energy) can be treated in a similar way. Also OpEx associated with setting up a network is close to the CapEx cost (together they form the first installed cost). All of those costs can be allocated together with the CapEx cost for equipment installation. Finally, the operational activities concerning network maintenance, repair and planning are probably generally coordinated and performed without any reference to individual services. For this reason, they can also be seen as shared costs.

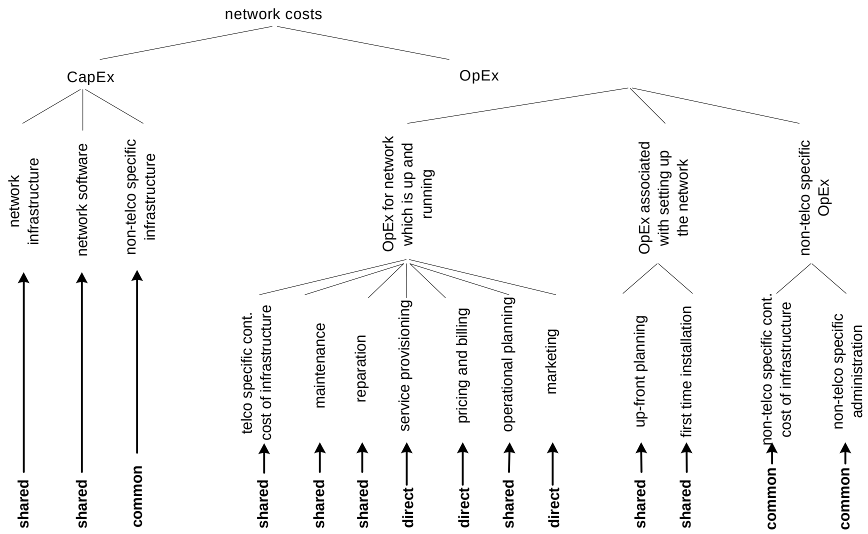

Figure 6.3: mapping of CapEx and OpEx parts on shared costs

6.2.3 A Fair Allocation of All Network Costs

The non-telco specific costs (infrastructure acquisition, continuous cost of infrastructure and administration) were indicated as common costs. They can (by definition) not be allocated to the offered services in a straightforward way.

The direct costs are directly to be allocated to the considered services. This is the case for service provisioning, pricing and billing and marketing costs. If billing or marketing activities are performed jointly for multiple services, the considered costs are to be seen as shared instead of direct costs. A fair cost allocation scheme in this case could be an equi-proportional distribution among all services. E.g. if one bill is sent for several services, this cost for the distribution of the bill (paper, stamp, processing) could be equally divided among all services.

The costs associated to the operational processes of the network (maintenance, reparation, service provisioning, pricing and billing, operational planning and marketing) should be evaluated individually, in order to allocate them fairly to the different network services. An activity-based costing approach [6.13], like the OpEx model discussed in the previous chapter can be helpful in this regard.

The network resources and the related costs to build and operate the network (network infrastructure, network software, telco specific continuous cost of infrastructure and OpEx associated with setting up the network) are indicated as shared costs in the previous section. They are all closely related to the infrastructure itself and therefore need to be divided in a fair way according to a specific cost allocation scheme for shared network costs. In [6.3], we propose a solution for allocating costs of network-usage in a converged network, taking into account both the peak-usage and the bandwidth-usage of each service in a two-phased scheme. A first part of the cost for using the converged network for each service is allocated through its average bandwidth-usage. The remaining bandwidth, necessary for running all services (peaks) over the network is allocated by the proportion of the peak-usages of each of the different services. Figure 6.4 compares the allocation of two traffic flows using four different allocation schemes: allocation based on average bandwidth usage, allocation based on the proportion of used capacity at peak time (using one peak over the entire interval, the global peak), allocation based on the proportion of the individual peaks per traffic flow and finally the two-phased approach we propose. It is apparent from the example in the figure that the two-phased scheme results in a more fair allocation decision.

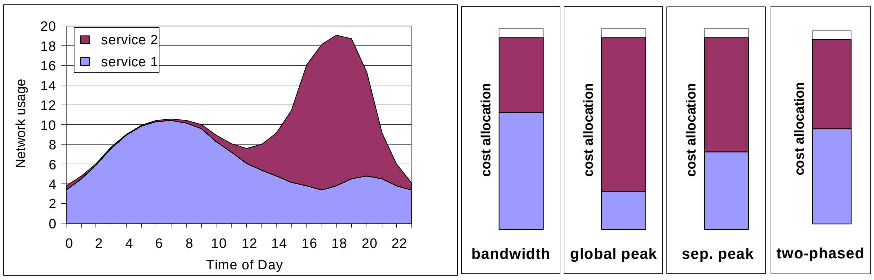

Figure 6.4: allocation of traffic flows with two distant peak hours (one broad and one small)

6.2.4 Cost Allocation and Market Interaction

In [6.2], attached as Appendix F, we illustrate the need for regulation using a fictitious telecom market with three players. The *incumbent I* owns a complete PSTN/ISDN network and has a strong market position in the considered market. On the other hand, two new entrants are entering the market. A *cable operator C* owns a complete cable network, which has the same functionalities, quality and range as the incumbent's network and can reach all end users on its own. The *alternative operator A* only disposes of a core network and is making use of the carrier select services of the incumbent to reach its end users.

The presented study deals with the costs for the access network for the different operators and distinguishes between fixed and variable costs. The fixed costs are mainly equipment costs and network installation costs. The variable costs are recurring operational and network costs, both for the technical processes and the business processes. We assume that the fixed cost is reflected in the subscription cost for the end user and the variable cost in the cost per minute. We assume, based on past network migration steps, that *I* is least efficient, *C* is already more efficient and *A* is most efficient, leading to a decreasing cost (both fixed and variable) in this order: *I, C, A*. However, *A* is completely dependent on I concerning its fixed costs (collecting service). Both *C* and *A* depend to some extent on *I* for the determination of their variable costs, based on the termination rates of *I*.

When we focus on the cost for the end user, apart from the costs described above, there is an additional cost to be taken into account, the so-called stickiness coefficient *Z*, which indicates the costs perceived by the customers who want to switch operators. The resulting cost trends and the corresponding market shares (*Si, Sc, Sa*) are shown in Figure 6.5.

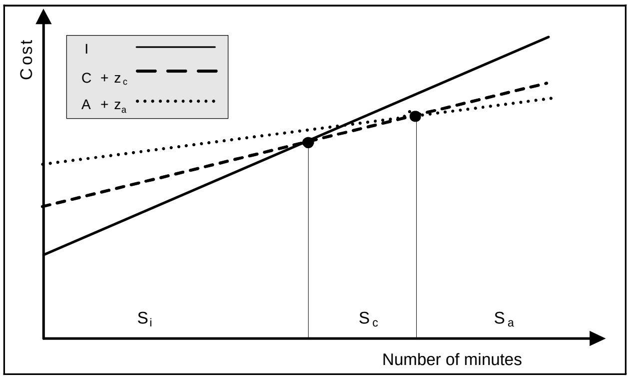

Figure 6.5: cost trends for incumbent, cable and alternative operator

In an unregulated market, the incumbent can set his collecting and terminating tariffs in such a way that it is impossible for the new entrants to obtain any market share. Cost-based interconnection prices, required by regulation, allow the new entrants to really enter the market. When they are able to attract customers and gain some market share, they also get some power. Finally, the incumbent will be required to reduce costs.

- If the incumbent lowers the termination costs, the cable and the alternative operator will benefit because they could lower their cost per minute they charge their customers.
- If the incumbent reduces his fixed network costs, the alternative operator will benefit because a lower collecting cost will be paid.
- The incumbent will only gain by decreasing its variable network costs because this has only effect on his own cost function without advantages for the other players. This will result in the preservation of his market share.

This example indicates that regulation indeed leads to competition in the market. Of course, the role of the regulator is very important. The results obtained by the regulator are to a large extent determined by the regulation itself. In case of fixed telephony, regulation is in force, as a result of which the European market has become competitive. On other markets, however, there is still a lot of work to do.

According to the Universal Service Directive, NRIs can regulate the lower speed Internet access and leased lines at retail level. All the other internet access services are regulated at a wholesale level. This means that also broadband internet access pricing is regulated via wholesale requirements. **Error! Not a valid bookmark self-reference.** indicates that the common price and cost-orientation requirements can impose some problems in some situation, e.g. if the incumbent operates the network both in the town and on the countryside and needs to apply the same interconnection and wholesale prices in both areas, it can be beneficial for a competitor to deploy his own network in the city and lease the incumbent's network in the countryside.

New market definitions and related obligations may increase competition and truly lower the prices for the end customer. The European Commission is currently carrying out a review of the legislative framework concerning electronic communications. Around the end of 2006 draft legislative proposals to amend the regulatory framework are expected. At the same time, a revised version of the Recommendation on relevant markets will be published. The revised framework is expected to be implemented in European Member States around 2009 - 2010.

6.3 Regulatory Costing

6.3.1 CapEx Calculation for Regulatory Purposes

In case of regulatory costing, the operator uses cost calculation and cost allocation schemes to prove his network costs, in order to justify his interconnection rates. In an early stage, mostly top-down cost allocation schemes are used. Their advantage is that they have a direct factual basis, namely the accounting books. The incumbent operator needs to look into his internal reporting and classify and allocate costs. As times go by, the NRI often becomes more stringent and requires the cost allocation to be based on a bottom-up model. This approach has as an advantage that it will eliminate inefficiencies in the existing network from the costing results. However, there is a chance that the bottom-up model lacks touch with reality.

A constant point of discussion between players with a Strong Market Position, new entrants and NRI is the question of spare capacity. If the network is modelled bottom-up, it is sometimes unclear how much and what type of spare to dimension for. When considering top-down models, the SMP player tries to find a way to allocate the costs for spare capacity he has made in the past. In this regard, it is important to distinguish several types of capacity, which can become visible when using a bottom-up cost modelling approach.

- *The average used capacity* is the average of the capacity used over time by the different services offered. This is definitely not spare capacity. The following categories, on the other hand, are to be seen as some type of spare.
- *Peak capacity* is the capacity necessary for providing traffic-peaks over the network. Dependent on the type of service, the difference between average and peak capacity can be bigger or smaller.
- *Capacity required for signalling* is the capacity necessary for signalling messages used for all kinds of purposes within the operational processes of the network (connection setup/teardown, management, etc.).

- *Granularity mismatch* causes some overhead capacity which is unavoidable because of the granularity of the used equipment.
- *Backup capacity for resilience schemes* is the capacity reserved for providing resilience over the network. It can either be dedicated or shared.
- *Capacity reserved for future growth* is some spare capacity that is expected (explicitly or implicitly) to be used in the future because of expected traffic growth.

The first two types of capacity described above (average and peak capacity) are the subject of the two-phased approach of Section 6.2.3. The following two types (capacity for signalling and granularity mismatch) are unavoidable spare for all services and therefore need to be allocated to the considered services somehow. Concerning backup capacity, the situation is complex, as different services often have different requirements concerning resilience. Finally, a lot of discussion can be caused by the capacity reserved for future growth. It is very difficult to allocate these costs to the existing services.

6.3.2 OpEx Calculation for Regulatory Purposes

A first traditional approach for calculating OpEx for regulatory purposes is to apply a fixed CapEx/OpEx ratio. This ratio can be obtained in several ways.

- The current CapEx/OpEx ratio can be derived from top-down figures (the actual situation of the SMP player) and then applied to the bottom-up calculated CapEx costs. However, this often causes a mismatch between top-down and bottom-up information, because top-down is backward looking whereas bottom-up is forward looking.
- The ratio can also be based on a benchmark, some widely accepted value, which could e.g. be based on the average ratio for several big operators. Of course such a type of benchmark is difficult to obtain. Consultancy information or something similar is required.

The use of a fixed safety margin might cause problems in case the situation is changing (mismatch between past and future situation), e.g. from a stable situation towards growth. Moreover, this approach neglects the possible technological impact. Automation of certain tasks might increase the CapEx while decreasing the OpEx, which cannot be captured by a fixed ratio.

A second traditional approach for OpEx calculation for regulatory purposes is to identify a cost driver per OpEx cost item, and determine the cost of this item proportional to this driver. E.g. the helpdesk staff cost could be proportional to the number of subscribers, the office rental cost could be proportional to the number of staff. A clear problem with this approach is the difficulty to determine the proportion factor per cost driver. Benchmarking will be needed again.

Activity-based OpEx cost models can be applied for regulatory purposes and allow to overcome some shortcoming of traditional approaches. No benchmarking is needed. Also the determination of a proportion factor for cost drivers is not required. If the activity-based model originates from a thorough observation of the actual situation and activity duration measurements are performed, it allows to model the real situation very closely and gives a good insight in the different cost sources.

6.4 Costing as a Basis for Pricing Decisions

In a liberalised market, it is important for a network operator to have a good insight in his cost structure. Apart from the regulatory purposes discussed above, competition forces the operator to be more efficient and to have a good price setting strategy. Figure 6.6 indicates how CapEx and OpEx calculations can form the basis for profit and profitability calculations.

Pricing can depend on these results to different extents. Within *cost-driven or cost-based pricing*, the total revenue of all customers is expected to cover all costs incurred for delivering this service to the customers. From these costs, pricing-margins can be calculated which give an indication of how low a tariff can be set and whether the tariff set is sustainable.

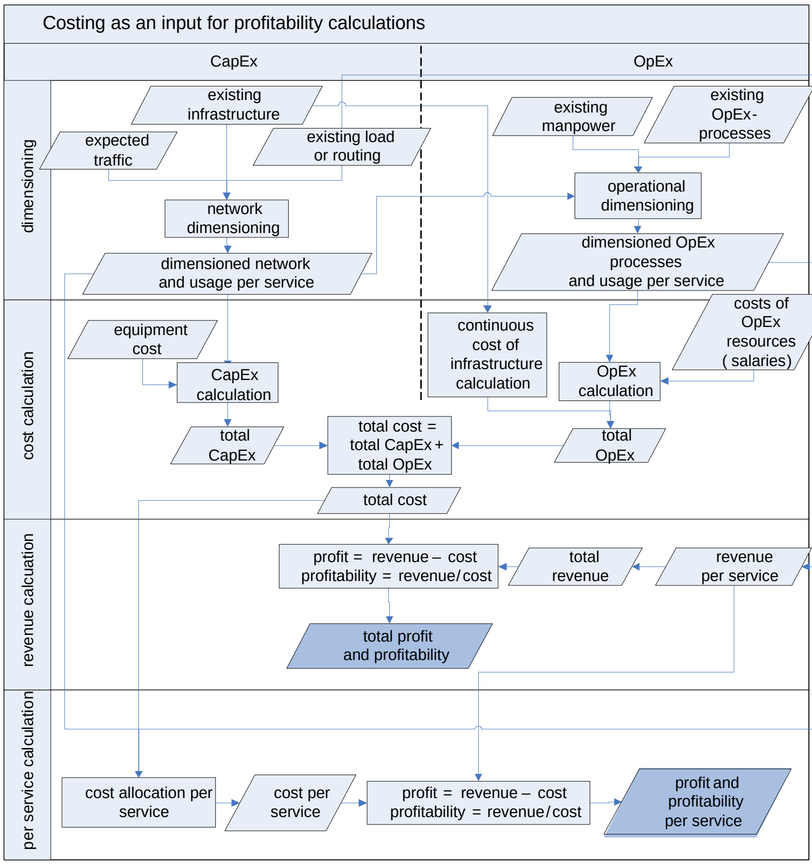

Figure 6.6: profit calculations based on costing

Figure 6.7 gives an overview of the different margins which can be identified according to the cost information available.

- The two outer margins on the tariff of the new service can be easily defined using only the forecasts and simple economic calculations. These two margins will only give a clear indication whether the proposed business scenario will result in a certain profit (when the tariff is set above the stand alone cost (SAC) or in a certain loss evolution (when the tariff is set below the break-even (BE) cost).

- The fully allocated cost (FAC) margin reflects the situation in which each service is paying the amount of resources it uses, regardless of the fact that it might actually be filling spare capacity of other services. All investment costs are allocated using a fair cost allocation scheme which reflects the actual usage of the resources available in the network.

- The long run incremental cost (LRIC) margin reflects the situation in which the new service is at each moment seen as an additional service on top of the main service(s). The costs allocated to the new service are equal to the additional investment costs necessary to provide the service when the cost for providing the increment for all existing services is already committed.

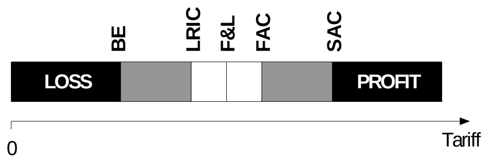

Figure 6.7: different margins to base pricing decisions on costing information

In order to determine a suitable tariff for a new product, the margins discussed can be a helpful starting point. The outer margins, calculated using break-even or stand-alone cost allocation give an indication whether a tariff will result in sure loss or sure profit. Between these two margins a grey zone exists.

Considering the adoption curve of a new service, it is clear that in an early stage it resembles most closely the LRIC situation of a very small service using mainly spare capacity of the existing services. In a later stage of its adoption it will possibly grow at a size justifying the use of FAC. A margin can be calculated using a combination of both (referenced by F&L), by setting a threshold level on the capacity and using LRIC as long as capacity-requirements for the new service stay beneath this level and FAC when the capacity requirements are above this level. Using such method might also give the new service a more competitive edge without pushing the existing services in a non-profitable situation.

6.5 Conclusions

In this chapter we have sketched the impact of a liberalised telecom market on the situation for the network operator and how cost modelling can be helpful in this regard. We have mapped the different CapEx and OpEx cost parts on the identified service cost categories, indicating how the cost models of the previous chapter can be used in a liberalised market. We have indicated the network resources and the related costs to build and operate the network (network infrastructure, network software, telco specific continuous cost of infrastructure and OpEx associated with setting up the network) as shared costs. They are all closely related to the infrastructure itself and therefore need to be divided in a fair way according to a specific cost allocation scheme for shared network costs, e.g. the proposed two-phased scheme based on a combination of average bandwidth usage and peak usage. We have briefly described CapEx and OpEx cost allocation for regulatory purposes and indicated how cost models can serve as a basis for pricing decisions.

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7 Conclusions

This thesis discusses several aspects of the network planning problem for IP-over-Optical networks. In this chapter we summarize the most important conclusions of our research and give some directions for future work.

7.1 Summary of Most Important Findings

As a network operator aims at fulfilling customer requirements (in order to obtain the required cash in-flows) while minimizing his costs (cash out-flows), a thorough knowledge of relevant planning techniques is extremely important. The goal of network planning is to provide the operator with guidelines to handle this trade-off between cash in-flows and cash out-flows. The research reported in this dissertation exactly aimed at deriving these kinds of guidelines, by studying some specific parts of the planning process.

Concerning the dynamic character of network traffic demands and equipment costs, our work focussed on the comparison of single period planning, anticipated planning and multi-period planning and their relation with investment decision techniques. We show that anticipated planning can lead to remarkable better results than single period planning, while avoiding the complexity of multi-period planning. The correct choice of the prediction interval is important in this case, because too short a prediction interval does not allow to sufficiently take into account the future evolutions and too long a prediction interval suffers from uncertain predictions. We also presented a cost-efficient migration scheme to introduce optical cross-connects in an IP-over-Optical network. For small traffic demands, the link-by-link grooming approach (efficiently filling the available capacity) is shown to be most interesting. As traffic increases, however, there comes a point where the savings in IP layer expenses realized by end-to-end grooming compensate the extra expenses of introducing the needed optical cross-connects. An intermediate solution is found in the technique of island based grooming, which gradually installs OXCs in the network at the most interesting locations and in this way allows to spread costs.

A second group of problems discussed in this thesis handled with the uncertainty inherent to planning input forecasts. We have evaluated a common approach using safety margins to cope with uncertainty. We have also indicated the relative impact of traffic and equipment cost uncertainties on the situation for the network operator and we emphasised that correlated uncertain input variables lead to important deviations of the considered output value from the estimated value. Finally, we have applied the idea of Real Options thinking to deal with flexibility in uncertain planning problems. We have considered several possible network migration approaches using dark fibre or wavelength lease and indicate how traditional, static planning approaches can easily overlook the value originating from flexibility in the future network deployment plan.

Concerning cost modelling for a network operator, we have presented an activity-based approach to quantify the costs of the network operator operational processes. We suggested reference numbers for activity duration and availability parameters for an IP-over-Optical network, which can serve as an input to calculate process costs for realistic network scenarios. In order to show its applicability, we applied our model to a German reference network scenario, for which we calculated the estimated CapEx and OpEx costs. We also indicated how the introduction of a control plane in the optical network layer can reduce the OpEx costs. The suggested OpEx cost model for a telecom operator is to be seen as a framework, which can be adopted to specific situations according to necessity. Its applicability was demonstrated via a joint cost modelling exercise with Belgacom.

Finally, we have also shown how the developed cost modelling approach can be applied in a liberalised telecom market, by using an appropriate cost allocation scheme. This can be useful for regulatory purposes as well as for internal cost assessment, e.g. for profitability analysis or to serve as a basis for pricing decisions.

The results obtained in our work cannot only be applied by a network operator, but are also very relevant for network equipment suppliers. For a network operator, it is important to determine the appropriate timing for the introduction of a new technology in the network and the estimated cost to do so. For an equipment supplier, on the other hand, it is important to determine the right time to put a new technology on the market and to estimate the price the operator will be willing to pay for it.

7.2 Suggestions for Future Work

The topics tackled in this thesis belong to the broad field of strategic network planning. Of course, this thesis doesn't finish the work in this field. Possible extensions can be found on different fronts. Mainly in the field of cost modelling and cost allocation, we see some possible research extensions.

The suggested activity-based OpEx cost model for a telecom operator is to be seen as a framework, which can be adopted to specific situations according to necessity. An interesting extension would be to define several template processes for the commonly used network technologies, based on the framework provided. Both the process flows themselves (some actions or process branches can disappear in some cases, e.g. on a network layer only consisting of mechanical connections, the input of an expert to find a failure cause will not be required) as well as the failure rates of the equipment will be different when considering different technologies. Reference implementations would ease the OpEx estimation for existing as well as new to build networks. An interesting study in this respect would be to find out the fundamental differences between OpEx costs for core versus access networks. Furthermore, the processes behind the infrastructure and product lifecyle could be studied in more detail (as the current work focusses on a network which is already up and running). More benefits could also be obtained from the OpEx model when it is directly coupled with a network model. In this case, the configuration of the network together with the failure rates of the different components would allow to calculate the number of occurrences of the repair process for example. Distinguishing between equipment on backup and working path could then also allow to estimate more accurately the impact of a repair action on the network operation, the number of paths to be rerouted, etc. Moreover, apart from estimating OpEx costs, the application of the model also allows to optimize the so-called operational dimensioning of the network, i.e. it could help in defining the number of people required, the optimal location of the intervention teams, etc.

On the other hand, the studies performed so far, only consider the impact of the technology at hand on the operational processes and in this way on the costs, e.g. the study on the introduction of the control plane. However, the introduction of the technology itself may also come at some cost, e.g. the costs for acquiring and configuration of the control plane at first time installation. In order to estimate this cost, an estimation needs to be made on the complexity of the actions required when configuring the control plane, based on an estimation of the number of parameters to be configured and their complexity (we can distinguish automatically generated parameters e.g. counters, fix values like maximum allowable values, parameters for equipment configuration or network configuration, etc). Adding the cost of configuring the control plane itself to the results for OpEx cost reduction from this control plane obtained so far, would lead to more realistic figures.

Concerning cost allocation, there is a lot of work to be done concerning the relation between the allocation of shared network costs to services and service prices. In the regulatory context, the problem of the price squeeze has even made this more important. The price squeeze test for a vertically integrated operator, adopted by most regulators, states that the retail prices should exceed the sum of the wholesale prices and the retail costs. A recent example is the case where WorldCom complained that EU Mobile Operators were price squeezing fixed operators in providing fixed-to-mobile calls by pricing the retail product below the termination rate. Appropriate allocation schemes for the different types of shared network costs, which are acceptable for the NRIs are to be developed.

Appendices

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A

Techno-Economic Evaluation of the Island based Introduction of Optical Cross-Connects in an IP-over-WDM Network

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Abstract

This paper compares several traffic grooming approaches, based on expected capital expenditures to dimension and expand the network. For small traffic demands, the link-by-link grooming approach (efficiently filling SDH frames) is most interesting. We illustrate that, as traffic increases, there comes a point where the savings in IP layer expenses realized by end-to-end grooming compensate the extra expenses of introducing the needed optical cross-connects. We study the network-wide migration from link-by-link towards end-to-end grooming at a single point in time, as well as a possible migration path, where OXCs are introduced gradually in so-called end-to-end grooming islands. This approach can lead to important savings in capital expenditures. We study total equipment costs as well as incremental and cumulative costs, indicating the total expenses to be paid by the operator over a certain time. The use of the Net

Present Value technique is clarified. Finally, also the sensitivity of the obtained results to changes in the component costs is studied.

Key words

optical cross-connect, OXC, traffic grooming, techno-economic evaluation, migration

A.1 Introduction

In the field of network planning, theoretical work was done in the late eighties [A.1][A.2] and based on that, several authors have studied different parts of the network planning problem, among which long term planning [A.3]. In the changing telecom landscape, techno-economic evaluations are very important when performing long term planning. During the past years, the Internet traffic has known an important growth, which is still going on [A.4]. With respect to the observed traffic growth in backbone networks, it is a challenge for a network operator to find the most economical way to transport this traffic. A popular way of working in this regard is the use of grooming. This means optimising the resource usage in a multi-layer transport network, e.g., efficiently packing low-capacity traffic streams into high-capacity optical channels in an IP-over-Optical network [A.5]. Another approach to lower the costs for the operator is to introduce optical cross-connects (OXCs) in backbone nodes. Those OXCs allow switching huge amounts of traffic on the optical layer. Among other benefits [A.6] this allows to avoid high IP layer costs, leading to important equipment cost savings. However, since OXCs are still very expensive today, it is important for the operator to find the optimal introduction time.

In this paper a capital expenditures (CapEx) comparison will be made between a network with and without optical cross-connects using the appropriate grooming approaches. Different from other grooming studies, e.g., [A.7][A.8] we study the impact of a growing traffic demand and thus the need to expand the network. Several migration scenarios are studied and compared to one another, using investment decision techniques.

Section A.2 introduces the two extreme grooming approaches, link-by-link and end-to-end grooming, and explains the existing trade-off between them. It also indicates several possible migration paths to introduce OXCs in an initially link-by-link grooming network (without OXCs). In Section A.3 the island based OXC introduction is identified to be the most relevant of the considered migration scenarios and it is compared to the two extreme grooming approaches, in terms of equipment costs. Section A.4 indicates how results for network planning and extension need to be interpreted in the context of long term planning. Section A.5 reports the results of a case study, applying the above mentioned techniques to a pan-European network. In Section A.6 we perform a sensitivity analysis and indicate how the previously obtained results are influenced by the used cost figures. The paper ends with conclusions and guidelines in Section A.7.

A.2 Trade-off between Several Grooming Techniques

A.2.1 Link-by-Link Grooming

In the traditional link-by-link grooming approach, link capacity is used as efficiently as possible. In an IP-over-WDM network with SDH/SONET framing, this way of working can lower the total SDH card expenses. When the SDH lines are filled more efficiently (with traffic originating from several source-destination pairs), fewer lines are needed to transport all traffic, which may result in serious savings in case of low traffic volume. An important benefit of this approach is the efficient usage of (line) capacity on the optical layer. It implies, however, that all SDH frames need to be ‘unpacked’ after transiting a single optical link. Those frames may contain some traffic terminating in the considered node and some other traffic that needs to be sent on to another destination node. Link-by-link grooming is explained in Figure A.1. Although OXCs are shown on the optical layer of this figure, the link-by-link grooming approach does not require their presence. Link-by-link grooming can also be used in a WDM point-to-point system without switching capabilities on the optical layer. If we assume the two traffic flows in the figure to be equal and their sum to be smaller than the capacity of one wavelength, we need only one wavelength between each pair of OXCs. On the IP layer we need plenty of interface cards: twice the capacity of an individual traffic flow in the first node, four times this capacity in the second node, three times in the third node and once in the last node.

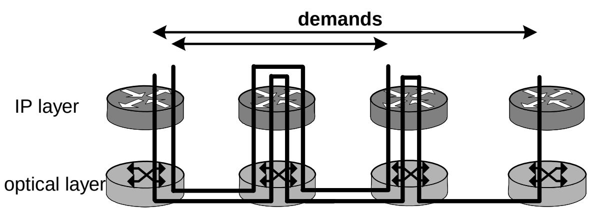

Figure A.1: link-by-link grooming

A.2.2 End-to-End Grooming

In the end-to-end grooming approach, a wavelength is dedicated to traffic originating from a single source-destination pair. This way of working is only possible if OXCs are present, allowing to set up an end-to-end light path. All transit traffic is bypassing the router optically, so that less router line cards are needed in case of large traffic volume, leading to an important saving in expenses on the IP layer. On the other hand, the optical line capacity is less efficiently used. An illustration is given in Figure A.2. Choosing between link-by-link and end-to-end grooming therefore means making a trade-off between efficient use of line capacities and node costs. As long as the size of the individual traffic flows is smaller than the wavelength capacity (independent of the size of their sum), we need two wavelengths between the first and the third OXC and only one between the third and the fourth OXC. On the IP layer, we only need interface cards with the capacity of the two traffic flows in the first node and with the capacity of one traffic flow in the third and the fourth node. Compared to the example for link-by-link grooming in Figure A.1, more capacity is needed on the optical layer, less on the IP layer.

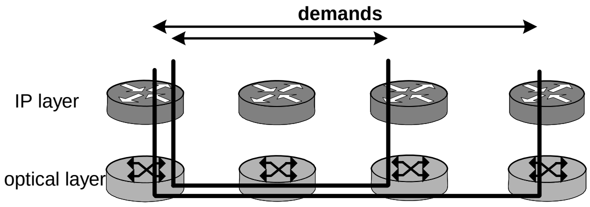

Figure A.2: end-to-end grooming

A.2.3 Trade-Off

When making a trade-off between link-by-link and end-to-end grooming, we need to consider both the expenses for the IP layer as well as for the optical layer. The expenses on the IP layer mainly consist of the SDH line cards. Because of transit traffic passing on the IP layer, these expenses are more important in case of link-by-link grooming. The expenses on the optical layer cost consist of the WDM line systems (mux/demux, optical amplifiers and transponders) and the OXCs. As each wavelength carries one SDH frame, more WDM line systems and more transponders will be needed in case of end-to-end grooming, leading to higher expenses on the optical layer. Moreover, in case of link-by-link grooming no OXCs need to be present in the network (and, indeed, they are not present in most of today's networks). They have to be introduced into the network especially in order to enable the use of end-to-end grooming. Remark that the "unit cost" of an OXC (to be paid at introduction time) is significant compared to that for other network equipment. The cost per bit, however, will be smaller for OXCs than for other equipment.

Note that we use the term *expenses* to denote actual expenditures. For instance IP router expenses denote the fraction of the overall CapEx spent on IP routers. By *cost*, on the other hand, we mean the price the vendor charges for a component, e.g., a single SDH line card. Cost is an input to our study, expenses an output. Expenses can therefore be calculated by the product of the number of installed components and the cost of this type, summed over all relevant component types.

It is clear from the above discussion that, for small traffic demands, the link-by-link grooming approach (efficiently filling SDH frames) is most interesting. As traffic increases, however, the gain in IP layer expenses may compensate the high cost of introducing optical cross-connects when using end-to-end grooming. The point in time where this happens will further be called the *cost intersection* *point*. From this point onwards (thanks to the growing traffic demand in the network) it will be more economical to use the end-to-end grooming than the link-by-link grooming approach. Link-by-link grooming is more interesting for small traffic demands, end-to-end grooming is more interesting for big traffic demands. The expenses to build a network according to the link-by-link grooming approach grow faster with the traffic demand to be routed over the network than the expenses to build a network according to the end-to-end grooming approach. A schematic illustration of the expected CapEx as a function of the demand is given in Figure A.3.

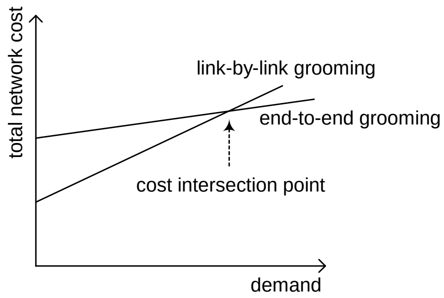

Figure A.3: cost intersection point

A.2.4 Migration Paths

Network expansion is a typical dynamic and uncertain problem. The traffic will grow over time and the actual traffic demand for a future time period is unknown beforehand. Also the cost of the network equipment needed to dimension the network for this growing traffic is not constant, but will typically decrease over time. Based on uncertain forecasts for future traffic demands and component costs, the network planner needs to decide in which way the network will be expanded. This means deciding on future investments for several points in time. The decision may include migrating to another technology, e.g., introducing OXCs. We have identified the following migration paths towards OXC introduction.

- *Network wide migration in a single step.* In this case we consider a link-by-link grooming network in which OXCs are introduced in all network nodes at a certain point in time and end-to-end grooming is used from that point onwards. The network is migrated from one extreme, link-by-link grooming (without OXCs) to another extreme, end-to-end grooming (with OXCs in all nodes). After this migration all traffic is routed directly from source to destination, without any special effort to fill the wavelength as well as possible. Critics may say that introducing OXCs will become interesting in the long run anyway (if we suppose that traffic will keep growing), and therefore suggest to introduce them right away. This way of working is not optimal, because of the equipment cost decrease and time value of investment. The OXC cost forms an important part of the equipment cost for a network operator using end-to-end grooming. If the OXCs are not needed right now, it may therefore be interesting to wait for the cost intersection point of Figure A.3. This point is determined by the cost evolution for a link-by-link and an end-to-end grooming network and (potentially) the transition cost between both approaches. Moreover, postponing an investment creates time value. If we can postpone an investment of e.g., € *1000* for two years and we can still earn a yearly interest of *3%* on it during those two years, we need less then € *1000* today. The current value of the € *1000* to be spent in two years is € $1000/(1+3\%)^2$.

- *End-to-end grooming on a per source-destination pair basis.* In the two extreme grooming situations (link-by-link and end-to-end grooming), the same grooming approach is used throughout the whole network in each period. However, it is also possible to use the end-to-end grooming approach for only some source-destination pairs. As the traffic is usually not uniformly distributed over the network, some source-destination traffic flows might be big enough to send them end-to-end, whereas others still need to be grouped to use the SDH frames efficiently. This approach requires that OXCs are available in those nodes over which the end-to-end traffic flows are routed. This way of working will reduce the IP layer expenses, because big traffic flows are sent end-to-end. On the other hand, an important cost is imposed by the requirement to have a lot of OXCs installed, namely on the path between all selected source-destination node pairs.
- *Island based grooming.* Another intermediate solution between link-by-link and end-to-end grooming is to introduce OXCs only in some nodes of the network. Those nodes are transformed into little islands where we use end-to-end grooming. Gradually more of these end-to-end grooming islands get introduced. An example is given in Figure A.4. In the beginning (step 1) link-by-link grooming is used throughout the whole network. If a certain node gets too heavily loaded, we install an OXC in that node, it becomes an end-to-end grooming island. In step 2 we notice one such node. As time passes, more of these islands get introduced and islands can be merged to become a bigger island. This is what we see in step 3, the island of the previous step has grown and a new one has appeared. Eventually (if the traffic keeps growing) the whole network can become end-to-end grooming.

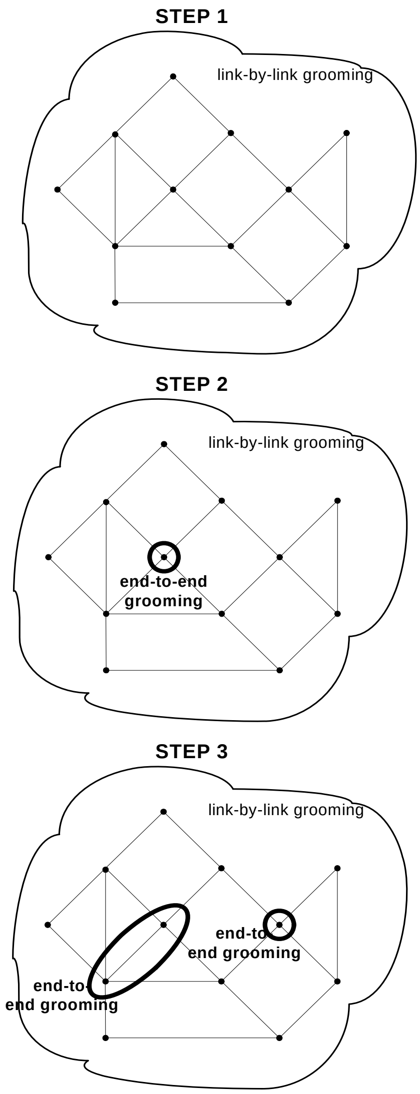

Figure A.4: introduction of end-to-end grooming islands in link-by-link grooming network

The first migration path *Network wide migration in a single step* compares two extreme situations and is thus very interesting as a reference scenario. On the other hand, it gives no flexibility to react on changes in the demand and cost. The intermediate solution of scenarios 2 and 3, on the other hand, allows the network planner to react on the dynamic and uncertain environment, by gradually introducing OXCs and migrating to end-to-end grooming. This means that the decision can be postponed a bit, till more information concerning actual traffic demands and equipment costs is available. We prefer scenario 3 *Island based grooming* over scenario 2 *End-to-end grooming on a per source-destination pair basis* as it allows to better spread the expenses for OXC introduction. In the remainder of this paper, we will therefore only consider scenarios 1 (as a reference) and 3 (as a possible approach to gradually migrate the network).

Gradual migration leads to an intermediate situation between link-by-link and end-to-end grooming. It is important to notice, however, that this approach tries to find the best solution over the entire planning interval, whereas optimized grooming algorithms or heuristics [A.12][A.7][A.8] aim at finding the best solution for a certain point in time (with a certain traffic). Those techniques consider a static situation. Some authors have studied the grooming problem with non-statistical dynamic traffic [A.13][A.14]. However, the study of network migration in terms of traffic grooming for dynamic traffic, growing over time, only received little attention so far. Our island based grooming approach considers growing traffic demand as well as changing component costs and studies the expected expenses over an entire planning interval.

A.3 Island based OXC Introduction

A.3.1 Impact on IP Layer Topology

In this section we discuss the intermediate step in the migration from link-by-link grooming towards end-to-end grooming, which allows to spread the expenses for OXC introduction. This way of working was introduced under the name *island based grooming* in the previous section. In those nodes where OXCs are introduced, the bypass traffic is sent on the optical layer, without going back to the IP layer, whereas in the other nodes all traffic still goes up to the IP layer. If the introduction of OXCs becomes beneficial in several adjacent nodes, those nodes can merge to a bigger island.

Figure A.5 indicates how introducing an OXC in the optical layer changes the IP layer topology. All nodes adjacent to the node *B* on the IP layer corresponding to the introduced OXC *A* on the optical layer are connected by a direct IP link. Between the *n* neighbours of node *B*, after the introduction of the OXC, there is a combination[1] of *2* out of *n* direct links, see equation (1).

$$C_n^2 = \frac{n!}{2!(n-2)!} \tag{A.1}$$

[1] Combination (order not of interest) of k out of n elements, without repetition: $C_n^k = \frac{n!}{k!(n-k)!}$

In the example of Figure A.5, *B* has *4* neighbours. Before the introduction of the OXC there is one direct IP link (between the two bottommost IP layer nodes in the figure), after the introduction there are $C_4^2 = 6$ direct IP links. If OXC introduction is beneficial in two adjacent nodes, the IP layer topology is additionally changed so that the two nodes can be bypassed optically at once. It is clear that, with an important amount of OXCs (end-to-end grooming nodes), the logical layer becomes densely meshed. With OXCs in all nodes, we end up with a full mesh.

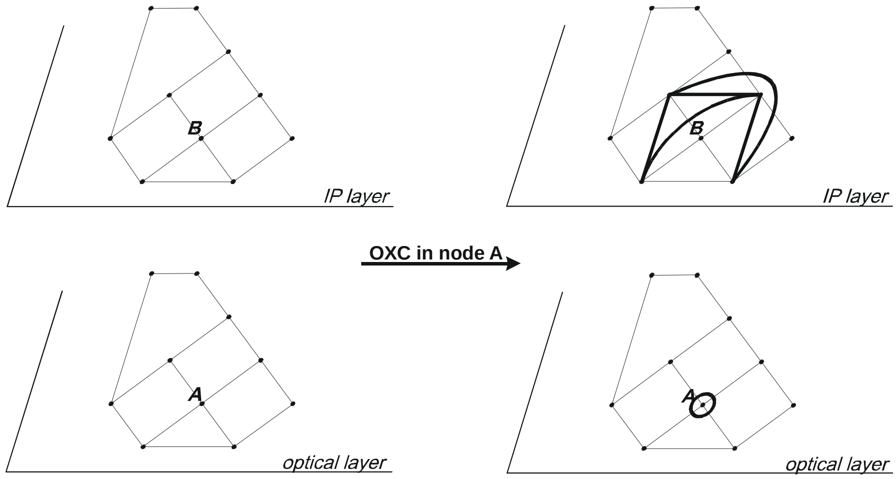

Figure A.5: introduction of an OXC in the optical layer and its impact on the IP layer topology

A.3.2 Cost Model

In order to decide if the introduction of an OXC is beneficial in a certain node, we base ourselves on a cost comparison for both solutions. The cost model we use in order to calculate the impact on the costs of the different network layers, is described below.

Several types of costs can be observed in the considered network, see Figure A.6. First of all, there is the IP layer cost, which consists of the unequipped IP router cost and the SDH line card cost. On the optical layer we differentiate between OXC cost, WDM line system cost and fibre cost. We consider an OXC that has an electrical switching fabric with short reach transponders (SR) on its interfaces. Those SR-transponders simply translate the electrical signal to an optical one, the nominal G.957 wavelength of *1310* nm [A.9], called λ^* in Figure A.6. The WDM line system is composed of a WDM mux/demux with integrated optical amplifier and the necessary long reach transponders (LR). The latter are also called coloured transponders because they translate the nominal λ^*-signal into the desired wavelength (or colour: *λ1*, *λ2*,…). We assume that transponders are installed on a per wavelength basis. This means that they are not physically integrated with the WDM mux/demux in some sort of transponder bank. Finally, there is the fibre cost, which consists of the physical fibre and optical amplifier cost. We assume that amplifiers are needed every *70* km. Recall that the proposed cost model only considers CapEx. Operational expenses for actual operation of these components are not taken into account here.

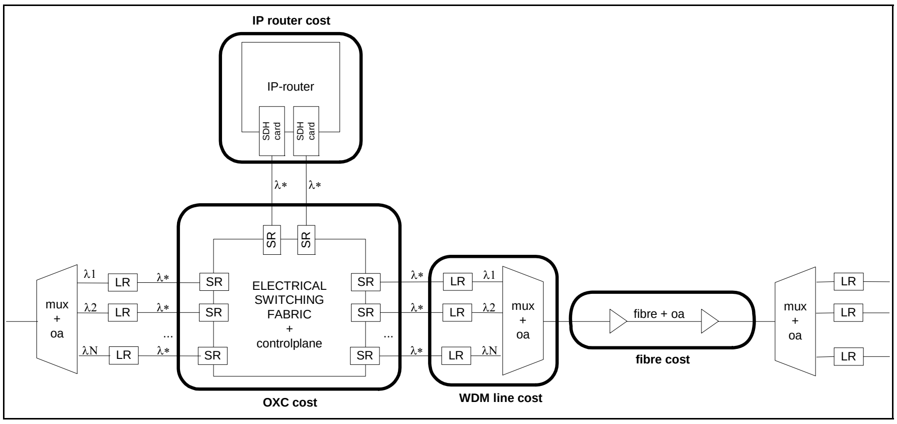

Figure A.6: cost model

For all components of the previously described model, a certain numerical cost is used. This cost, charged by the component vendor, is expressed as an unqualified number, relative to some base unit cost. The numbers used in this study are realistic cost figures, taken from the (partially confidential) cost model suggested by the IST-Lion project [A.10]. We have made some minor changes to this model. We differentiate between the cost of a SR and a LR transponder, assuming their cost ratio (SR/LR) to be *0.8*. In the total fibre cost, we do not take into account the cost of the physical fibre and the digging cost. In our model, fibre cost only consists of the optical amplifier cost (every *70* km). This assumption is based on the wide availability of dark fibre.

As mentioned before, in case link-by-link grooming is used, no OXCs are needed in the network. Therefore, the overall network costs in case of link-by-link grooming are given by the sum of the IP router cost (including SDH cards), the WDM line system cost (including LR transponders) and the fibre cost. In case of end-to-end grooming the overall network costs are the sum of these three costs plus the OXC cost (including SR transponder cost), because sending the traffic from source to destination on the optical layer is impossible without the presence of OXCs.

A.3.3 Methodology

Given this cost model, in the remainder of the paper, we compare several grooming approaches on a basis of cost. When deciding on the introduction of on OXC in the network in the island based grooming approach, we base our decision on a local cost comparison between link-by-link and end-to-end grooming. Consecutively, we consider all nodes on the optical layer where no OXC is installed. We start from a pure link-by-link grooming network, so that, initially, no OXCs are installed. Therefore, we can start by randomly selecting a node on the optical layer. For the considered node, we dimension it using link-by-link and end-to-end grooming and compare the costs of both approaches. If the node is cheaper with the OXC (thanks to a reduction in the IP layer expense), the OXC is introduced, leading to an end-to-end grooming island (as explained in the previous section). The procedure is described in Figure A.7.

When considering network planning over a longer planning interval (multiple planning periods, as described in the following section), the loop of Figure A.7 is executed for all nodes of the network (where no OXC has been installed so far) and the entire procedure (starting by selecting a first node) is repeated for every planning period.

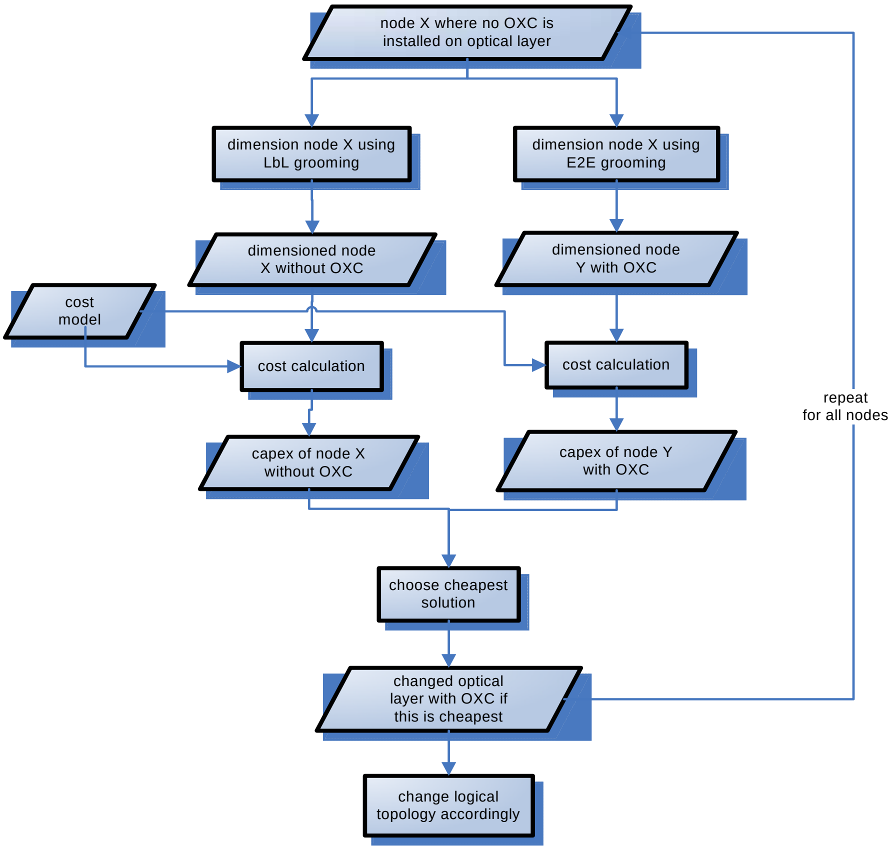

Figure A.7: procedure to decide on OXC introduction

A.4 Long Term Planning Decisions

When making strategic network planning decisions, a longer term planning interval (e.g., 5 to 10 years) will be taken into account. In that case, estimated equipment costs for several periods into the future, as well as total cost analysis over an entire planning interval will come into play. Those concepts are discussed in the current section.

A.4.1 Network Equipment Cost Erosion

As time comes goes by, network equipment costs will typically decrease. The RACE Project TITAN [A.11] proposes some evolutionary trends for network component production costs versus their technological maturity. This model is based on a combination of an extended learning curve model (based on the Wright empiric law: “Each time the cumulated units production doubles, the unit cost decreases with a constant percentage") and a logistic growth curve model (where the market penetration volume is expressed as a function of time). Important parameters in this model are the observed component cost at reference time, the percentage of penetration volume at the reference time, the time it takes for the growth curve to go from *10%* to *90 %* of the maximum penetration volume (viz. the time the product needs to be widely commercialized, Δt) and the relative decrease in the cost by doubling the production (learning curve rate or cost reducing factor *K*). Figure A.8 illustrates the meaning of the last two parameters. An important advantage of this model in the current fast evolving telecom environment is that it can also be used when only a few observations are available or if historical costs are absent. In the IST-Lion project realistic values were assigned to the parameters in this model [A.10], based on market experts' opinions and vendors' information. Those realistic equipment cost values are used in this case study.

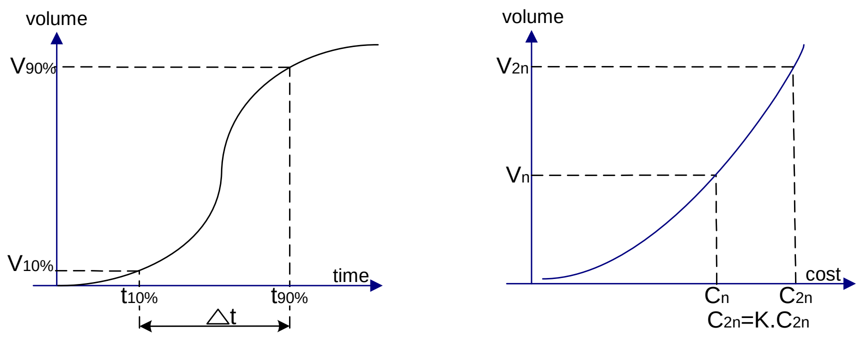

Figure A.8: definition of parameters in extended learning curve model

A.4.2 Investment Decisions based on Costs for Entire Planning Interval

When planning the expansion of his network, a network planner is interested in the expected expenses needed for this expansion over an entire planning period, rather than just for some future discrete time points. In order to compare expenses at several points in time in the future, the concept of the time value of money needs to be taken into account. This concept has been touched upon already briefly in Section A.2.4. Therefore, cash flows spent on different time points need to be discounted to the same reference time in order to be comparable. This concept forms the base for the well-known *Net Present Value* investment decision technique [A.22]. Net Present Value (*NPV)* compares the present value of several investment projects and chooses the solution with the highest present value. The present value of an investment project is defined as the sum of the expected cash flows C_n over the economic lifetime of the project N, discounted with the expected rate of return i (the discount rate). Equation (A.2) gives the formula to calculate the NPV. The used discount rate should reflect the expected return to be earned on the project. It grows with the amount of risk involved in the project. For a riskless project, it equals the interest rate that can be earned on a simple bank account. For a telecom project, a common interest rate is *10-15%*.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+i)^n} \tag{A.2}$$

Remark that, apart from NPV, some older and less reliable decision criteria are still used in practice today (instead of or in addition to the use of NPV). Those include *maximum initial investment cost* (incremental investment for first time period: C_0), *total cost of ownership* (*TCO*, the total cost of the project over the entire life time, neglecting the income), or *maximum (discounted) payback time* (the time it takes till the expected revenues for a certain time interval compensate the cumulative equipment cost over that interval).

Below, we are going to study the following three network migration approaches:

- *Capacity expansion using link-by-link grooming* The network is expanded using link-by-link grooming. There are no OXCs installed.
- *Capacity expansion by network-wide migration towards end-to-end grooming* At migration time, OXCs are installed in all network nodes and from that point onwards end-to-end grooming is used throughout the whole network. Before migration time, there are no OXCs and the network is expanded using link-by-link grooming.
- *Island based migration* Starting from a link-by-link grooming network, OXCs are gradually installed in end-to-end grooming islands.

For the different migration approaches, we will compare the total costs to build to network to cope with the traffic in the different planning intervals. This is interesting for a new entrant into the market, trying to find the optimal approach when entering the market from a green field situation. However, for an incumbent operator already disposing of a network that is up and running, the total cost (to build the network from scratch) is not the most important parameter as a basis for his network expansion decisions. The incremental costs (needed investment per time period) to expand the network from the existing situation will be more relevant. When expanding an existing network, the incremental costs are exactly the cash flows that need to be considered when applying *NPV* as an investment decision technique.

A.5 Case Study

A.5.1 Definition

We consider a pan-European IP-over-Optical network with *28* nodes and *41* links in its physical topology (base topology of [A.15]), see Figure A.9. In order to dimension the network over a time period including the current situation, we use the traffic estimated by the traffic volume forecast model first proposed by Vaughn and Wagner [A.16][A.17] and applied to the pan-European network in [A.18] (model 2 of [A.18], with the reference data for year *2002* and an annual growth of *10%* for voice traffic, *34%* for transaction data traffic and *100%* for IP traffic). This traffic model estimates the total pan-European traffic. We assume that a big pan-European operator will be able to attract *30%* of this traffic and therefore we dimension the network for *30%* of the traffic predicted by the traffic forecast model. We study the time period *2004* till *2014*. (All information concerning topology and traffic can be found in [A.18].)

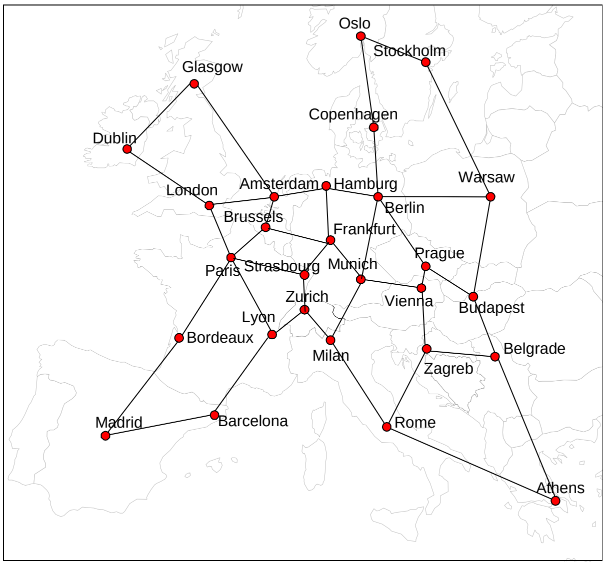

Figure A.9: pan-European network under study

We use the node model and the associated equipment cost model of Figure A.6. Only one size of a certain component type is considered. We assume that all SDH line cards have a capacity of *10* Gbps, the IP routers have a capacity of *200* Gbps, the WDM line systems take *40* wavelengths and the OXCs have *512* ports. When an IP router or an OXC is full (all capacity used), it needs to be upgraded by adding another router or OXC of the same size. Hereby we neglect the interconnection: if *512* ports do not suffice in a certain node, several identical OXCs are installed next to one another. In practice, however, more ports are needed for OXC-to-OXC interconnection as the number of interconnected OXCs grows. The same goes for IP routers, as described in [A.19]. Several types of interconnection could be studied in order to minimize the number of interconnection ports, but this is not considered here. We consider opaque OXCs (with an electrical core) so there is no problem of wavelength assignment and regeneration [A.20].

A.5.2 Link-by-Link versus End-to-End Grooming

For the traffic growth described above over the time period *2004-2014*, the total costs to dimension the network according to the two extreme grooming approaches (link-by-link versus end-to-end), are shown in Figure A.10 (only plotted till *2012*). We see that until *2008* the link-by-link grooming approach is most economical. As the demand is fairly small compared to the capacity of the considered SDH frames, efficiently filling those frames leads to an important gain. As the demand increases, the capacity of an SDH frame is better approximated by the demand for a single source-destination pair. The intersection point of the graphs is situated around late *2008*. This means that, for a new operator entering the market, it would be interesting to set up a network with OXCs and use end-to-end grooming right away from that time onwards. After *2009*, end-to-end grooming is cheaper than link-by-link grooming, which means that the gain in IP layer expenses obtained by applying end-to-end grooming is able to compensate the additional expenses for introducing OXCs in all network nodes. Note that the end-to-end grooming graph decreases a bit between *2004* and *2008*. Although the traffic grows in this interval, the overall CapEx to dimension the network decreases. This can be explained by the used decreasing equipment cost. In this interval the equipment cost decreases faster than the growth of the traffic. Remind that the yearly cost decrease is not constant, but rather given by the learning curve model.

It is clear that the total considered traffic demand has an important impact on the cost intersection point between link-by-link and end-to-end grooming. If the operator is able to attract more traffic than the *30%* market share assumed above or if the traffic grows faster than predicted by the traffic model we used here, the intersection point will come sooner than *2009*. In case of less traffic, the intersection point falls later. [A.21] shows that the intersection point for a monopolist operator (attracting all traffic) falls *2* years sooner than for an operator attracting only a *25%* market share (using a slightly different cost model and a smaller network). This finding can be explained by the fact that annually doubling IP traffic (which constitutes the dominant traffic fraction) was assumed.

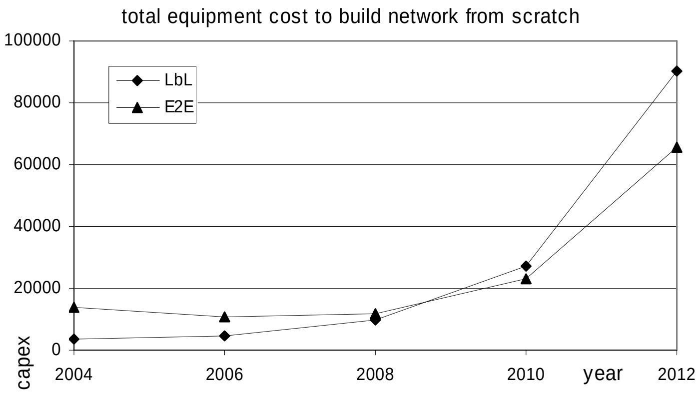

Figure A.10: CapEx comparison for different grooming approaches, green field situation

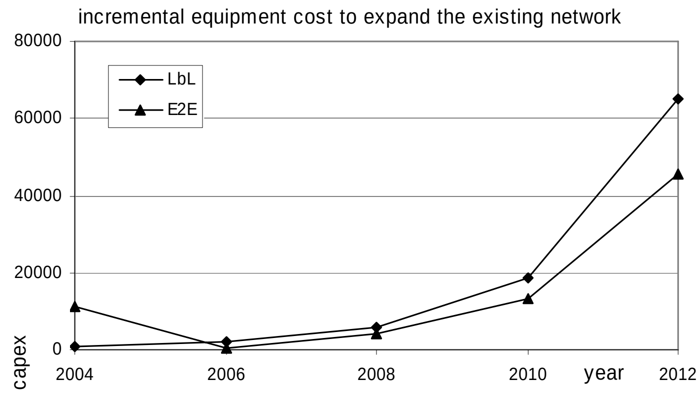

Figure A.11: CapEx comparison for different grooming approaches, situation for incumbent

Figure A.11 considers an operator with an existing link-by-link grooming network (dimensioned for the traffic of *2002*) and indicates the incremental costs to expand this network, either using link-by-link grooming or using end-to-end grooming (and thus introducing OXCs in all nodes in *2004*). The important investment of introducing the needed OXCs, can clearly be observed in *2004* in the curve for end-to-end grooming in Figure A.11. In subsequent time intervals, the incremental costs denote the cost of the additional equipment needed because of the observed traffic growth. These costs are lower in case of end-to-end grooming, because less expensive SDH line cards need to be installed in this case. The situation for an incumbent operator is studied in more detail in Section A.5.4.

A.5.3 Island based OXC Introduction

Figure A.12 shows the nodes where OXCs are introduced in the pan-European network when considering island based OXC introduction as a way of gradually migrating from link-by-link towards end-to-end grooming. In *2004*, the most economical solution is to use link-by-link grooming in the entire network, without introducing any OXCs. With the traffic of *2006,* it becomes interesting to bypass the traffic in some nodes in the core the network. Two end-to-end grooming islands appear: an end-to-end grooming island with *6* nodes containing Amsterdam, Hamburg, Berlin, Munich, Zurich and Milan and an isolated end-to-end grooming node in Paris. As the traffic grows further, more and more OXCs should be introduced. In *2008*, the two islands have merged and grown to an island containing *13* nodes, whereas a new isolated end-to-end grooming node appears in Dublin. In *2010*, the big island grows to *15* nodes and now also includes the new end-to-end grooming nodes in Bordeaux and Zagreb. In *2012*, nearly all nodes (*19*) in the core of the network (no OXC in Prague) have OXCs and end-to-end grooming is used in this entire domain. After this, the situation does not change very much any more. In *2014* also London enters the end-to-end grooming part of the network, so that the two islands merge to one. This brings the total number of end-to-end grooming nodes in the network to *20*. Only in *8* (mainly) edge nodes the transit traffic is not big enough to justify the introduction of an OXC. In those nodes, all traffic keeps passing through the IP layer. The fact that it takes so long till an OXC gets introduced in London can be explained because the used traffic model only considers European traffic. In London we expect an important amount of transatlantic traffic towards the United States, not considered here.

When we compare the CapEx (total equipment cost) to dimension the network using link-by-link, end-to-end and island based grooming, we find that island based grooming is indeed a good compromise between both extreme approaches. As there are no islands installed in *2004*, the expenses for the island based grooming approach are equal to those for the link-by-link grooming approach. In this case, the gain which can be made compared to end-to-end grooming is *75%*, so that introducing OXCs would definitely not be a good idea here. As the traffic grows, more islands are suggested by the island based grooming approach, so that the gain compared to end-to-end grooming (with OXCs in all nodes) decreases, towards *3%* for *2014* (*20* of the *28* nodes have OXCs). On the other hand, the gain to be made compared to link-by-link grooming increases with growing traffic, from *0%* in *2004* to *34%* for *2014*.

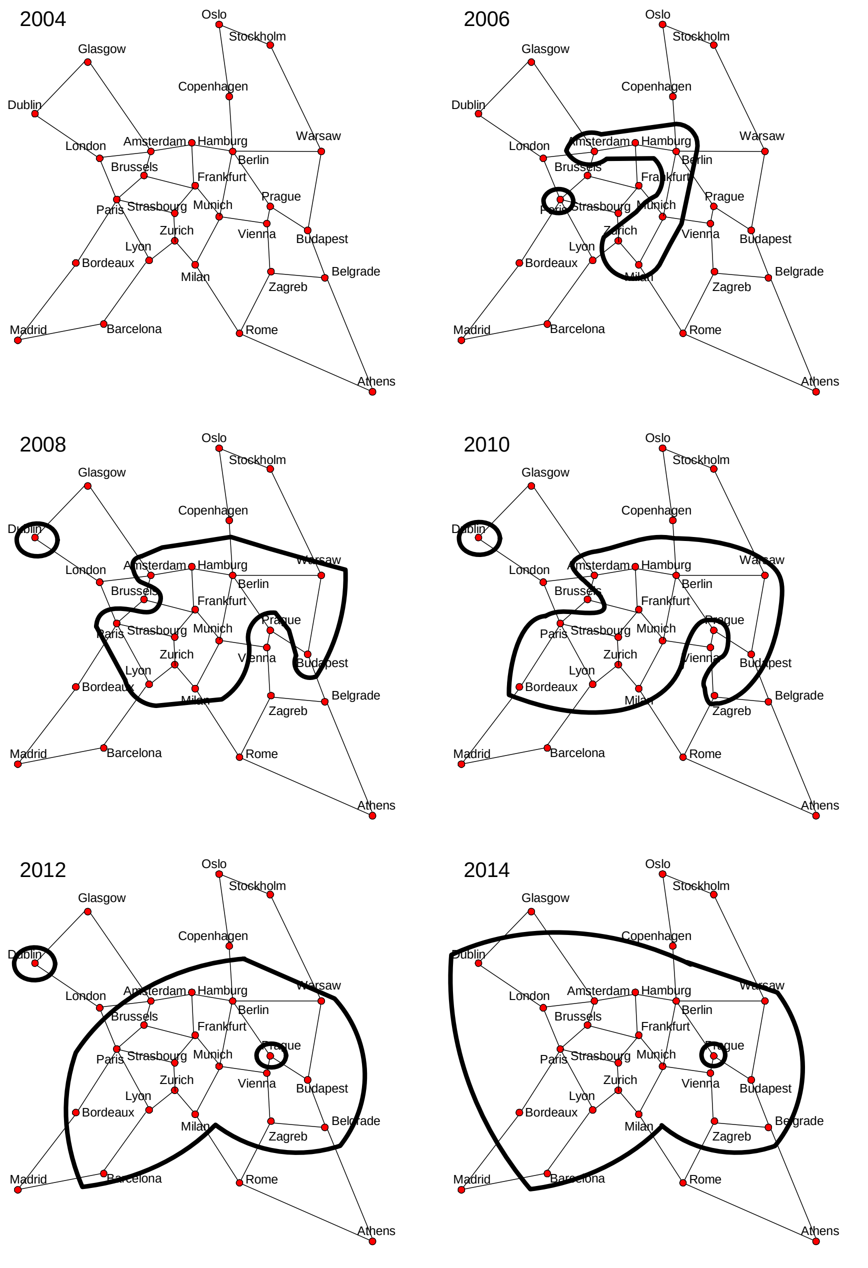

Figure A.12: evolution of end-to-end grooming islands in pan-European network

A.5.4 Long Term Planning Decisions

Considering the network-wide migration from link-by-link towards end-to-end grooming, the optimal migration time can be determined using the NPV technique. We consider the incremental costs over the time period *2004-2014* to expand the network according to the growing traffic demand. We consider several possible timings to perform the network-wide migration from link-by-link towards end-to-end grooming. (This extends the study of Figure A.11, where the migration in *2004* for an incumbent operator was already studied.) Figure A.13 indicates the NPV the sum of those incremental expenses[2], discounted using a discount rate of *10%*. We observe that *2010* would be the best migration time from link-by-link towards end-to-end grooming (lowest NPV).

Both the green field situation and the situation for the incumbent are shown in the Figure A.13. We observe the same trends for both cases, the only difference is the cost in the first period (building the network from scratch in the green field situation and expanding the existing situation for the incumbent). This initial cost difference between the green field and the incumbent situation can be observed in the difference in height between the corresponding bars in the two graphs of Figure A.13.

[2] We have calculated the NPV based on the network equipment expenses to expand the network. To calculate the total NPV for the network operator, apart from expenses, also income for the operator needs to be counted in the considered cash flows. In our study, we have always dimensioned the network to be able to carry the entire demand (30% of demand predicted by traffic forecast model). This means that the incomes are equal under all grooming scenarios. Neglecting them in the NPV calculations influences the actual NPV values that are obtained, but does not influence the comparison between the approaches.

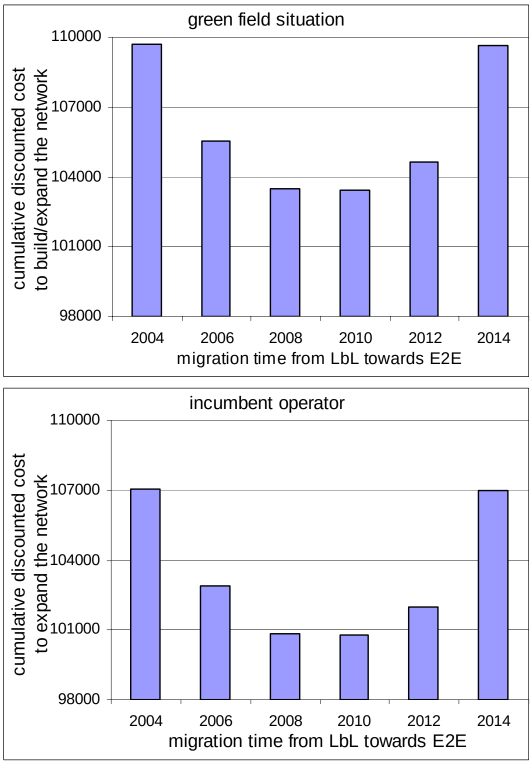

Figure A.13: determination of optimal migration time from link-by-link towards end-to-end grooming

An important parameter in the NPV formula is the economical life time of the project *N*. It indicates the time over which the investments can be used in an economical way. In case of long term network planning, this should correspond to the planning interval. In Figure A.13 the planning period was set to ten years, *2004-2014*. In Figure A.14 the impact of a smaller planning interval is studied. We see that, for *N* up to four years (considered interval *2004-2008* or smaller), three of the considered options have similar NPV: *expansion using link-by-link grooming*, *island based migration* and *network-wide migration in 2010* (which is actually equal to link-by-link grooming in the considered interval). *Network-wide migration in 2004*, leads to significantly higher NPV and therefore needs to be avoided. When considering a planning interval of six years (*2004-2010*), it becomes clear that network-wide migration in the year *2010* is a better option than continuing to keep expanding the network using link-by-link grooming. Island based grooming is clearly the best option. Enlarging the planning interval even further, makes clear that migration towards end-to-end grooming definitely is to be preferred over the continued use of link-by-link grooming. With a planning interval of eight years (*2004-2012*), network expansion based on link-by-link grooming is the worst option. Even immediate migration towards end-to-end grooming (in *2004*) is better.

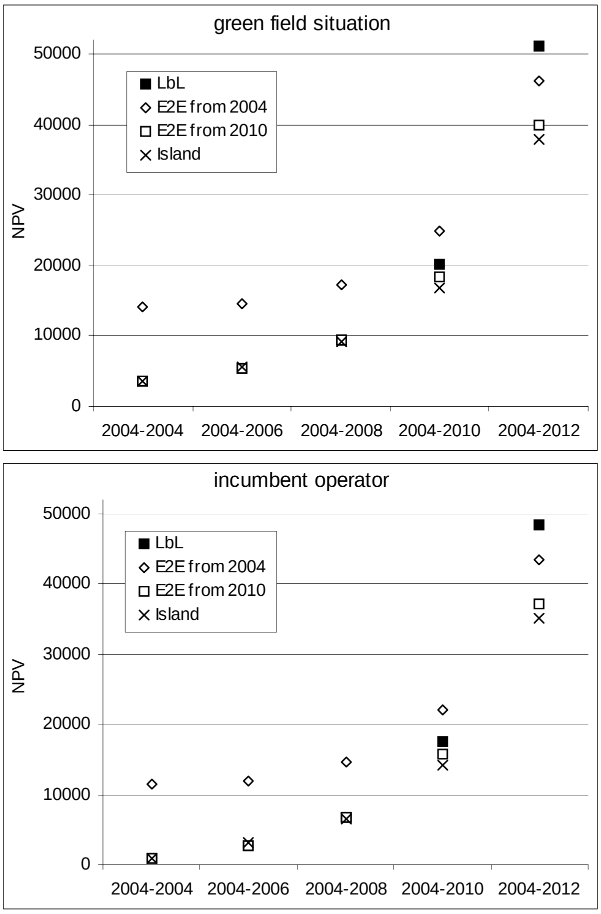

Figure A.14: CapEx comparison between grooming approaches, based on cumulative equipment costs

A.6 Sensitivity on Equipment Cost

As mentioned before, in our case study the cost figures (decreasing over time) suggested by [A.10] were used. In this section, we want to find out the sensitivity of the overall expenses to the equipment cost figures. Therefore, we will change the cost per component type. Table A.1 shows the cost intersection point between link-by-link and end-to-end grooming if the cost for a certain component type is changed to half of its original cost, while the cost of the other components is left unaffected. It was shown before [A.23] that this approach leads to similar sensitivity results as the use of a cost decrease over time for the considered component type.

The cost intersection point found above for the equipment costs of [A.10], was July *2008*. The sensitivity to changes in the WDM mux cost is very low, the CapEx intersection point remains unchanged. The same goes for changes in the cost of the optical amplifiers. If the cost of an SDH line card were half of what is expected by the model of [A.10], link-by-link grooming would stay the cheapest approach till January *2011*. If the transponder cost (SR and LR) were half of its original, the end-to-end grooming approach (requiring a lot of transponders) would be favourized sooner (from October *2007* onwards). Lowering the cost of an unequipped OXC, finally, slightly favours the end-to-end grooming approach, leading to a CapEx intersection point in June *2008*. Remark that the cost ratio SR transponder/ LR transponder is kept constant (at *0.8*) throughout this study. We believe this to be a realistic assumption. However, some previous studies [A.23] have shown that the sensitivity of the overall expenses to changes in this ratio is big.

Component with decreased price	Cost intersection point
None	July 2008
WDM mux	July 2008
Optical amplifier	July 2008
SDH line card	January 2011
Transponder (SR and LR)	October 2007
Unequipped OXC	June 2008

Table A.1: impact of component cost decrease on cost intersection point

The impact of the SDH line card cost on the cost intersection point can easily be understood from the importance of this cost in case of link-by-link grooming, see the top part of Figure A.15. In case of big traffic demands (*2006* and later), the SDH line card cost definitely is the dominant factor in the link-by-link grooming expenses. Reducing this cost therefore leads to a more cost efficient solution in case of link-by-link grooming and therefore a better position of this scenario so that OXC introduction becomes interesting only later on. The bottom part of Figure A.15 shows that the expenses going to unequipped OXCs are relatively high in case of small traffic demands (until *2006*), which explains why OXC introduction is not beneficial in this case. The middle part of Figure A.15 clearly illustrates that the use of island based grooming avoids the high costs for OXCs in case of small traffic demand as well as the high costs for SDH line cards in case of big traffic demands. Note, finally, that the relative expenses going to the different component types are more or less stable from *2010* onwards, because the granularity of the components fits the traffic demands rather well.

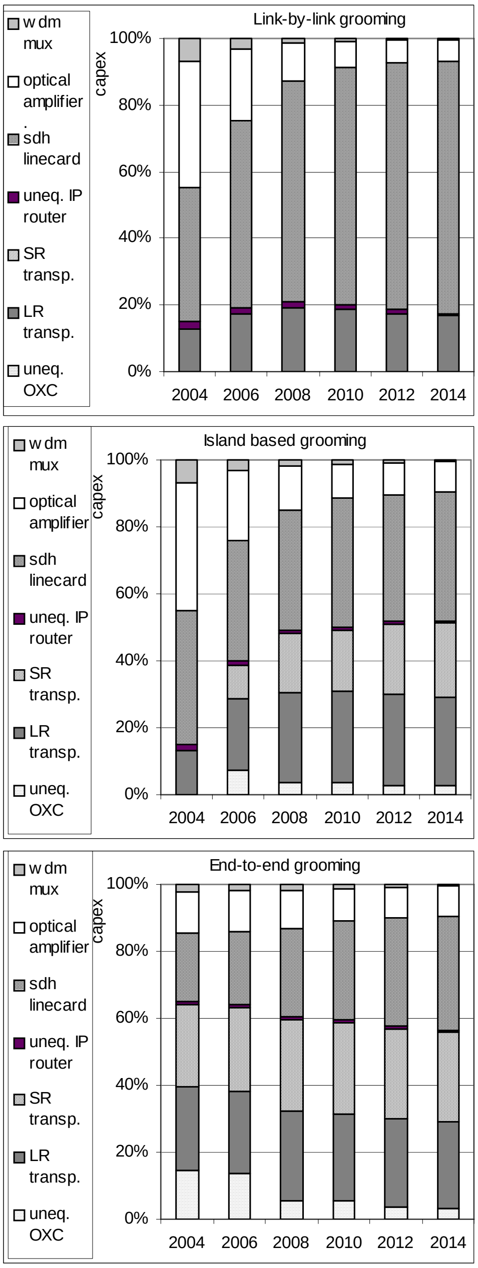

Figure A.15: cost distribution over time for several grooming approaches (original cost figures)

As explained before, in case of island based grooming, the dimensioning of a certain node is calculated according to both approaches (link-by-link and end-to-end grooming) and the solution of this cost trade-off determines whether or not to introduce the OXC. As the equipment costs can influence this trade-off, they also influence the island evolution. Figure A.16 indicates the number of end-to-end grooming nodes installed according to the island based grooming approach, in case of reduced equipment costs (to half of their original value). The graph legend indicates which equipment type has a reduced cost in which curve (the other costs are unaffected). In case no component type has a reduced cost, we find the results already shown in Figure A.12. The number of end-to-end grooming nodes evolves from *0* to *20* over the time period *2004-2014*. Exactly the same evolution is found in case of reduced WDM line system or optical amplifier costs. With reduced SDH line card costs, far less OXCs are installed. Until *2006* no OXCs are used, in *2008* they become beneficial in ten nodes and for *2014* we find only sixteen end-to-end grooming nodes. It is clear that a reduced SDH line card cost favours the use of link-by-link grooming (drastically reducing its cost) over the introduction of OXCs. A reduced transponder cost leads to the introduction of more end-to-end grooming nodes (up to *24* in *2014*). Reducing the unequipped OXC cost only slightly favours the introduction of OXCs. The sensitivities found in Figure A.16 correspond to the observations of Table A.1.

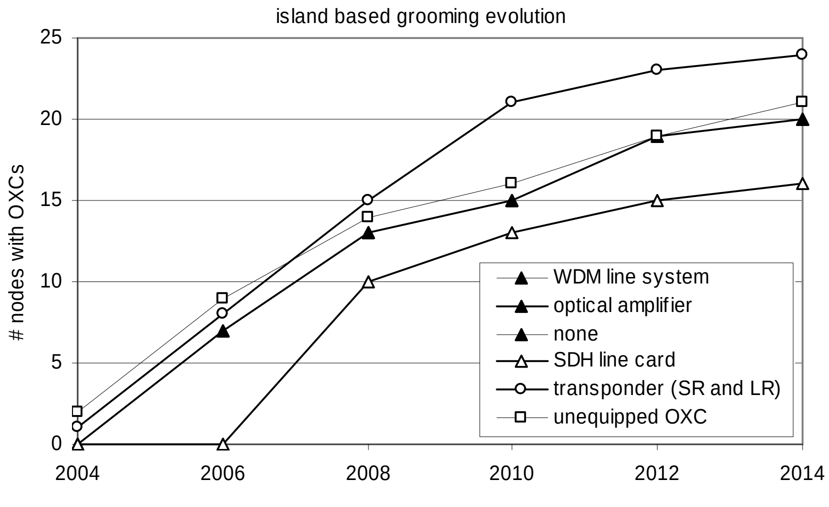

Figure A.16: sensitivity of equipment costs on island evolution (curves for original costs, reduced WDM line system cost and reduced optical amplifier cost coincide)

A.7 Conclusions and Guidelines

To goal of this paper was to compare several traffic grooming approaches, based on expected CapEx to dimension and expand the network. When making a trade-off between the traditional link-by-link approach and the use of end-to-end grooming, with OXCs in all nodes, we observe that, for small traffic demands, the link-by-link grooming approach (efficiently filling SDH frames) is most interesting. As traffic increases, however, there comes a point where the savings in IP layer expenses realized by end-to-end grooming compensate the extra expenses of introducing the needed optical cross-connects. In practice, however, it is very unlikely that the migration from link-by-link towards end-to-end grooming happens at a single point in time. Therefore, we also studied a possible migration path, where OXCs are introduced gradually in so-called end-to-end grooming islands. Simulations have shown that this island based grooming approach can lead to important savings in CapEx. In order to study the realistic case of an incumbent operator, we did not only consider total costs, but also incremental and cumulative costs, indicating the total expenses to be paid by the operator over a certain time interval to extend his network. In this regard, the use of the Net Present Value technique was clarified. Finally, we also studied the sensitivity of the obtained results to changes in the component costs. It was shown that a reduction in the SDH line card cost leads to less OXC introductions.

The following guidelines can be drawn from our work:

- To determine a reliable network expansion plan, it is important to estimate (current and future) network equipment costs as accurate as possible. If actual cost figures are impossible to obtain, relative figures indicating the most important trends can already give a lot of valuable information. Especially the costs of SDH line cards, SR and LR transponders and unequipped OXCs have an important impact on the cost comparison between the different grooming approaches.
- The main cost driver in case of link-by-link grooming is the SDH line card costs. A lower line card cost favours the use of link-by-link grooming, whereas a higher cost favours the introduction of OXCs and the use of end-to-end grooming. It can therefore be interesting to thoroughly compare the SDH line card costs set by different vendors.
- With a growing traffic demand, introducing OXCs in the network and migrating towards end-to-end grooming will become beneficial. To be able to spread the expenses and gradually adapt to the growing traffic demand, the island based grooming approach is a straightforward and effective approach.
- For an incumbent operator, long term investment decision should be based on incremental instead of total costs. When comparing different network solutions over a certain time frame, cumulative discounted costs are to be considered.

Acknowledgement

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B

On Planning of Optical Networks and Representation of their Uncertain Input Parameters

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Abstract

This paper studies the use of uncertain inputs in the strategic network planning process. To model uncertain planning inputs three essential parameters are needed: the predicted value expressing for instance an expert's view, the uncertainty level indicating the doubt there is about the predicted value, and the confidence parameter denoting the probability that the output parameter was estimated big enough (compared to the actual output). Several planning approaches that handle uncertain variables are distinguished and their strengths and shortcomings are indicated. This allows to indicate the pitfalls in some common planning practices that use a fixed safety margin to handle uncertainty. It is shown that they can lead to incorrect planning decisions, such as underestimation of the impact of the input uncertainty and overdimensioning in case of inaccurately modelled dimensioning problems. Both a theoretic model

and simulation results are shown. A real-life planning problem is studied, including forecasting future network traffic from uncertain inputs and dimensioning a network to accommodate an uncertain traffic demand.

Key words

optical network planning, uncertain inputs, traffic prediction, robustness against demand uncertainty

B.1 Strategic Planning of Today's Optical Telecommunication Networks

B.1.1 The Network Planning Process and the Changing Environment

The telecommunication landscape has undergone dramatic changes in recent years, especially due to the advances in optical networking. The number of customers grows, as well as the required bandwidth per user, causing the so-called *market pull*. This effect is very important for Internet traffic [B.1][B.2] and is not expected to stop shortly [B.3]. Moreover, the operator's cost to be able to accommodate this demand (equipment cost, etc.) is subject to dynamic changes over time as a consequence of the *technology push.* The latter is apparent from major technological breakthroughs. We are witnessing an important evolution in optical networking technology, moving from point-to-point WDM transmission towards all-optical networks using Optical Path Cross-Connects [B.4]. Finally, the liberalization in most countries has completely changed the telecommunication environment, confronting network operators with fierce competition [B.5][B.6]. In this dynamically changing environment, intelligent network planning has even become more important than it used to be [B.7][B.8]. Figure B.1 gives a graphical overview of the strategic planning process. The overall goal of the process is to provide a network deployment plan optimising the profit of the network operator (trade-off between the expected revenues generated by the customers and the expected costs to realize the network), while taking into account the indirect customer requirements concerning survivability etc [B.9][B.10][B.11].

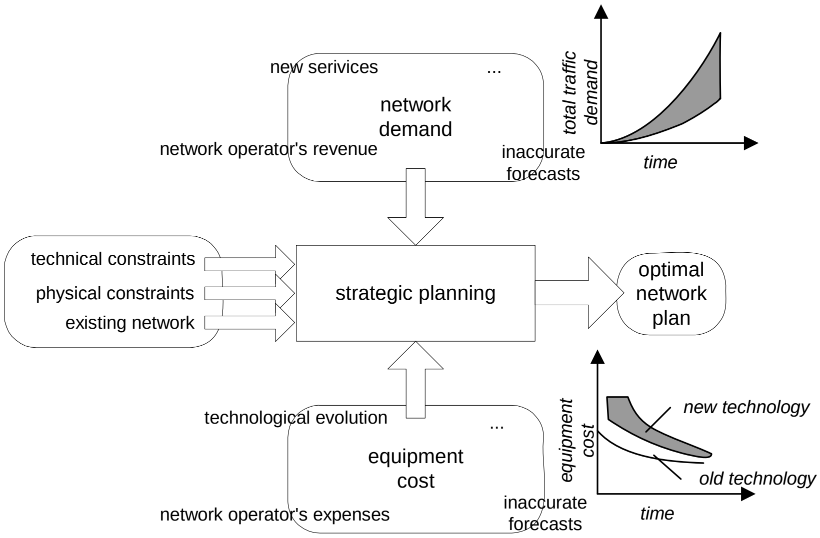


Figure B.1: strategic planning process

Especially when planning over a longer time horizon, the uncertainty of the considered planning data becomes important. Forecasting future customer demand is a difficult problem [B.12][B.14] with an associated unavoidable forecast error, typically increasing exponentially with the horizon length. Forecast unreliability is problematic to operators, as they are -legitimately- concerned that the investments in network capacity will not match the actual requirements. Insufficient dimensioning may cause a loss of revenue because of displeased customers and penalty costs for unsatisfied Service Level Agreements (SLA). Overdimensioning, on the other hand, results in unused capacity that does not generate any revenue. Using optical technology, the equipment cost per unit is big, e.g., the cost of an OXC is enormous compared to the cost of an IP router line card (a ratio of *40/1* is common). As a consequence, investment decisions for optical networks, dealing with important traffic amounts, are critical for network operators. Understanding the impact of planning input uncertainty is therefore especially relevant in the context of optical networking.

B.1.2 Paper Outline and Related Work

A lot of attention has been paid in the literature to the problem of network planning with uncertain inputs. The fundamentals of the network planning problem were described by Gupta [B.15] and King [B.16]. Results of multiple case studies were published: planning approaches using stochastic programming [B.17][B.18], the use of sensitivity analysis when considering uncertain inputs [B.19] and network dimensioning under traffic uncertainty [B.20][B.21][B.22] [B.23]. Furthermore, consulting companies emphasized the importance of handling uncertainty in strategic decisions [B.24][B.25].

In this paper, we focus on the evaluation of some widespread planning practices. The use of a safety margin to handle uncertainty is compared to the representation of uncertain planning inputs as random variables. In Section B.2 of the paper the considered uncertainty handling methods and their parameters are introduced. The safety margin is studied in more detail and a reference scenario is discussed, which allows to determine a useful safety margin value. Section B.3 compares this reference scenario to what actually happens in practice, revealing some pitfalls of the use of safety margins in real-life situations. Section B.4 covers a realistic case study. As a starting point, a traffic model with uncertain inputs is considered. In a second stage, the uncertain traffic forecasts resulting from this model are used for the dimensioning of a pan-European IP-over-Optical network. The last section ends the paper with some conclusions.

B.2 Uncertainty Modelling Approaches

In this section, we indicate where uncertainty comes into play in the long term network planning process and explain the approach we follow to model this uncertainty.

B.2.1 Our Model

Roughly speaking, an uncertain variable consists of a predicted value (sharp number) and some description of the inherent uncertainty. The predicted value of a planning input variable (future demand, cost, ...) will for instance be obtained by hiring an expert for the considered planning domain. However, the real future value of the considered planning input will probably not equal the predicted value, even if made by the best expert. An uncertain variable therefore has some inherent uncertainty which should be taken into account during the planning process and can be represented in several ways (see Figure B.2:). *A priori and a posteriori adjustment* are straightforward approaches: they make use of a so-called safety margin, added to the predicted values before or after the planning calculations. The *probabilistic approach* is more formal as it uses probability distributions to model the uncertain character. All parameters needed to describe our model are introduced below.

- The *predicted value* v is the expected value for the uncertain variable under consideration. It is the forecasted value proposed by an expert, an extrapolation model, or the average of multiple forecasted values proposed by several experts. For instance, the predicted value for next year's traffic may be obtained by an extrapolation of the traffic measured during previous years and the current year.

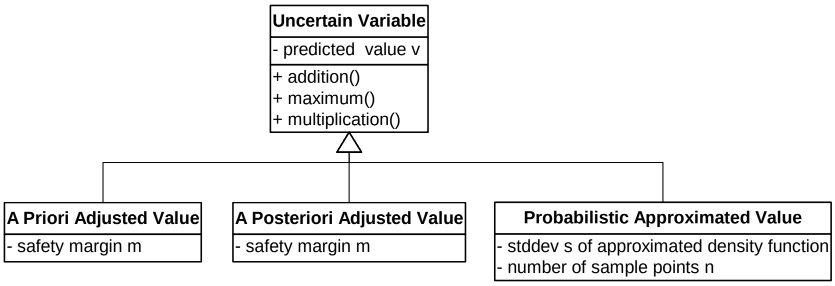


Figure B.2: uncertain variable: proposed models

- In the a priori and a posteriori adjustment method, a relative *safety margin m* is used to take the uncertain character of the forecasts into account in a very straightforward way. In a priori adjustment, a margin is added to the predicted value of every input variable before the start of the calculations. It indicates the uncertainty inherent to these inputs and may be different for every input variable. For instance, we could add a safety margin of *10%* to all demand matrix entries so that they represent some kind of upper limit on the expected traffic. In a posteriori adjustment, on the other hand, the margin is added to the sharp calculated result at the end of all calculations: only a single safety margin is used, independently of the number of inputs. For instance, if the predicted traffic for next year on a certain network link is *3000* Mbps, one might take a safety margin of *10%* and thus decide to foresee *3300* Mbps to be able to cope with the real demand that might be bigger than expected[3]. As an illustration, the results found by a priori or a posteriori adjustment for some operations are given in Table B.1. Remark that even when using a posteriori adjustment the intention of the safety margin is still to incorporate the uncertain character of the input variables. The a posteriori added margin should show how the input uncertainty is reflected in the output variables. It is possible to indicate the a posteriori margin m as a function of the a priori margins $m1$ and $m2$, giving the same result, e.g., for the sum of two uncertain variables: $m = (m_1 \cdot v_1 + m_2 \cdot v_2)/(v_1 + v_2)$. If the predicted values of both inputs are equal to each other, the appropriate a posteriori margin equals the mean of the a priori margins.

[3] From this example it is clear that the safety margins we consider in this paper always indicate positive margins: we add a safety margin m to the sharp calculated result v, so that the actual result (taking into account uncertainty) equals v+m . For the planning problems considered here, a negative safety margin (resulting in v-m) would be meaningless. However, cases where negative margins would make sense (e.g., when considering the minimal demand needed for the minimal expected revenue) could be studied in a completely similar way.

- In the probabilistic model, an uncertain variable is represented as a random variable with an associated probability distribution. The predicted value *v* is used as the mean value for this distribution. The standard deviation of a probability distribution can be seen as an indication of the uncertainty associated with this mean value. As it is likely that this uncertainty will grow with the magnitude of the forecasted value, the standard deviation *s* is chosen to be a percentage of the predicted value: $s = p \cdot v/100$ with *p* being the *percentual standard deviation*. In this model the operations on uncertain variables are performed using the common formulae for continuous random variables on piecewise linear approximations of the considered density functions. Piecewise linear functions allow to approximate any probability distribution, even if it cannot easily be described analytically. For scalability reasons, the result of each operation is resampled to have the same number of 'pieces' (= number of samples - 1) as its operands. The accuracy of the approximation grows with the amount of samples, as illustrated in Figure B.3 for the standard deviation of a sum (where the exact result can easily be determined analytically). A complexity analysis showed that the computational complexity of the addition of probabilistic approximated variables grows with the third power of the number of samples, which is also apparent in the figure. In contrast to the traditional discrete sampling approach, our model uses continuous probability distributions and imposes lower memory requirements (see the appendix for more details on this model).
- The last important parameter is the so-called *confidence parameter c*. For example, if a network planner is interested in the amount of capacity that has to be foreseen to accommodate the future traffic on the network with some (given) chance, this chance is indicated by the confidence parameter. Mathematically speaking, we want to indicate a limit value y_{limit} that will be greater than or equal to the real future outcome of the uncertain value *y* with a probability *c*:

$$\begin{aligned} y_{limit} &= y_{predicted} + y_{margin} \\ \Pr[y \leq y_{limit}] &= c \end{aligned} \tag{B.1}$$

where y_{limit} is the desired limit value, obtained as the end result of planning calculations using one of the proposed uncertainty models, $y_{predicted}$ is the predicted value of the result obtained by neglecting uncertainty and y_{margin} is determined by the used uncertainty model. It can be different for all three implementations (a priori, a posteriori adjustment and probabilistic adjustment). The percentual confidence parameter value indicates the confidence interval, e.g., if we want a network link to be robust to uncertain traffic demand with a probability of *95%*, *c* is set to *95%*. Note that this can be an important factor in SLAs. The penalty costs to be paid because of an underdimensioned network can be enormous. Therefore, it is very important to be prepared for uncertain traffic changes.

	a priori adjustment	a posteriori adjustment
operand 1	*Aprio* (v_1, m_1)	*Apost* (v_1, *m*)
operand 2	*Aprio (v2, m2)*	*Apost (v2, m)*
sum	$v_1 \frac{(100+m_1)}{100} + v_2 \frac{(100+m_2)}{100}$	$(v_1 + v_2)\frac{(100+m)}{100}$
maximum	$MAX\left[v_1 \frac{(100+m_1)}{100}, v_2 \frac{(100+m_2)}{100}\right]$	$MAX[v_1, v_2]\frac{(100+m)}{100}$
product	$v_1 \frac{(100+m_1)}{100} \cdot v_2 \frac{(100+m_2)}{100}$	$(v_1 \cdot v_2)\frac{(100+m)}{100}$

Table B.1: a priori and a posteriori adjustment methods

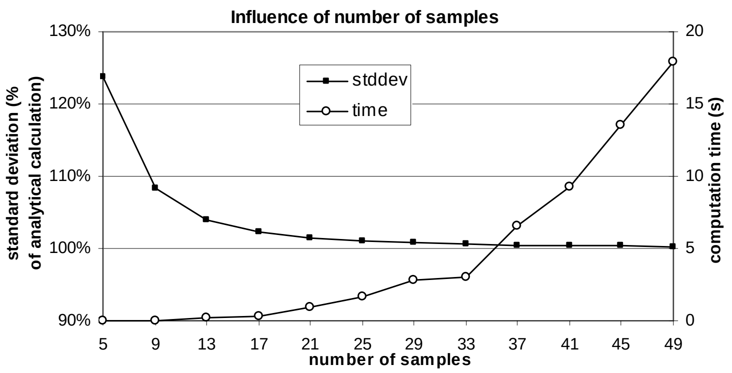


Figure B.3: influence of number of samples (n) on results found for the sum of probabilistic approximated uncertain variables (v1= 10, v2= 1000, p= 10%)

B.2.2 How to Choose an Appropriate Safety Margin Value

A priori and a posteriori adjustment are popular planning approaches because of their ease of use (both conceptual and computational). When using those methods, however, it is crucial to determine a suitable safety margin value. Below, we indicate a possible way of working to obtain a safety margin that allows to approximate the analytical value as closely as possible.

We find a *reference scenario* in the addition of two uncertain planning inputs *x1* and *x2*, represented by normally distributed variables. They have *v1* and *v2* as mean values, respectively. The percentual standard deviation p is equal for both.

We know from probability theory that their sum y is normally distributed with as standard deviation the square root of the sum of the variance of both inputs. From the *68, 95 and 99.7% -rules* for the normal distribution (Figure B.4:), it is clear that approximately *68%* of the observations fall within one standard deviation from the mean.

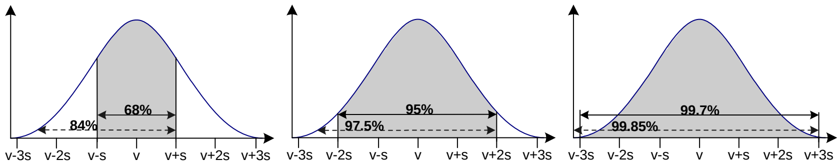


Figure B.4: the 68, 95 and 99.7% rules for normal distribution

For a confidence parameter of *84%,* the limit value y_{limit}[4] can thus be expressed analytically by

$$\begin{aligned} &y_{limit} = y_{predicted} + y_{margin} \\ &\Pr[y \le y_{limit}] = \Pr[y \le v_y + s_y] = 84\% \\ &y_{margin} = s_y = \sqrt{(pv_1/100)^2 + (pv_2/100)^2} \end{aligned} \tag{B.2}$$

where

$$\begin{aligned} &x1: N(v_1, s_1) = N(v_1, pv_1/100) \\ &x2: N(v_2, s_2) = N(v_2, pv_2/100) \\ &y: N(v_y, s_y) = N(v_1 + v_2, \sqrt{(pv_1/100)^2 + (pv_2/100)^2}). \end{aligned} \tag{B.3}$$

x: N(v,s) denotes a normal distributed random variable x with mean value v and standard deviation s. As long as the safety margins considered in a priori and a posteriori adjustment are equal, both approaches yield an equal sum. In this case, $y = x1 + x2 = Aprio(v1,m) + Aprio(v2,m) = Apost(v1,m) + Apost(v2,m)$. We recall the following formulae from above:

$$\begin{aligned} &y_{limit} = y_{predicted} + y_{margin} \\ &\Pr[y \le y_{limit}] = \Pr[y \le (v_1 + v_2)(100 + m)/100] = c \\ &y_{margin} = (v_1 + v_2)m/100. \end{aligned} \tag{B.4}$$

Identification of y_{margin} calculated analytically and y_{margin} found by a priori or a posteriori adjusted values leads to the following expression for the safety margin

[4] Remark that we focus on the limit value y_{limit} because this value has most practical importance: it is used in planning decisions where it indicates for instance actual link capacities to foresee for the future.

m as a function of the percentual standard deviation p, the relative magnitude of the predicted values $r=v_1/v_2$ and the confidence parameter c: $m(p\ ,r\ ,c)$.

$$\begin{aligned}
&(v_1+v_2)*m(p,r,84\%)/100=\sqrt{(pv_1/100)^2+(pv_2/100)^2}\\
&m(p,r,84\%)=\sqrt{(pv_1)^2+(pv_2)^2}\ /(v_1+v_2)\\
&m(p,r,84\%)=p\sqrt{r^2+1}\,/(r+1)
\end{aligned} \tag{B.5}$$

This last equation learns that the sum of normally distributed variables (where the standard deviation is a percentage of the mean value) can perfectly be approximated by a priori or a posteriori adjustment if the confidence parameter equals *84%*. The needed safety margin is proportional to the percentual standard deviation p and the proportion factor is a function of r, the ratio between the operands' magnitudes. For the special case where both operands are equal ($v1 = v2$, $r = 1$) this leads to $m(p, 1, 84\%) = p/\sqrt{2}$. If one operand is infinitely small compared to the other ($v1 >> v2$, $r >> 1$), we find $m(p, +\infty, 84\%) = p$. Note that exactly the same result is obtained when $v1 << v2$,($r = 0$), $m(p, 0, 84\%) = p$. In what follows we will always assume that $v1 > v2$.

Following the *68, 95 and 99.7%* -rules we can make a similar calculation for a confidence parameter of *97.5%* or *99.85%*, resulting in $m(p, 1, 97.5\%) = p\cdot\sqrt{2}$, $m(p, +\infty, 97.5\%) = 2p$, in $m(p, 1, 99.85\%) = 3p/\sqrt{2}$ and $m(p, +\infty, 99.85\%) = 3p$. A summary of the obtained results can be found in Figure B.5.

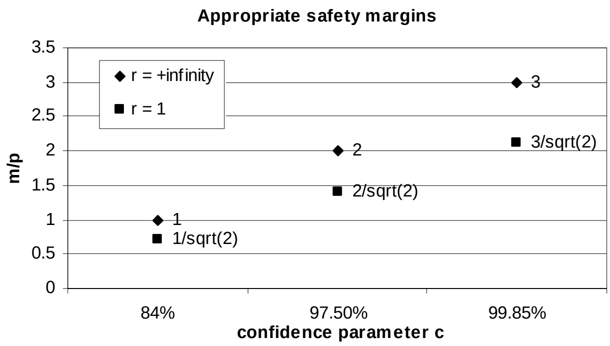


Figure B.5: appropriate safety margin value (m) as a function of the confidence parameter (c)

To determine the safety margin for other confidence parameters, we need numeric values for the cumulative distribution of normal distributed variables. This information is widely spread in the form of distribution tables for the normalised x*: N(0,1)* -distribution [B.26]. Note that via the transformation $z = (x-v)/s$ these tables provide information for all normal distributions z*: N(v,s)*.

B.2.3 General Observations concerning the Safety Margin

In this paragraph, some general properties of the margins *m(p ,r ,c)* obtained from cumulative distributions (as indicated in the previous paragraph) are discussed.

The influence of the ratio *r* of the predicted values on the choice of the safety margin value is examined in Figure B.6, which plots the limit value y_{limit} for the sum found by a priori adjustment relative to the analytical value (analytical value is shown by the *100%*-line in the figure) for a confidence parameters of *84%* and *97.5%*. Leaving all the rest unchanged, a growing ratio *r* of the operands causes the appropriate safety margin to increase (for small values of the ratio), as could be expected by the obtained formulae for *m(p, r, c)*. Remark that unexpected results can be obtained if the wrong *m*-value is used. For instance, naively setting the safety margin to p·√*2* when adding uncertain future traffic demands in a dimensioning problem where the confidence parameter equals *97.5%*, may result in serious capacity shortage if the actual ratio of the predicted values turns out to be *100* or more (which might be the demand ratio between a busy and a quiet link).

In Figure B.6 the distance between the *lines m(p, 1, c)* and *m(p, + ∞, c)*, and thus the difference between the appropriate safety margins for operands in the same order of magnitude and in a completely different order of magnitude, grows with an increasing confidence parameter *c* (*p* is fixed). An intelligent choice (taking into account the ratio of the parameters) for the safety margin is thus even more important when the confidence parameter grows. Remark in this context that confidence parameters in the range of *95%* (or higher) are common in realistic planning problems.

So far we have considered the addition of only two uncertain variables. It is known, however, that the relative standard deviation (stddev/mean) of the sum of positive uncertain variables decreases as we add more variables. As a consequence, the appropriate safety margin value decreases with the number of operands. In real network dimensioning problems, multiple (> 2) uncertain demands might be added. Using the safety margin for two values will in this case lead to results that are much larger than the analytically calculated ones. This problem can be overcome by adding the variables two-by-two and recalculating the appropriate margin in every step or by adjusting the margin in the following way (for the sum of *n* uncertain variables with equal predicted values *v* and percentual standard deviations *p*)

$$\begin{aligned} &\sqrt{n(vp/100)^2} = nv * m(p,1,84\%)/100 \\ &p/\sqrt{n} = m(p,1,84\%). \end{aligned} \tag{B.6}$$

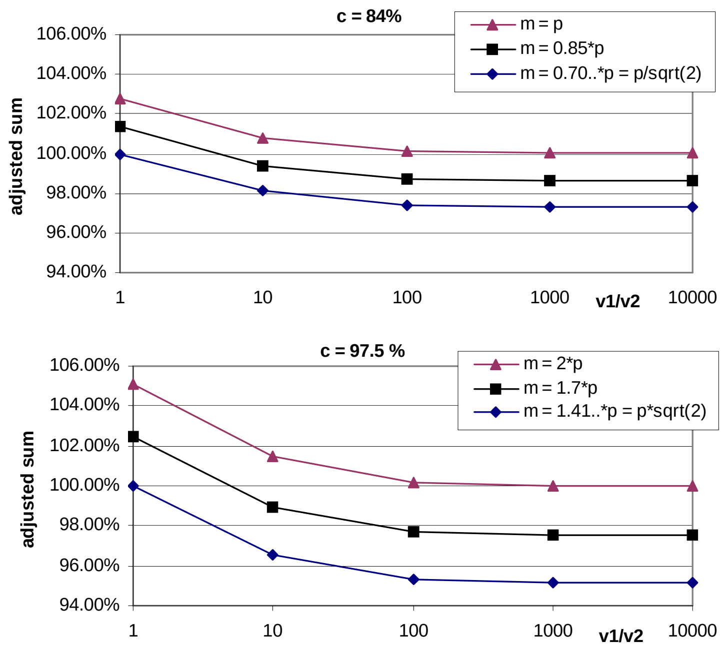


Figure B.6: influence of the predicted values ratio (r)

B.3 Practical Use

So far we have shown how a safety margin value can be determined for the a priori or a posteriori adjustment approach which allows to approximate the analytical results. But what happens if the result of the operation under study no longer has a known distribution (Gaussian in the considered case)? If there is no information available concerning the cumulative distribution of the expected result, a safety margin value cannot be obtained in the way indicated by the reference scenario.

B.3.1 Why the Reference Scenario Cannot Always be Followed

First of all, the inputs can cause the result not to be normally distributed anymore. Figure B.7 shows the influence of the input distribution skewness on the limit value y_{limit} for the sum of two equal uncertain variables. For a symmetric input distribution a priori or a posteriori adjustments give the same results as the approximated probabilistic model (when following the reference scenario approach). For a positively skewed distribution (tail to the right) however, the limit value obtained by a priori or a posteriori adjustment underestimates the actual limit value. For a negatively skewed distribution, the value is overestimated. The probabilistic approximated value technique is far best suited to model uncertainty in this case, because it calculates the limit value based on the area underneath the density curve.

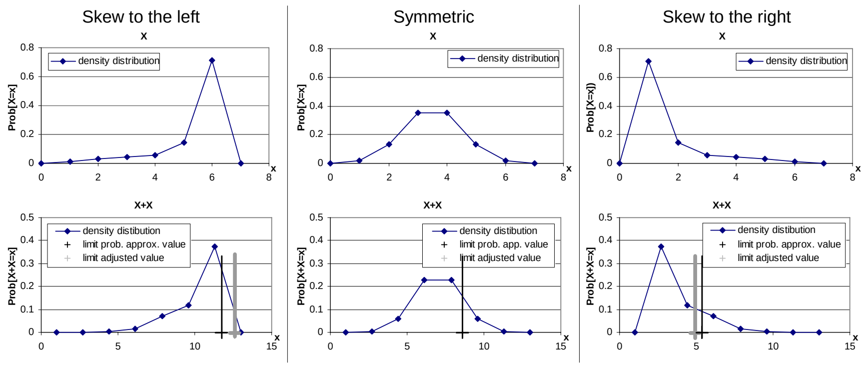


Figure B.7: influence of the skewness of the probability distribution on the performance of the models

Also the actual operation performed on the uncertain variables has its influence. If the input variables are represented as normally distributed variables, the sum will be normally distributed as well. Maximum and product will have different distributions. Furthermore, from the information of Table B.1 it is clear that the sum and maximum of uncertain variables is equal for both a priori and a posteriori adjustment (as long as all considered safety margins are the same). The product obtained by a priori adjustment, on the other hand, will always be *m%* bigger than that obtained by a posteriori adjustment:

$$\frac{a-priori\ adjusted\ product}{a-posteriori\ adjusted\ product}=\frac{\dfrac{v_1(100+m)}{100}\cdot\dfrac{v_2(100+m)}{100}}{\dfrac{v_1\cdot v_2(100+m)}{100}}=\frac{100+m}{100} \quad \text{(B.7)}$$

B.3.2 Pitfalls of Common Practices

A priori and a posteriori adjustments are common practices today. Despite the insights of the previous paragraphs, however, the safety margin value is often chosen in an ad-hoc way. A particular value is chosen at the start of the study and then used throughout all calculations.

In Figure B.8, we illustrate that the use of a fixed safety margin value is a dangerous practice. It may, for example, lead to inaccurate dimensioning decisions if uncertain demands are involved. In the figure, the safety margin m is set to $p\sqrt{2}$, irrespective of the ratio of the operands r. The confidence parameter c equals *97.5%*. The results are shown relative to the solution obtained by the probabilistic approximation case, which approximates the analytical value well:

the discrepancy between analytical and approximated values obtained when adding two uncertain variables is always below *0.5%*.

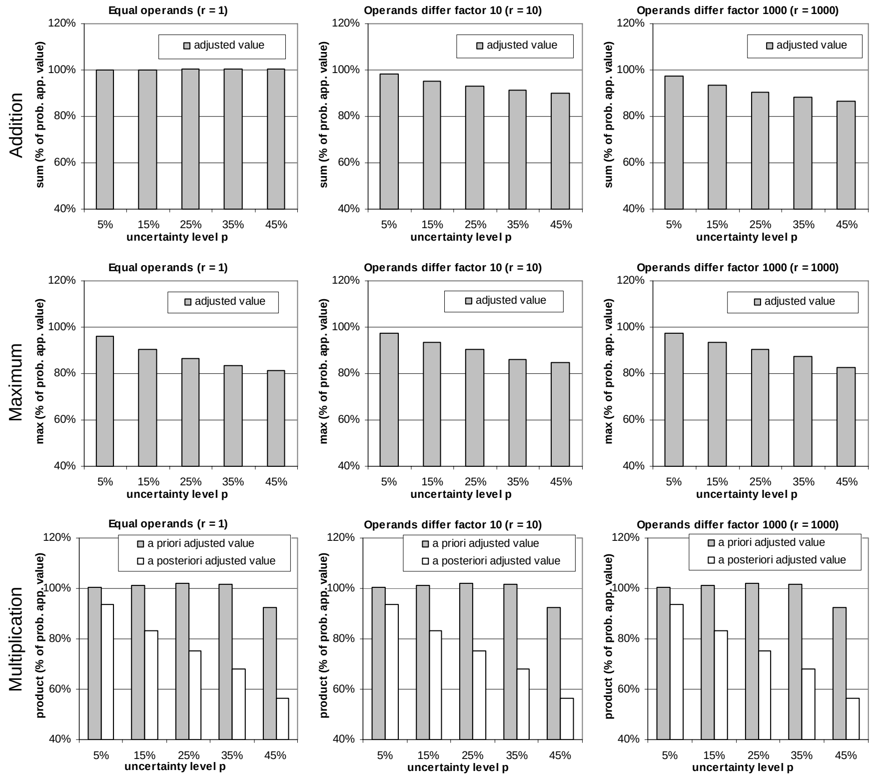


Figure B.8: influence of uncertainty level (p = s/v) on sum, maximum, and product

The uppermost part of Figure B.8 shows that, for equal operands, the adjusted sum (equal for a priori and a posteriori adjustments) is exactly the same as the sum found by probabilistic approximation, independently of the uncertainty level value. This is what we expected with the used value for the safety margin (reference scenario). When the operands are not equal anymore, there is a difference between both results which grows with the uncertainty level and with the ratio of the operands' magnitudes. The fact that the adjusted value is always smaller than the probabilistic approximated value can be understood from the influence of the ratio $r = v1/v2$. The bigger this ratio, the more the ideal value for m moves away from $p\cdot\sqrt{2}$ towards $2p$ and thus the bigger the fault made by choosing m = $p\cdot\sqrt{2}$. The fault grows linearly with the uncertainty level value.

The middle part of Figure B.8 studies the maximum of uncertain variables. The adjusted value (again, equal for a priori and a posteriori adjustments) is always smaller than the value found by probabilistic approximation, which is understood from the density curve of the maximum of two normally distributed variables. This curve will be higher on the right hand side, so that the abcissa of the limit value having 97.5% of the area underneath the curve to its left will be bigger than the corresponding abcissa on a Gaussian curve with the same mean value. This discrepancy between the adjusted value and the probabilistic approximated value grows with the uncertainty level. It decreases with the ratio of the operands.

The product of uncertain variables is given in the bottom part of Figure B.8. A priori adjustment and probabilistic approximation lead to almost identical results for most considered cases. The inaccuracy observed for very large uncertainty levels (*45%*) could be avoided by using more sample points. However, in contrast to the case for addition and maximum, the operands' ratio does not influence the performance at all. The three bottommost parts of Figure B.8 are identical despite the fact that they represent different ratios of the predicted values. This is because the relative fault on the product of two variables always equals the sum of the relative faults of the operands, independently of their absolute values. The discrepancy between the a priori and a posteriori adjusted product is striking. This is the ratio $(100+m)/100$ that was explained above. Because the chosen safety margin m is a linear function of the uncertainty level p, the discrepancy grows with this p. These observations make clear that a posteriori adjustment will often not lead to the expected results, therefore planners should definitely prefer a priori adjustment over a posteriori adjustment when multiplicative operations are involved.

Probabilistic approximation is conceptually more complicated than a priori or a posteriori adjustment and has a higher computational complexity as well, but will always give a good approximation of the analytically calculated results. If there is no information available concerning the cumulative distribution of the expected results (and therefore it is infeasible to determine an appropriate safety margin value for a priori or a posteriori adjustment), probabilistic approximation certainly is the best uncertainty handling technique.

B.4 Real-life Planning Problems using Uncertain Variables

In this section, a realistic planning problem is studied. Based on the uncertain traffic forecasts resulting from a traffic prediction model, the dimensioning of the pan-European IP-over-Optical network of Figure B.9 (similar to the topologies described in [B.27], [B.28] is performed. This happens in two steps. Section B.4.1 determines the expected future traffic from a traffic model with uncertain inputs (based on the forecasts of [B.28]), Section B.4.2 performs the dimensioning of the network links based on the obtained traffic matrix.

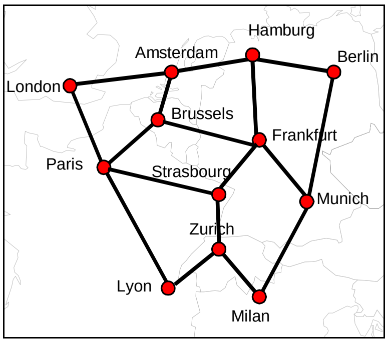


Figure B.9: pan-European network topology under study

B.4.1 Forecasting Future Traffic

The considered traffic model, proposed by [B.12]-[B.14][5], distinguishes voice, transaction data, and IP traffic. It is based on the population, the number of non-production business employees, and the number of internet hosts in the considered cities, respectively. Moreover, the three traffic types have different distance dependencies. The total traffic is given as the sum of those three types, as shown in Figure B.10. In this figure, uncertain variables are shown in grey boxes, sharp values in white boxes. Consider for example the prediction of IP traffic between city *i* and city *j*. The number of hosts in those cities are estimations and thus the resulting amount of IP traffic will be an estimation as well. The planner's goal is to determine a realistic upper bound on the expected IP traffic.

[5] In the presented simulation results, the formulae of [B.14] are used.

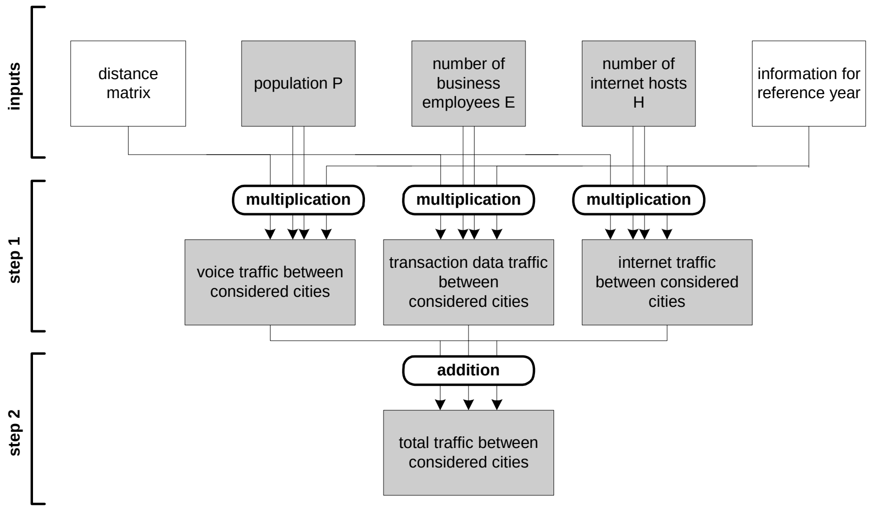


Figure B.10: traffic prediction model proposed in [B.12]-[B.14]

The uncertain inputs are represented as uncertain variables and the upperbounds for the considered traffic types (and the total traffic) can be calculated according to the three uncertainty handling approaches. When using the probabilistic approximated case, uncertain variables are represented as normally distributed variables, approximated by a piecewise linear function with *19* sample points. Although this model can deal with all kinds of distributions, we use normal distributions for our planning inputs because we suppose them to be obtained from multiple experts' forecasts. According to the central limit theorem, the average of (infinitely) many forecasts provided by independent experts will in most cases be approximately normally distributed.

First, we consider the *immediate introduction of uncertainty*: the inputs of Figure B.10 are considered as uncertain variables. It is our impression that the uncertainty level associated with the three kinds of uncertain inputs is different. The population (P) for the next year in a certain city region is probably known rather accurately. The number of non-production business employees (E) might be more difficult to forecast and the prediction for the future number of hosts (H) is probably most uncertain. For this reason, we set different p-values for the different inputs: $p(P) = 5\%$, $p(E) = 10\%$, and $p(H) = 20\%$. For a confidence parameter of 97.5%, we have chosen the safety margin value as $m = p\cdot\sqrt{2}$. As we want to illustrate the practical use of the safety margin, the operands' ratio is not taken into account here (this is the so-called *use of fixed safety margin value*). Figure B.11 – B.13 show results for the traffic to and from a single source node (London). In the considered case, the forecast for the transaction data traffic is about four times as big as the voice traffic. IP traffic is approximately twice as big as voice traffic, because of the used reference information for the considered year *2003*. Using realistic forecasts for future years would probably result in an important growth of the expected IP traffic. A priori adjustment and probabilistic approximation give similar results, the used safety margin value was a good choice because the relative magnitude of the predicted values does not influence the choice of the safety margin in case of multiplication. This is clear for all three traffic types. A posteriori adjustment results in smaller values, which was expected as well. The difference between the a priori and the a posteriori adjusted values equals *m%* (which was indicated theoretically before) and therefore is smallest for voice traffic, bigger for transaction data traffic and, the biggest for IP traffic (reflecting the growth in the uncertainty level of the input values for these traffic types).

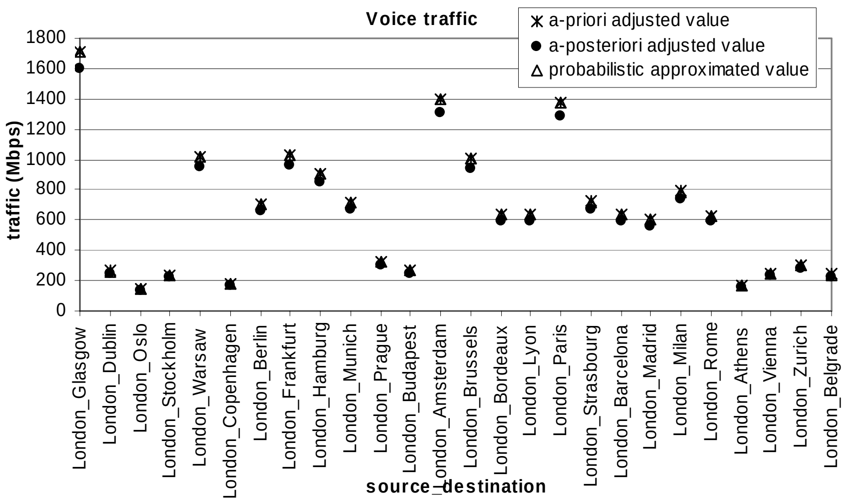


Figure B.11: limit values (y_{limit}) for expected voice traffic demand

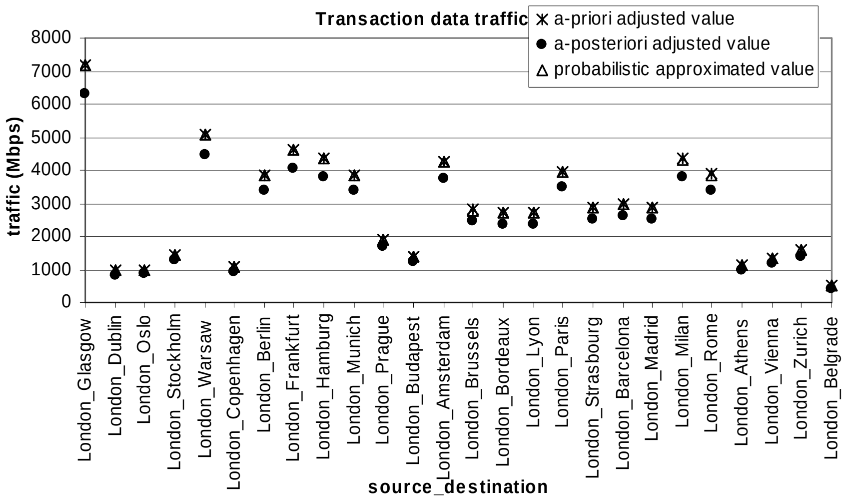


Figure B.12: limit values (y_{limit}) for expected transaction data traffic demand

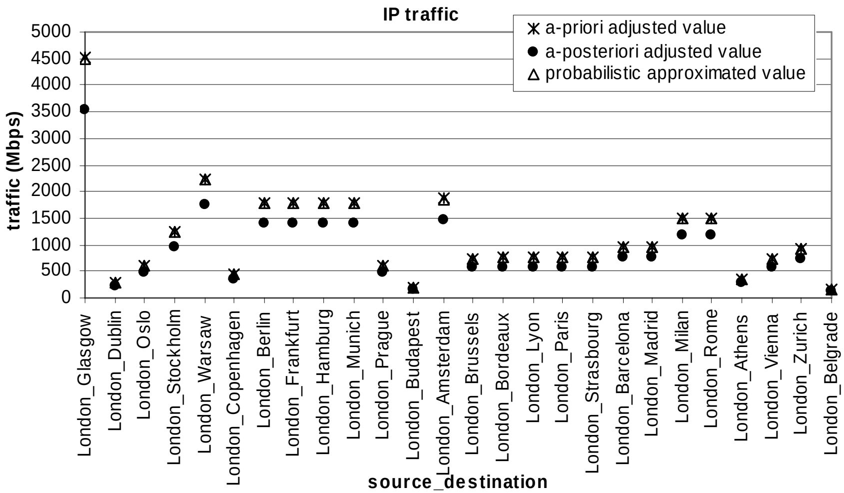


Figure B.13: limit values (y_{limit}) for expected IP traffic demand

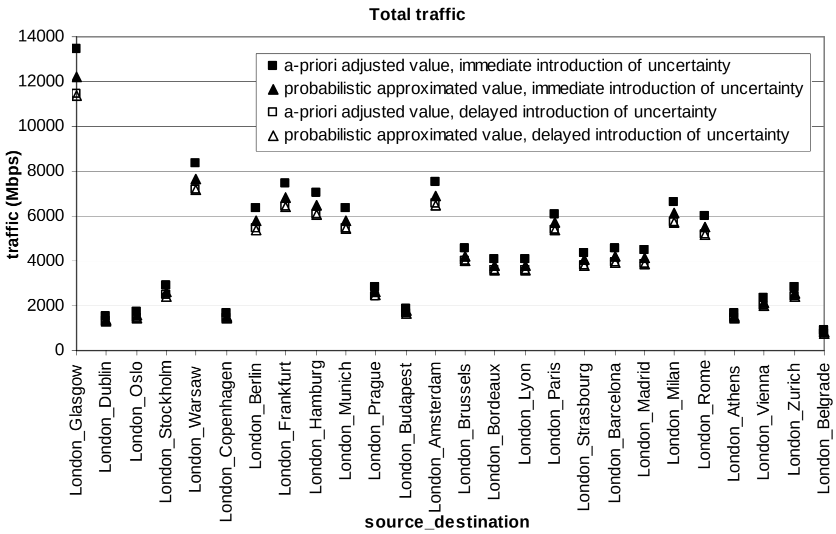


Figure B.14: limit values (y_{limit}) for expected total traffic demand

The total expected traffic per link is obtained by summing up the above amounts of traffic for the three considered types (voice, transaction data, and IP traffic). We find the results in Figure B.14, indicated by the black points. The uncertainty has been introduced in the first step of the model (Figure B.10), which justifies the name *immediate introduction of uncertainty*. Remark that, from hereon, we will only consider a priori adjusted values and probabilistic approximated values. A posteriori adjustment of uncertain variables indeed cannot handle the different safety margins used for the different traffic types in a straightforward way (see remark in Section B.2.1). Moreover, for equal safety margins a priori and a posteriori adjustments would give the same result, indicated by the square black points.

It is apparent that a priori adjustment and probabilistic approximation no longer give equal results, despite the chosen values for c and m. This example shows that it is very difficult to find a reliable safety margin in cases where several kinds of operations are involved and a wide range of predicted values is considered. Therefore, the a priori adjustment method should be used with care in real-life situations.

In practice, it can happen that the network planner does not know the traffic prediction model (the first step of Figure B.10), but only disposes of its outcome (amount of voice, transaction data, and IP traffic). This means that he knows forecasted values for the three traffic types as sharp numbers without knowing where they come from. However, he still wants to incorporate the inherent uncertain character of those forecasts and therefore models the amounts of voice, transaction data, and IP traffic as uncertain inputs for the determination of the total amount of traffic. In other words, the *introduction of uncertainty is delayed* till the second step of the traffic model of Figure B.10. The transparent points of Figure B.14 show results for this case when *c = 97.5%, p(voice traffic) = 5%, p(transaction data traffic) = 10%, p(IP traffic) = 20%* and $m = p \cdot \sqrt{2}$. The results obtained by a priori adjustment and probabilistic approximation are similar. If the uncertainty level on all inputs would have been the same, both results would have been identical. When we compare the two ways of calculating the total expected traffic on our pan-European network (immediate introduction versus delayed introduction of uncertainty), we notice that delayed introduction leads to smaller limit values for the total traffic in the considered case. This can be explained using the information of Table B.1. This table shows that the uncertain variables obtained for the different traffic types as intermediate results in case of immediate introduction of uncertainty have bigger percentual standard deviations than the values that are introduced in the case of delayed uncertainty introduction. A bigger standard deviation means a wider density curve and thus a bigger abscissa value for the limit having *c%* of the area below the density curve to its left. The method of delayed uncertainty introduction therefore may lead to an underestimation of the total future traffic.

Traffic type	stddev (obtained from step 1) in case of immediate uncertainty introduction	stddev (introduced) in case of delayed uncertainty introduction
voice	*7.21%*	*5%*
transaction data	14.47%	10%
IP	29.27%	20%

Table B.1: values for relative standard deviation (p) of different traffic types

B.4.2 Network Dimensioning based on Uncertain Traffic Predictions

Knowing the expected future traffic on the network, the network planner can take dimensioning decisions to accommodate this future traffic. Resilience questions come up at this point in time. Do we want to protect this traffic? Do all traffic types have to be protected in the same way? Also in this planning phase, uncertainty has to be taken into account. Below we study the dimensioning of the considered pan-European network under traffic uncertainty.

If we send all traffic unprotected, the total required capacity on each link l can be calculated as the sum of all voice, transaction data, and IP traffic over that link:

$$\textit{required capacity}(l) = \sum_g [V_g : l \in P_g] + \sum_g [TD_g : l \in P_g] + \sum_g [IP_g : l \in P_g] \quad \text{(B.8)}$$

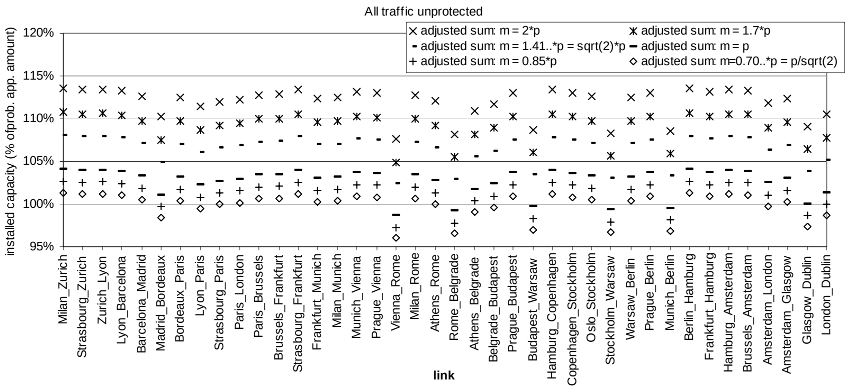
with P_g being the path of the traffic for source-destination pair g; V_g, TD_g, IP_g, the amounts of voice, transaction data and IP traffic for source-destination pair g.

The amounts of traffic are not known exactly, they are modelled as uncertain variables with an uncertainty level of *10%.* The first part of Figure B.15 plots the results for a confidence parameter of *97.5%*. The required capacity on every link is shown relative to the amount determined by the approximated probabilistic method. The latter method closely approximates the actual required capacity to be robust to an uncertain demand with a chance of *97.5%.* For a priori and a posteriori adjustments several *m*-values are considered. The appropriate value for the addition of two uncertain variables in the considered case ($m = p\cdot\sqrt{2}$) leads to an important overprovisioning on most links, compared to the probabilistic case. This can be understood by the decreasing appropriate safety margin with a growing number of operands and the fact that the safety margin is not recalculated here for every single operation (fixed safety margin value). A better approximation of the *100%* -line is obtained for smaller values of the safety margin (e.g., $m = p/\sqrt{2}$). On some links on the other hand (e.g., the link Vienna-Rome) we notice a capacity shortage, even for rather big values of the safety margin. In this regard, remark that a part of the capacity shortage could be solved by performing some form of traffic engineering (which is not considered here). It is clear from the observations in this paragraph that the usage of a fixed safety margin to incorporate uncertainty leads to unexpected dimensioning decisions.

Another approach is to differentiate the protection schemes for the considered traffic types, as they may have different survivability requirements. Voice and transaction data traffic can be protected by a pre-calculated link restoration scheme, while IP traffic is sent unprotected. Restoration is especially important in optical networks. Because of the huge traffic amounts a single failure may have a dramatic impact, while the cost of spare resources (optical equipment) is substantial. Sharing resources among several paths is a good option in this case. The differentiated restoration scheme, we use here implies that for IP traffic the formula from the previous section still holds, while for voice and transaction data traffic, the value stated there has to be augmented by the maximum of all traffic that can be affected by a single link failure, resulting in

$$\begin{aligned}&\mathit{required\ capacity}(l) = \\ &\sum\nolimits_g [V_g : l \in P_g] + \underset{k \neq l}{MAX}\left[\sum\nolimits_g [V_g : k \in P_g \wedge l \in S_g]\right] + \sum\nolimits_g [TD_g : l \in P_g] \\ &+ \underset{k \neq l}{MAX}\left[\sum\nolimits_g [TD_g : k \in P_g \wedge l \in S_g]\right] + \sum\nolimits_g [IP_g : l \in P_g]\end{aligned} \quad \text{(B.9)}$$

with P_g and S_g being the working and backup path for the traffic for source-destination pair g; V_g, TD_g, IP_g, the amounts of voice, transaction data, and IP traffic for source-destination pair g.



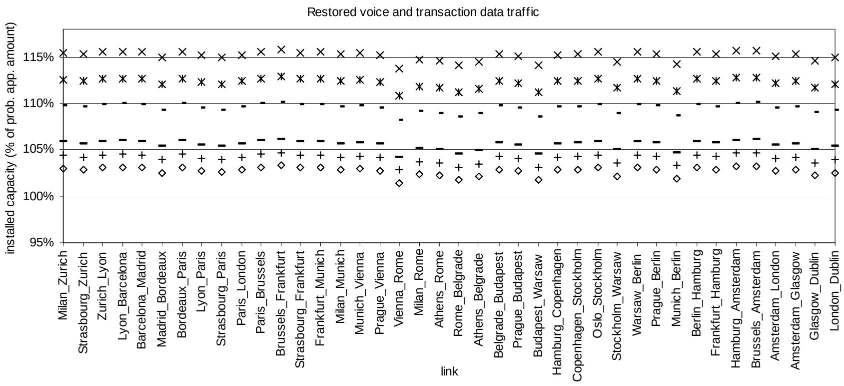


Figure B.15: limit values (ylimit) for link dimensions in the pan-European network

The dimensioning decisions obtained for an uncertainty level of *10%* associated with all traffic types (*V, TD, IP*) and a confidence parameter of *97.5%* are shown in the second part of Figure B.15. In this case the overdimensioning compared to the probabilistic case is even worse than it was for unprotected traffic.[6] A network operator following a priori adjustment would make an overinvestment, compared to one following the approximated probabilistic case. Because determination of maxima is involved here, the result is not normally distributed

[6] Note that there can be some confusion concerning the word overdimensioning. With overdimensioning in the context of traffic uncertainty we mean that there is more capacity installed that what is needed to fulfill the requirements set by the confidence parameter (to be robust to changes in the traffic with a probability of 97.5%). The actual amount of capacity to be foreseen to fulfill this requirement is indicated by the approximated probabilistic case. Overdimensioning in the context of survivability to network faults on the other hand, may indicate the extra capacity we foresee compared to the unprotected case, because of the use of backup paths.

and therefore it is not possible to determine a suitable safety margin in the indicated way. Moreover, the changing number of operands involved complicates the issue even more. For the sake of completeness, we remark that the extra capacity needed to protect voice and transaction data represents *40%* of all capacity in this case.

B.5 Conclusions

Strategic network planning needs forecasts for all major planning inputs. These forecasts are uncertain in nature and in order to model them as uncertain variables three essential parameters are needed: the predicted value expressing for instance an expert's view, the uncertainty level indicating the doubt there is about the presented predicted value, and the confidence parameter denoting the importance that the estimated output parameter exceeds the actual outcome. We distinguish several planning approaches for handling uncertainty, starting with a priori and a posteriori adjustments, which are widely used in practice today. Both use a safety margin to incorporate the effects of uncertainty. In the first case, the margin is added to the inputs of the planning problem, in the latter to the sharply calculated result after all calculations are performed. The popularity of those models can be explained by their conceptual as well as computational simplicity. The third considered approach represents uncertain variables using probability distributions. To be able to approximate all kind of density functions, a scalable piecewise linear approximation method is implemented.

We have shown that under some specific conditions it is possible to determine a safety margin value which allows a priori or a posteriori adjustment to approximate the probabilistic case. This appropriate value is a function of the confidence parameter, the ratio of the predicted values, and the number of operands. In practice, however, it is often infeasible to determine a useful safety margin value before the start of the planning calculations. This can for instance be the case when the shape of the distribution of the result is not known in advance, because of the skewness of the input distributions, the considered operations, etc. As a consequence, network planners often use a fixed safety margin value. We have shown that this may lead to incorrect planning decisions. Our findings were based on a theoretic model as well as on simulation results for a realistic planning problem.

Acknowledgement

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Appendix: Some Implementation Details

When using the probabilistic approximated value model, the input distributions are sampled in *n* equidistant sample points. For normally distributed variables *N(v,s),* we choose to sample in *v-4s*, *v+4s* (where the density is set to *0*) and *n-2* equidistant points between those extremes. A piecewise approximation of the original distribution is obtained, which, from this point onwards, is used as the continuous density distribution of the considered uncertain variable.

To determine the sum of two probabilistic approximated uncertain variable *x1* and *x2* (each having *n* sample points), the following steps are performed:

Determine n^2 sample points for *Y*: *y = x1+x2*, with *x1* and *x2* sample points for *X1* and *X2.* Sort these *y*- values in increasing order.

Calculate $F_Y(y)$ for all sample points *y* by calculating $F_{X1}(y-x2) \cdot f_{X2}(x2)$ and determining the area below the linear interpolation between those points. Connecting all points for $F_Y(y)$ results in a piecewise linear approximation of F_Y.

$$\begin{aligned} F_Y(y) &= Prob[Y \le y] = Prob[X1 + X2 \le y] \\ &= \int_{-\infty}^{+\infty} Prob[X1 \le y - x2 \text{ and } x2 \le X2 \le x2 + dx2] \\ &= \int_{-\infty}^{+\infty} F_{X1}(y - x2) \cdot f_{X2}(x2) \cdot dx2 \end{aligned} \tag{B.10}$$

Determine a piecewise linear density function *f(y)* from this cumulative function *F(Y)* by the following formula (for two consecutive sample points y_i and y_j:

$$F_Y(y_j) - F_Y(y_i) = (y_j - y_i) \cdot \frac{\lfloor f_Y(y_j) + f_Y(y_i) \rfloor}{2} \tag{B.11}$$

Resample *f(y)* to *n* sample points and normalise (area below *f(Y) = 1*)

Figure B.16 illustrates how the density curve of the operands is approximated by a piecewise linear curve. The result is represented by a piecewise linear curve with the same amount of sample points (due to resampling) to order to serve as an input for another calculation lateron.

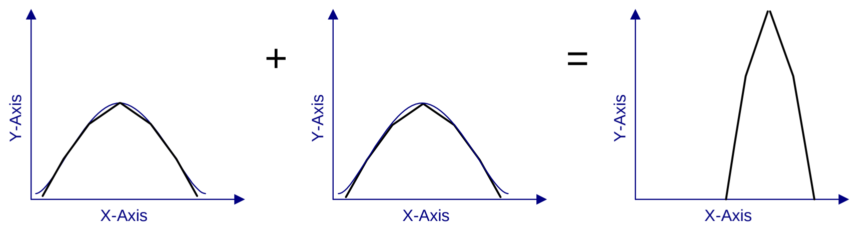

Figure B.16: piecewise linear approximation of the density curve

A similar way of working is followed to determine the maximum and product of uncertain variables. A complexity analysis showed that the determination of a maximum is of the order $O(n \cdot log(n))$, while addition and multiplication are of the order $O(n^3)$.

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C
The Options behind Dark Fibre or Wavelength Lease

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Abstract

This paper discusses the economical evaluation of different network deployment scenarios, based on dark fibre and wavelength lease. Different forms of flexibility inherent to the different network deployment scenarios are studied. Upfront planning based on predicted traffic evolutions was shown to lead to a network expansion plan which, most probably, is not optimal for the actual traffic evolution. Real Options theory is a suitable technique to determine the value of starting the network deployment with a certain scenario, taken into account the ability to switch to another scenario based on information that is unknown upfront, but becomes available during the course of the planning horizon. Based on some realistic assumptions for equipment costs and lease contract costs, we have shown that the lambda lease is not competitive compared

to dark fibre acquisition. Indefeasible Right of Use on dark fibre and dark fibre lease are competitive in terms of costs, whereas dark fibre lease is more flexible.

Key words

optical communication, networks, real option valuation.

C.1 Introduction

The current telecom market remains very uncertain. Changes are observed in the number of customers as well as in the type of the demanded services. Although the growth for network traffic is not expected to stop, future traffic demands are not precisely known in advance, therefore predictions have to be used. Within this uncertain environment, network operators are often a bit reluctant to make big investments. The presence of multiple telecommunication providers and their past investments in optical layer capacity, have led to a wide availability of dark fibre throughout Europe. Therefore, for a network operator planning to deploy a new network, there is no need to acquire all physical capacity himself. Leasing capacity gives more flexibility and is therefore considered an attractive solution. This paper describes several capacity leasing scenarios and indicates useful approaches to evaluate the associated investment decisions. After introducing the considered network scenarios, a static analysis is performed. We focus on the flexibility to switch between network scenarios and the relation between future traffic uncertainty and network flexibility, using Real Options thinking.

The term Real Options was introduced in 1977 [C.1]. It referred to the application of financial option pricing theory to the valuation of investments in real assets where a large part of the value can be attributed to flexibility and learning over time. Real Options theory has been successfully applied in modular plant expansion [C.2], R&D for new drug development [C.3][C.4], mine exploration [C.5] and other fields. In the telecom sector, it has been applied to value telecom companies during the dotcom-boom, explaining why it was handled sceptical afterwards. [C.6] describes a theoretical model to find the optimal time to open a new segment in an already existing network (not necessarily a telecom network). [C.7] studies the application of the problem of optimal timing of investment into new capacity in a telecom network, presenting a mathematical model. [C.8] values lighting decisions on dark fibre based on Real Options tree valuation. This paper focuses on the ease to apply Real Options within a common network planning study, avoiding complex mathematical consideration but emphasizing the base concepts.

C.2 Dark Fibre versus Leased Wavelengths

For an operator wanting to deploy a new network, we distinguish the following scenarios:

- acquisition of an Indefeasible Right of Use on dark fibre (IRU on DF)
- leasing of dark fibre (DF lease)
- leasing of wavelengths (lambda lease)

Leasing is a well-known concept, e.g. leasing a car, where the *grantor* grants the use of the asset to the *user* for the duration of the lease. A *lease* usually applies for a relatively short term, e.g. one to five years. An *Indefeasible Right of Use (IRU)* is similar to a lease. In telecom, an IRU is a type of long term lease of capacity on someone else's network. For instance, assume operator X aggressively builds a worldwide fibre-optic network. If another operator Y is building a network but not in the same places as operator X, to expand its reach, operator Y might buy an IRU for two fibres in operator X's network for 20 years [C.9]. In most cases, an IRU applies to longer terms than a traditional lease contract, e.g. 15 or 20 years. In the remainder of this paper, we are going to consider both IRU and lease of dark fibre, assuming a duration of 15 years for the former and 5 years for the latter. For the contract of leasing wavelengths, we assume a duration of one year. A summary of the fibre and wavelength scenarios is given in Table C.1. The mentioned link prices are in line with values found in the literature [C.10]. The absolute cost for an IRU on dark fibre equals the cost for a fibre lease contract for 5 years, so that the annual cost for the lease is three times that of the IRU. For the sake of simplicity, we assume lump sum payments for all contract types at the beginning of the contract.

	IRU on DF	**DF lease**	**lambda lease**
duration (years)	15	5	1
linkprice (euro/meter/duration)	6	6	1.5

Table C.1: overview of fibre and wavelength scenarios

Both a dark fibre and a wavelength network are based on wavelength infrastructure in the network nodes. Several candidate node configurations can be distinguished, depending on the physical topology at hand and the requirement to have grooming capabilities (packing low capacity traffic in high capacity streams). More information on possible node configurations can be found in [C.11]. In a dark fibre network, the multiplexers and the transponders are owned by the network operator acting as the user of the lease or IRU, whereas in a leased wavelength network this transmission equipment is owned by the external service provider (grantor of the lease). We study the cost of the optical layer for the user of the lease/IRU. In case of a leased wavelength network, this cost is entirely constituted of the cost of the leasing contracts. In case of a leased (or IRU) dark fibre network, apart from the cost of the leasing contract, we need to include the costs of the optical amplifiers, the transponders, the (de)multiplexers and the OADMs.

In our study we refer to the configuration of Figure C.1, where the cost of the DXCs is not considered, as this cost is present in both leased wavelengths and dark fibre scenarios. We focus on the cost differences between the distinguished scenarios. We don’t refer to any vendor-specific equipment, but rather assume a simplified node model with the base cost assumptions of Table C.2. For the sake of simplicity, in case of growing traffic demands, we assume several identical OADMs can be combined, without dealing with interconnection between them.

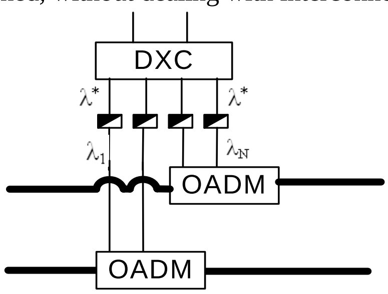

Figure C.1: considered node configuration

equipment	cost (euro)
OADM	17000
MUX dwdm	37500
transponder 10G	23000
optical amplifier	20000

Table C.2: collected availability numbers

In the remainder of the paper, we consider a network on the Belgian scale (*32,545* km^2) consisting of *3* interconnected rings with a total link length of *1488* km. We consider a planning horizon of *15* years, with an annual traffic growth of *60%*. The reference traffic described in [C.11] was assumed to be obtained in the fourth year of the period studied.

C.3 Static Cost Comparison of the Considered Scenarios

In a first step, we performed a static analysis of the costs[7] (cash-out flows) for the three considered scenarios (IRU on DF, DF lease and lambda lease), taking into account the described traffic growth of *60%* a year as well as a yearly *10%* cost erosion on the network equipment. The costs for dark fibre and wavelength lease, on the other hand, are considered to be constant over time. This assumption originates from the observation that labour costs increase over time (contrary to equipment costs) and that in the future dark fibre might become scarcer. All network scenarios (IRU on DF, DF lease and lambda lease) are dimensioned to cope with the expected traffic demand. For lease contracts with durations of over one year (granularity of the traffic predictions), i.e. the dark fibre lease for *5* years and the IRU on dark fibre for *15* years in our study, the expected need of capacity is calculated at the beginning of the contract term in order to determine the required contract size. In case the traffic demand is rather static or well predictable, this approach leads to good results, as better rates can be negotiated in case the contract is taken for multiple fibres at the same time. When the actual demand exceeds the forecasts, additional wavelengths/fibres are leased or equipment is bought according to necessity. As all scenarios are dimensioned according to demand, the network operator’s revenues (cash-in flows) are equal for all scenarios.

Figure C.2 indicates the total costs (cash-out flows) for all scenarios on a logarithmic scale. Considering the undiscounted cumulative costs (left part of the figure), the leased wavelength scenario has by far the highest cost, the IRU on DF and lease DF scenario lead to a similar undiscounted cost, the equipment cost is equal for both, whereas the lease itself is more expensive than the IRU, as shown in Table C.1. The middle part of Figure C.2 represents the discounted total costs for all scenarios, taking into account a risk-free discount rate of *3%* to discount all costs to their (present) value at the beginning of the planning horizon. In this case, the leased wavelength scenario remains most expensive. Thanks to the positive impact of the discount rate DF lease has a lower cost than IRU on DF in this case. The right part of Figure C.2 shows the total costs for all scenarios discounted using a *15%* discount rate, which is an often cited rate for telecom projects where investors face high risk. Here, the impact of the discount rate is very clear in the observed differences between the cost for the IRU on DF and the DF lease scenario. A higher discount rate favours DF lease.

[7] Note that financing costs etc. are not considered, so that, as a matter of fact, we count cash-out flows. They include what we pay for the IRU and lease contracts as well as the network equipment.

The fact that a lease contract on a shorter term is more expensive per year is somewhat compensated by the impact of discounting, as you can see from the fact that the ratio between IRU on DF and lease lambda decreases from left to right on Figure C.2.

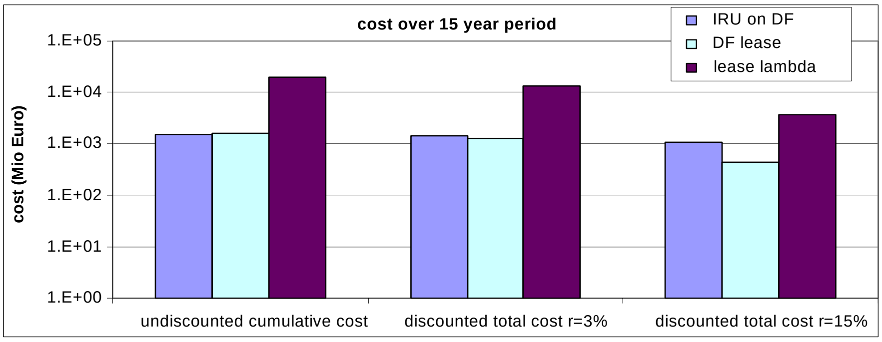

Figure C.2: total costs for all scenarios over 15 year period

Comparing the cost of a wavelength lease and the equipment cost for lighting a fibre shows a cost ratio of *2* (lambda lease more expensive) in the first year of the planning horizon. The ratio gets even higher for later years because the equipment cost is positively impacted by the costs erosion, contrary to the cost for the wavelength lease case.

C.4 Impact of the Length of the Planning Horizon

An important parameter when performing long term network planning is the length of the planning horizon. The *15* years horizon considered in the previous paragraph is probably longer than the time intervals usually considered in (uncertain) telecom projects: *5* till *10* years seems to be more common. The impact of the length of the planning interval on the cost comparison is shown in the top part of Figure C.3 for a discount rate of *15%*. The left group of bars indicates the total discounted costs over a period of *15* years, as described in the previous section. With these figures, the lambda lease scenario is most expensive, followed by the IRU on DF scenario. The middle bars in Figure C.3 indicate the total discounted costs over *5* years. The cost difference between *5* and *15* years is small in the IRU scenario, because the IRU is still paid upfront for *15* years and there is only a small saving on network equipment for later years. For the DF lease and lambda lease scenario, the costs over *5* years are significantly lower than those over *15* years, because the DF or the lambdas are only leased for the considered period. However, in case of the IRU on DF with a duration of *15* years, the DF can still be used (at no cost) for *10* more years after the *5* year planning interval. This should be taken into account in the analysis.

For this purpose, we use the concept of an *end value* which can be substracted from the costs for the *5* years study, it can be seen as a revenue in year *5*. As we assume no cost erosion on DF, the end value is calculated as a fraction of the original value, corresponding to the fraction of the remaining life time. Of course, this value is to be discounted to its present value. The right group of columns in Figure C.3 displays the total discounted cost over *5* years minus the end value. There is no end value in the DF lease or lambda lease scenarios, as the life time of these scenarios is shorter than or equal to the *5* years. The height of the corresponding bars is equal in the right and the middle group. The cost of the IRU on DF scenario is impacted by the end value (lower bar in the right group than in the middle group), allowing a more fair comparison. Figure C.3 compares the results for a discount rate of *15%* (top part) to those for *3%* (bottom part). A lower discount rate leads to a higher impact of the end value.

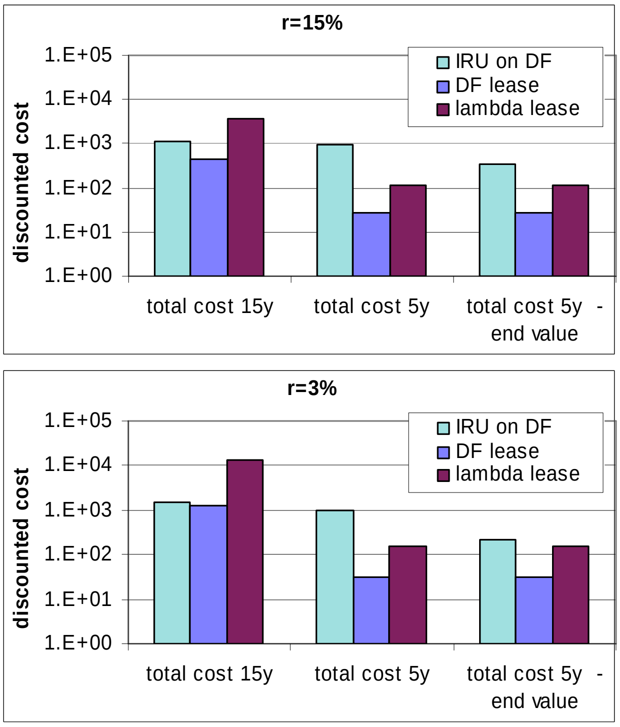

Figure C.3: discounted costs over planning horizon of 5 and 15 years (mio euro)

C.5 Analysis of Upfront Decision to Deploy a Single Scenario under Traffic Uncertainty

In section C.3, we analyzed the cash-out flows for the different network scenarios over the 15 year time frame, in a static situation i.e. in case the traffic evolves exactly as predicted. In this section, we study the impact of an uncertain traffic evolution. We consider the situation where the choice between the three scenarios is made at the beginning of the planning interval and based on the predicted traffic evolutions. Within a certain network deployment scenario, there is some flexibility to easily increase or decrease the capacity at the end of the lease contract, this is at the dots on the lines within a certain scenario (e.g. release a wavelength on a yearly basis in case of lambda lease or increase the amount of dark fibre leased after 5 years) in Figure C.4. The full lines represent IRU on DF, the dashed lines represent DF lease and the dotted lines lambda lease. In this section, we assume that it is impossible to switch to another scenario.

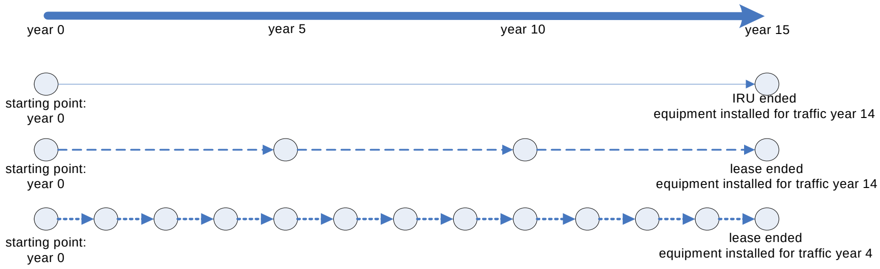

Figure C.4: limited flexibility within the different scenarios

The discounted cost over *15* years for the three scenarios when the traffic indeed evolves as predicted is shown in the first column of Table C.3. The DF lease scenario is the cheapest, as shown already in Figure C.3. However, when we experience an unpredicted, abrupt traffic growth with a factor *10* in year *6*, the situation changes. Now the IRU on DF scenario benefits from the fact that there is some room for growth within the available dark fibre capacity, so that it is not required to upgrade capacity immediately. In case of the DF lease on the other hand, the available dark fibre capacity is insufficient, so that additional costs need to be made in order to cope with this unexpected additional traffic demand. This results in the situation depicted in the right column of Table C.3, where the IRU on DF is the most cost-efficient solution. This observation learns that upfront planning based on the predicted traffic evolution can easily lead to a network which is not optimal for the actual traffic evolution.

	traffic evolves as predicted	unpredicted traffic growth of factor 10 in year 6
IRU on DF	1082	2734
DF lease	419	3688
lambda lease	1493	13713

Table C.3: discounted cost over 15 years in case of upfront decision with limited flexibility under traffic uncertainty

C.6 Analysis of Upfront Decision with Flexibility to Switch Scenarios under Traffic Uncertainty

Apart from the limited flexibility to increase or decrease capacity within a certain scenario (at the end of a contract term) indicated above, in practice, there is also the flexibility to switch between the considered scenarios at the end of the contract term, this means after *15* years for the IRU on DF, after *5* years for the DF lease and yearly for the leased wavelengths. Note that, in real life, there is also the possibility to prematurely end the contract, e.g. end the IRU before the end of the *15* year period by paying a kind of penalty fee, but this is not considered here.

In order to keep the problem comprehensible, we split the planning horizon in two parts. We assume the predictions for the first *5* years to be more or less reliable and therefore consider the case where the traffic evolves as forecasted for the first *5* years and has an uncertain evolution during the last *10* years. We consider year *5* to be the only point which allows flexibility, which is a simplification of the realistic situation. The flexibility to change the network scenario based on the uncertain evolution assumed in this section is illustrated in Figure C.5.

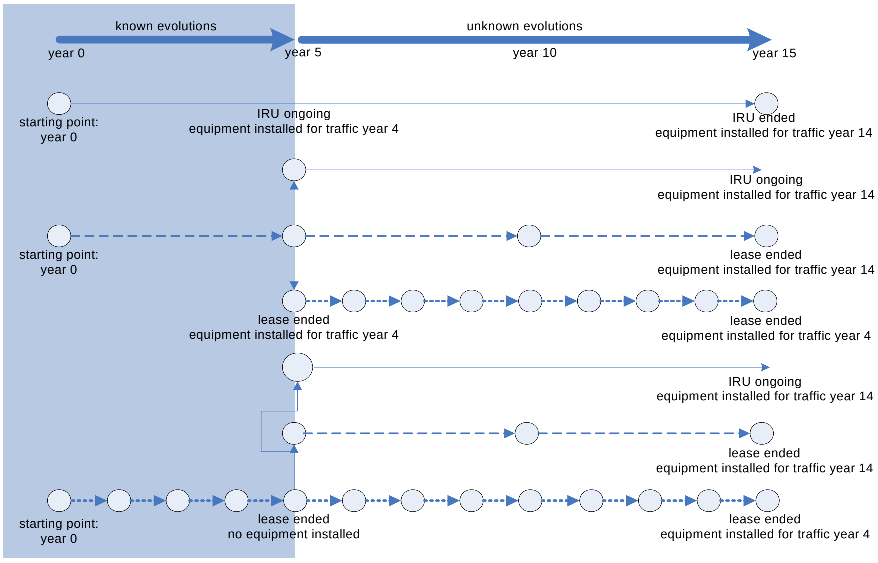

Figure C.5: considered flexibility to switch between scenarios

The situation of Figure C.5 is mapped to the network migration tree of Figure C.6, where the bottom part reflects the first *5* years, the top part the last *10* years. Again, the full lines indicate the IRU on DF scenarios, the dashed lines indicate the DF lease scenarios and the dotted lines the lambda lease scenarios. The nodes in Figure C.6 indicate the situation concerning acquired network equipment and status of the lease contracts, this explains why the edges *a, c* and *f* all end in a situation where the lease or IRU contract is finished and equipment is installed to cope with the of year *14*. As we don't consider the possibility to prematurely end the contracts, there is only *1* arrow starting from the "IRU ongoing" node. For the DF lease and lambda lease scenarios, the contract is ended in year *5*, so that all scenarios are possible for the second planning interval.

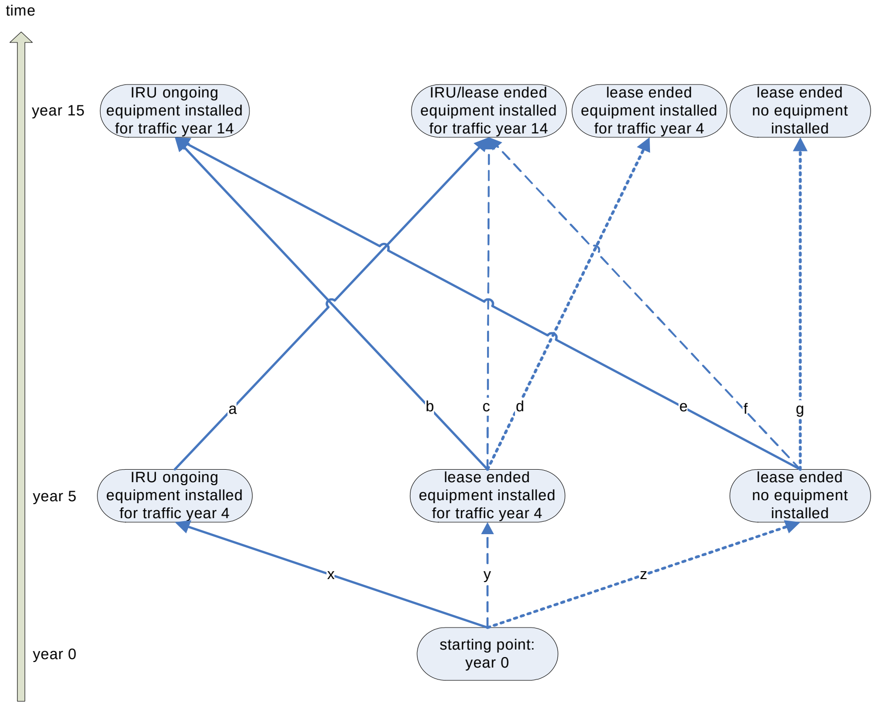

Figure C.6: network migration tree

The costs for the first five years are easy to be calculated and are shown in Table C.4. In case of the IRU on DF there is an end value after the first *5* years, as the dark fibre can still be used for *10* more years in that case, as already explained in Section C.4. Note that the end value is not taken into account when considering the costs for the entire *15* years planning horizon (as the end value of the fibres will be used in the last *10* years).

	cost	**end value**	**adjusted cost for the first 5 years**
x	944	385	559
y	28	0	28
z	113	0	113

Table C.4: discounted cost over first 5 years for different scenarios for traffic evolutions as expected

The top part of Figure C.6 shows the situation for the last *10* years. Within the network migration tree of Figure C.6, the optimal path (the shortest path from the root node to one of the node on the top level, taking the costs of the scenarios as edge weights) may be different for different traffic evolutions. The costs of all edges of the tree for the second part of the planning horizon (year *5* till *15*) are given in Figure C.5. If we assume that the traffic growth stays constant at *60%* a year, the costs of the arrows in the top part of the figure are given by the values of the first column of Table C.5. The dashed edges (*c* and *f*) have the lowest costs for the last *10* years. Combined with the information for the first *5* years, this shows that in case the traffic grows as predicted during the entire planning interval, the dark fibre lease leads to the most economical solution. The shortest path in the graph of Figure C.6 is given by the straight path from the root node to the "IRU/lease ended, equipment installed for traffic year 14" node in this case. On the other hand, in case of an important unexpected traffic increase (we assume, traffic growing a factor 10) in year 6 of our planning horizon (at the beginning of the uncertain traffic period), the situation is different, as shown in the last column of Table C.5. In this case the solution with the IRU on DF starting in year *6* has the lowest cost (edges *b* and *e* in the figure). Note that in this case the end value of the fibres in year *15* is taken into account, what has a positive impact on the overall cost of this solution (the fibres can indeed still be used for *5* more years after the end of year *15*). The shortest path is now given by edge *y* followed by edge *b*.

source node	**edge**	**edge cost**	
		traffic growth according to predictions: annual growth rate 60%	60% annual growth, plus abrupt traffic growth factor 10 in year 6
IRU ongoing, equipment installed for traffic year 4	a	1.38E+02	1.79E+03
lease ended, equipment installed for traffic year 4	b	5.12E+02	2.16E+03
	c	3.91E+02	3.66E+03
	d	1.38E+03	1.36E+04
lease ended, no equipment installed	e	5.19E+02	2.17E+03
	f	3.98E+02	3.67E+03
	g	1.38E+03	1.36E+04

Table C.5: edge costs for second planning interval in the graph of Figure C.6 (mio euro)

As no network equipment needs to be bought by the operator in case of the lease wavelength scenario, the costs of edges *d* and *g* are equal to each other for all scenarios, see Table C.5 for some examples. The small cost difference between the edges *e* and *b* and *f* and *c*, respectively, is the cost for the additional equipment required for the DF lease from year *5*, because no equipment was available in year *5* in case lambda lease was used up to that time.

The example discussed in this section shows that the flexibility to switch between scenario can add value (i.e. reduce cash out flows). However, it is impossible to take this into account in traditional planning schemes that are entirely based on the predicted evolutions.

C.7 Analysis of Flexible Upfront Decision under Traffic Uncertainty

A solution to the problems described above (planning is entirely based on predicted evolutions) could be to identify several possible future traffic evolutions instead of a single prediction. We consider the following uncertain traffic evolutions[8] for the last *10* years of the planning horizon, which are simulated using Monte Carlo simulation, performed by Crystal Ball [C.12].

- *traffic deviations from the expected value:* the estimated yearly traffic growth of *60%* is considered uncertain and it is modelled as a random variable with uniform distribution between *0* and *60%.*
- *abrupt traffic change in year 6*: the traffic is supposed to follow the forecasted traffic growth of *60%* a year, except from an abrupt change in that trend in year *6* (beginning of second planning period). The abrupt change is modelled as a traffic increase or decrease somewhere between *0.01* times its current size and *10* times is current size. A continuous variable with uniform distribution is assumed.
- *abrupt traffic decrease at unknown time*: the traffic change is supposed to be a decrease to a fraction of *0.05* till *1* of its current size, modelled as a continuous uniform random variable. The timing of the occurrence of the abrupt change is modelled as a discrete variable with uniform distribution over the second part of the planning horizon (year *6* till *15*).
- *abrupt traffic increase at unknown time*: similar to abrupt traffic decrease at unknown time, but with a traffic increase of *1* till *10* times its current size.

We distinguish between two methods to use these future traffic evolutions in order to find the most suitable network deployment plan:

- We could perform a simulation analysis of a set of future evolutions and choose the network scenario (IRU on DF, DF lease or lambda lease) which

[8] We could also use the term “traffic scenarios” for these uncertain future evolutions, but we prefer not to use this terminology, in order to avoid confusion with the “network scenarios” used in this paper (IRU on DF, DF lease, lambda lease).

leads to the cheapest network, on average over the considered future traffic evolutions. This means that we calculate the average of the costs of the edges in the second part of the planning horizon (*E[a], E[b], E[c], E[d], E[f], E[g]*) and choose the edges with the lowest cost amongst those originating from a single node in the network migration tree *(min[E[b,c,d]* and *min(E[e,f,g]))*.

- If we assume that some information concerning the future traffic evolutions becomes available in year *5* (which is not known in year *0*), we need to recognize the fact that only one outgoing edge of the nodes in year 5 will be selected, namely the one with the lowest cost given the actual traffic situation at that time (not based on the average of all possible scenarios). This means that we take into account the fact that our strategy can be changed in year 5, *based in the additional information available by that time*. This is represented by choosing the average of the minimum of the outgoing edges of the nodes in year *5* (*E[min(b,c,d)]* and *E[min(b,c,d)]*) and refects the ideas of Real Options thinking.

Whereas the traditional technique of scenario analysis explained in the first bullet aims at maximizing the value given the information available in year *0*, based on the expected evolutions, the Real Options approach aims at maximizing the value given the information available today and later, where the information becoming available later can and will be used for revising the network migration strategy during the course of the planning horizon. In case there is no uncertainty involved, both approaches lead to the same solution as the shortest path solution described in the previous paragraph.

Several real options valuation techniques exist [C.13]. In this study, we applied a simulation based valuation on the tree of Figure C.6, as explained below. The fact that the best edge out of the nodes “lease ended, equipment installed for traffic year 4” and “lease ended, no equipment installed” can be chosen in year *5*, taken into account any additional information one might have by that time, gives an additional value to those nodes. This flexibility is not present in the “IRU ongoing, equipment installed for traffic year *4*”, as this node has an outdegree of *1*. The value of the flexibility to switch to another network scenario (which is called the option value) should be taken into account already at year 0 when deciding on the solution for the first *5* years. Indeed, choosing the IRU on DF solutions limits our options in year *5*. Therefore, the actual cost of the different network scenarios for the first *5* years is calculated as the sum of the actual costs in the first *5* years and the minimum of the costs in the last *10* years.

In Table C.6, we study the impact of traffic uncertainty on the solution concerning the best network scenario. In case of the “traffic deviation from the expected value” and the “abrupt traffic decrease at unknown time”, the most economical situation is given by the DF lease scenario. This is shown by the average of the minimum of the costs of the edges out of a node as well as by the minimum of the individual average costs of the edges. In case of the “abrupt traffic change in year 6” and the “abrupt traffic increase at unknown time”, on the other hand, the average of the minimum of the edge costs is lower than the minimum of the individual averages per traffic evolution path. This indicates that, e.g. in case of the “abrupt traffic change in year 6”, the lease DF scenario is not always (i.e. not for all possible future scenarios) the best solution. This was already shown in the right most column of Table C.5, were IRU on DF was more economical in case of a factor *10* traffic increase. The difference between *min(E[a,b,c])* and *E(min[a,b,c])* is exactly the value associated with the flexibility in the node “lease ended, equipment installed for traffic year 4”. This is the value of the option to switch between network scenarios. Note that in option terminology the option value is defined as the different between the value of the flexible situation (in our case, change the network scenario according to the actual traffic evolution) and the static situation (in our case, stay with the same network scenario). However, as we assume the revenues for all scenarios, the difference in costs equals the difference in value (different sign).

The results of Table C.6 indicate that, the use of Real Options valuation succeeds in taking into account the flexibility to change the network migration strategy during the course of the planning interval, which is not possible with traditional approaches.

		traffic deviation from expected	abrupt traffic change in year 6	abrupt traffic decrease at unknown time	abrupt traffic increase at unknown time
IRU ongoing, equipment installed for traffic year 4	E[a]	2.89E+01	5.70E+02	8.73E+01	6.80E+02
lease ended, equipment installed for traffic year 4	E[b]	4.47E+02	8.09E+02	5.06E+02	9.02E+02
	E[c]	2.82E+02	1.87E+03	2.95E+02	1.20E+03
	E[d]	1.38E+03	6.92E+03	9.37E+02	6.38E+03
	E(min[b,c,d])	2.82E+02	*7.80E+02*	2.95E+02	*6.98E+02*
	min (E[b,c,d])	2.82E+02	*8.09E+02*	2.95E+02	*9.02E+02*
lease ended, no equipment installed	E[e]	4.54E+02	8.16E+02	5.13E+02	9.09E+02
	E[f]	2.89E+02	1.88E+03	3.02E+02	1.21E+03
	E[g]	1.38E+03	6.92E+03	9.37E+02	6.38E+03
	E[min(e,f,g)]	2.89E+02	*7.87E+02*	3.02E+02	*7.05E+02*
	min (E[e,f,g])	2.89E+02	*8.16E+02*	3.02E+02	*9.09E+02*

Table C.6: costs for second planning interval in the graph of Figure C.6, in case of uncertain traffic evolution

In order to determine the most suitable network scenario to start deploying in year 0, taking into account all types of flexibility described above, we need to add the value for the second part of the planning horizon (based on Real Options) and add this to the value for the first *5* years, which was suppose to be static. Referring back to Figure C.6 the costs to be compared at the beginning of the planning horizon are given by the formulae below.

$$cost\ IRU\ on\ DF = x + a$$

$$cost\ DF\ lease = y + E[min(b,c,d)]$$

$$cost\ lambda\ lease = z + E[min(e,f,g)]$$

The results can be calculated from Table C.4 and Table C.6 and are given in Table C.7. The results indicate that, for all uncertain evolutions considered in this paper, the best scenario to start deploying in year *0* is the DF lease scenario.

Dependent on the actual traffic evolution, it might be useful to switch to another scenario lateron.

	traffic deviation from expected	abrupt traffic change in year 6	abrupt traffic decrease at unknown time	abrupt traffic increase at unknown time
Start with IRU on DF in year 0	9.73E+02	1.51E+03	1.03E+03	1.62E+03
Start with DF lease in year 0	3.10E+02	8.08E+02	3.23E+02	7.26E+02
Start with lambda lease in year 0	4.02E+02	9.00E+02	4.15E+02	8.18E+02

Table C.7: total costs for the different network scenarios taking into account the option values

C.8 Suggested Methodology

Bringing together all steps described in the case study, we suggest the following methodology for evaluating investment decisions, e.g. when comparing different network scenarios:

1. Study the static case, leading to a cost breakdown over the planning horizon and giving a good insight in the most important cost drivers in the problem for the different network scenarios under study. In case of DF or wavelength lease, the cost of the lease contract is the main cost to focus on.
2. Perform a sensitivity analysis to find out the most important uncertain variables in the static scenario. For telecom network planning problems, the uncertain future traffic evolution is most important. Although the future equipment costs can, to some extent, also be uncertain, the traffic has the most important impact [C.14].
3. Identify several uncertain traffic evolution paths.

4. Identify the different network scenarios in order to determine their ability to flexibly respond to the uncertain evolutions. Apply the real options valuation technique to determine the value of the different network scenarios.

C.9 Conclusion

In this paper, we have studied long term network planning decisions, comparing wavelength lease to dark fibre lease with different contract durations. We have focused on the economical evaluation of the different scenarios. Based on some realistic assumptions for equipment and lease contract costs, we have shown that the lambda lease is not competitive compared to DF acquisition. In case the duration of the lease contract is longer than the planning interval, the end value of this ongoing contract is to be taken into account in the analysis. IRU on DF and DF lease are competitive in terms of costs.

We have studied the different forms of flexibility inherent to the network deployment scenarios under study. Whereas IRU on DF allows to cope with growing traffic without the need to update the contract immediately, the flexibility of the DF lease scenario is twofold: shorter contract terms allow to respond to traffic decrease sooner and the end of the contract time always to easily switch to another network scenario. Upfront planning based on predicted traffic evolutions was shown to lead to a network expansion plan which is most probably not optimal for the actual traffic evolution. We applied Real Options theory to evaluate the flexibility to switch between the scenarios, taking into account that information becoming available during the course of the planning horizon might influence the strategy followed. Real Options theory was shown to be the suitable technique to determine the value of starting the network deployment with a certain scenario, taken into account the ability to switch to another scenario based on information that is unknown upfront, but becomes available as time goes by.

Acknowledgment

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D

Impact of Resilience Strategies on Capital and Operational Expenditures

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Abstract

This paper studies the impact of resilience schemes on both the capital and the operational expenditures for a network operator. CapEx can be calculated from the network dimensioning. In order to determine the expected OpEx, we use a process-based approach. A case study is performed, considering a reference German 17-node network, based on WDM technology. The continuous cost of infrastructure (floor space, energy, etc.) is an OpEx part which is directly influenced by the number of network components and therefore strongly linked to the net-work dimensioning and the CapEx. The routine operation and reparation processes are impacted by the dimensioning as well, because more

equipment leads to more possible failures. On the other hand, the availability of backup capacity strongly reduces the time to get the network operational after the occurrence of a failure and therefore reduces these costs. Realistic figures are given for the case study and some more general trends are derived.

D.1 Introduction

In the past, several studies have been published indicating the impact of resilience strategies on network equipment costs, e.g. [D.1]. The impact on the operational expenditures, however, was neglected in most cases. This paper indicates a process-based approach to describe OpEx for a telecom operator. Apart from defining the process-based model, to goal of this paper is to clearly illustrate its use in a specific case study and to show how it can be complementary to common CapEx based studies. We will elaborate on the concrete input data and assumptions for all operational processes. This includes network equipment characteristics, failure statistics and estimated duration of some operational activities, needed in order to calculate labour costs. It is shown where the considered resilience scheme can impact the operator’s OpEx. In the case study, we consider a reference German *17*-node network, using WDM technology. Quantitative results on CapEx and OpEx costs are given, indicating the cost driving factors. Finally, some general thoughts about the CapEx/OpEx ratio are discussed.

D.2 Process based Approach

We use the process-based OpEx cost model first described in [D.2]. It analyses the OpEx for an operational network, i.e. one that is up and running. We therefore don’t consider the costs of the initial installation and those of network extensions.

All infrastructure is counted as CapEx in our model, as suggested in [D.3]. For an operational network, several OpEx categories can be distinguished. The general framework is defined by the continuous cost of infrastructure; what needs to be paid in any case to keep the network operational (also in the failure free case). It includes the costs of (floor) space, power and cooling energy. In principle, also leasing of network equipment and right-of-ways, i.e. the privilege to put fiber on the property of someone else (e.g. along rail-ways) are part of this cost, but this is not considered in the quantitative study below. The continuous cost of infrastructure forms the general framework in which several operational processes can be distinguished, as illustrated in Figure D.1.

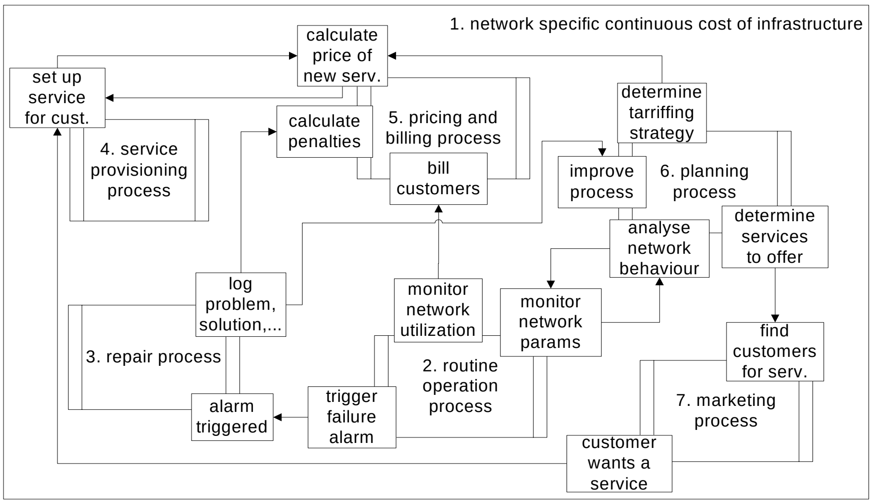


Figure D.1: operational processes for network which is up and running

In practice failures can occur, so that monitoring the network's correct behaviour becomes important. The routine operation process therefore becomes the central process. Several activities define its interaction with other processes. Network utilization info will serve as an input to the pricing and billing process. There is also a constant interaction between the planning process and the routine operation process. The first determines the parameters to be monitored by the latter and takes the monitoring results as an input to analyze the network behaviour and suggest improvements for the future. In case of a failure alarm, the re-pair process is triggered. This process deals with actually repairing the failure in the network, if this cannot happen in routine operation. Reparation may lead to actual service interrupts, dependent on the used protection scheme. The actions involved in the reparation process are diagnosis and analysis, the technicians travelling to the place of the failure, the actual fixing of the failure and performing the necessary tests to verify that the failure is actually repaired. The service provisioning process is another central process which sets up the service requested by a customer. This means providing a (previously defined and negotiated) service to a customer. It follows after the service request by the potential customer and includes the entire process from order entrance by the administration till per-forming the needed tests. Also the actions in case a service is ceased should be counted here. This includes accepting the cessation request, deactivating the circuit, switching off and physically recovering the equipment. There is an interaction with the pricing and billing process to calculate the price of the provisioned service and another one with the repair process that indicates the downtime caused by a failure and therefore the potentially associated penalties to be paid to the customer. The marketing process can be seen as a side process trying to attract new customers, it therefore influences the service provisioning process. The actions involved are promoting a new ser-vice, provide information concerning pricing etc. The planning process interacts with all other processes as a steering process. It includes all planning performed in an existing network which is up and running, including day-to-day planning, re-optimization and planning upgrades.

In [D.2] all processes are described in a graphical way, with boxes indicating the actions and diamonds for questions indicating processes' branches. In this paper, we will attach costs to the actions and probabilities to the branches in order to perform some quantitative studies.

D.3 Assumptions and Input Data

In order to perform a quantitative study, a specific case needs to be selected. We study the optical layer of a national German network. Specific assumptions for network equipment characteristics, labour costs and failure probabilities are described in this section. Unless stated otherwise, the numbers are taken from [D.4].

equipment type	MTBF (h)	power (kW)	footprint (ETSI)	price (k€)
WDM line system (40 lambda)	2.00E+05	1	3 racks	12.00
fiber	7.00E+06	0	0	0.00
optical amplifier	2.00E+05	0.5	0.25 rack	7.90
SR transponder (2.5 Gbps)	3.00E+05	0.5	0 (inserted in OXC)	2.00
LR transponder (2.5 Gbps)	3.00E+05	0.5	0 (inserted in OXC)	2.50
unequipped OXC (512 ports)	1.00E+05	3	3 racks	100.00

Table D.1: network equipment characteristics

D.3.1 Network and Equipment

We consider an optical (WDM) network, carrying *2.5* Gbps leased lines. Although, in a realistic network, leased lines would probably be offered via SDH or OTN over WDM, we focus on this leased-line-over-WDM architecture for the sake of having a very simple architectural model and focus on the expenditures modelling. The topology is the reference German network [D.5] with *17* nodes and *26* links and the associated traffic for *2004*. The total and average link distances are *4427* and *170* km, respectively.

The characteristics of the considered network equipment are listed in Table D.2. We consider WDM line systems (mux/demux, excluding transponders) with a potential of *40* lambdas, optical amplifiers are placed every *70* km, the transponders (both short reach as long reach) have a capacity of *2.5* Gbps. The optical cross-connects (OXCs) allow transit traffic to bypass the intermediate nodes on the optical layer. The considered OXCs have *512* ports. We assume opaque OXCs, with identical characteristics for WDM transponders and OXC interface cards. For every equipment type, we indicate the expected failure rate (Mean Time Between Failures, MTBF) and energy consumption. Apart from the energy consumption to operate the equipment (power in Table D.1), we assume additional energy is needed for cooling this equipment. This is assumed to be *1/3* of the power indicated in Table D.1. The footprint of the equipment is expressed in ETSI racks (*60*60*cm). The component prices are determined from a combination of [D.6][D.7][D.8] and some own assumptions. Please note that those numbers indicate only rough estimations, without any reference to specific equipment. We assume that fibre is available anyway (dark fibre), so that we don’t need to count a price for it.

parameter	**value**
price per kWh	0.08 euro
price floor space rental per m^2 / month	10 euro
correction factor for floor space	2.5
Equipment life time	10 years

Table D.2: additional equipment cost assumptions

Additional equipment cost assumptions are given in Table D.2. We consider a price of *0.08* Euro per kWh. Although prices may vary across several countries and for different customer categories, we consider this to be a realistic assumption [D.9]. As price for floor space rental we assume *10* Euro per square meter per month. Moreover, we assume the required free floor space (to allow the technician to configure and replace equipment) to be a bit bigger than the floor space taken by the equipment itself, expressed by the floor space correction factor of *2.5*. Note that this value can, to some extent, also be determined by the maximum allowed load per square meter. Finally, the equipment life time is set to *10* years. In order to be able to calculate the yearly capital equipment costs, the total equipment costs are divided by this equipment life time.

D.3.2 Operational Activities

The description of the operational processes involves several actions/activities that need to be performed by the operator's personnel. The duration of the activity determines, to an important extent, the cost of the action. Table D.3 summarizes the actions in the routine operation and reparation process with their expected duration. Several phases are distinguished. The activities of the helpdesk people include helpdesk calls and customer notification. The time for diagnosis and isolation depends on the type of the failure. The costs for transport (going to the location of the failure) are calculated from the topology characteristics. We assume that technical teams are present on average *2* links away from one another, this is every *340* km. The average distance to the failure location is therefore *85* km. One way and return adds to *170* km, with an average speed of *50* km/h, this means *3.4* hours for transport. The actual time for reparation again depends on the type of failure and the test consists of a component test to be performed by a technician on site and an end-to-end test, to be performed from the NOC.

In addition to the activities in Table D.3, some rather continuous actions are also included in routine operation. We assume *1* person year for monitoring and *0.5* person year for access and data integrity control.

The activities for the other operational processes are listed in Table D.4. Pricing and billing involves calculating the price of the requested service. As we only consider standard leased line services here, this means getting the price from the coverage map. Furthermore, assigning costs to the customer accounts also includes calculating penalties if needed (in case of service interrupt). Please note that the costs to pay the penalties themselves (which is also an operational cost for the operator) are not considered here. In general, also the costs to trace bad payers should be included. In this study, however, we consider business customers and not the mass market, so that we assume tracing bad payers can be neglected here. The activities for service provisioning are a simplified version of [D.11]. We consider service delivery, while neglecting service cessation. We differ between the costs for planning, installation and configuring in the local domain and externally and assume that the probability for a problem in the internal domain is *1.5* times as big as that for an external problem. The costs/durations for service provisioning indicate the time needed to provision a single connection. Note, as will be explained below, that in case of 1+1 protection actually *2* connections need to be set up. Therefore, in this case, the number given here need to multiplied by *2*. The marketing and operational planning processes are modelled in a straightforward way, only including one activity. One hour for planning per leased line, is assumed for the unprotected case. In case of shared path or 1+1 protection, we believe this time to double to *2* hours.

action		duration (hours)
helpdesk	customer reporting problem	1
	notify customer notification on expected problem	0.5
	notify customer on problem solution	0.5
	create trouble ticket	1
diagnosis & isolating	network fault diagnosis	0.5
	isolating fault at CPE	1
	isolating internal fault	1
	finding cable cut location and isolating it	2
transport	going to location of failure	3.4
reparation	preventive replacement	0.2
	repairing and testing at CPE	1
	repairing problem from NOC	0.5
	repairing HW or replacing and reconfiguring	1
	fixing cable	4
test	component test	1
	e2e test	0.5

Table D.3: activities in routine operation and repair process

action		duration (hours)
pricing and billing	get price from coverage map	0.5
	calculate penalty	0.5
	assign cost to customer account	0.5
	distribute bill	0.2
	check payment	1
service provisioning	contract handling and administration	1
	create work packages	2.5
	plan, install, configure local domain	0.5
	plan, install, configure external	1
	progress information to customer	0.2
	customer care delivery report	0.5
marketing	time to handle a service request (sales)	4
planning	planning time	1

Table D.4: activities in pricing and billing, service provisioning, marketing and operational planning

D.3.3 Personnel

The costs of a certain operational activity can be calculated by its duration (from the tables above) multiplied by the hourly cost of the employee performing this activity. We distinguish several personnel categories: sales, technical field personnel, technical personnel in the NOC, administrative and helpdesk personnel, researchers and engineers. Personnel cost information is given in Table D.5. The overhead indicates a factor with which the salary needs to be multiplied in order to find the fully accounted cost of this person for the company. Apart for the wages and the taxes, this also includes additional costs such as tools and transport, see also [D.2]. Exactly calculating the amount of training and the tools needed for each of the considered actions is probably impossible. But the overhead factor allows to indicate the general trends. There will be more training needed for personnel performing difficult technical tasks than for people answering help desk calls. Technicians also need more tools than administrative personnel. The use of the overhead factor is based on a suggestion by [D.10]. To calculate an hourly cost from a yearly cost, we assume *38* working hours in a week and *46* weeks a year, taking into account holidays.

department	salary, incl. taxes (euro/year)	overhead factor	fully accounted cost (euro/hour)
sales	90000	3	154
technical	78300	3	134
NOC	64800	2	74
administration, helpdesk	72000	2	82
research, engineering	81000	2	93

Table D.5: personnel cost

D.3.4 Failure Probabilities

We assume two types of alarms in the network: preventive alarms and failure alarms. Based on the observation of [D.12] that *39%* of all outages longer than *2* min were scheduled, we assume *39%* of all alarms to be preventive alarms. Considering failure alarms, we observe several problem causes: CPE problems, external problems (power disruptions, ...), misconfigurations or software failures and hardware failures incl. cable cuts. The probabilties of these problem causes are specific for an optical network [D.4]. For higher network layers (SDH or IP) the probability for a configuration or software failure is much higher. The considered failure probabilities are listed in Table D.6.

Based on the MTBF information of Table D.1, the total number of hardware failure in one year over the entire network was determined to be *925*. With the ratios of Table D.6, this adds to a total of *1171* failure alarms and *749* preventive alarms per year.

alarm type	probability		
preventive	39%		
failure	61%	CPE problem	3%
		external problem	4%
		misconfiguration/ SW problem	14%
		HW problem (incl. cable cut)	79%

Table D.6: failure probabilities

D.3.5 Customer and Contract Information

The final category of relevant data to calculate the expected OpEx concerns the customers and their contracts.

We consider an (optical) backbone network, therefore the customers are probably no end users, but rather business customers (companies). The number of actual leased lines is estimated as *1214*. This is a rough estimation, obtained by dividing the total traffic of *3035* Gbps by the leased line capacity *2.5* Gbps). As we are dealing with business customers, we assume all of them to have business contracts including notification on expected problems and on the solution of a problem. None of the considered contracts include customers support. Furthermore, we believe the network monitoring to work well, so that all problems are apparent from that. Helpdesk calls only report known problems. We assume *1.5* helpdesk call per network problem, as a problem is probably noticed by more than one customer.

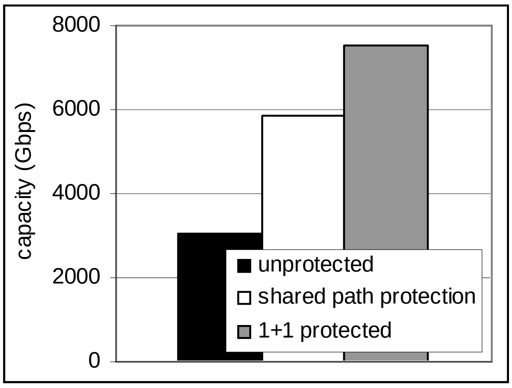
D.4 Impact of Resilience Scheme

We consider three different resilience schemes. In case of an unprotected network, there is no protection against failures. The advantage of this way of working is the absence of overdimensioning. The dimensioning results are shown in Figure D.2. A small dimensioning has a positive impact on CapEx (equipment itself) as well as OpEx (in terms of energy, floor space to operate this equipment). When a failure occurs, a new path needs to be calculated and set up.

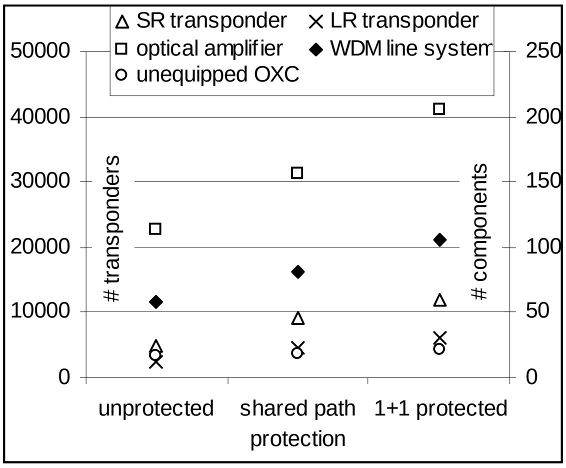
We assume path calculation to be done by an online tool in all cases, so that it doesn't generate any cost. In case of an unprotected network, the configuration happens manually, which can take quite some time. We assume 8 hours in Table D.7. During this time, the network will be unavailable, so that probably penalty costs need to be paid. Note that those penalties are not considered further in this study, which also explains why we don't consider outage times, but rather recovery times (time till the network recovers from some failure). Note that probably not all capacity can be restored because the unprotected network was not dimensioned to allow restoration, but this is not taken into account here. Also re-rerouting was not considered.

Shared path protection allows to share backup capacity between several backup paths. The end-to-end backup paths are precalculated, but not set up beforehand. In case of a failure, the path is set up automatically. We assume this to take *0.05* hours (= *3* minutes), instead of *8* hours in the unprotected network. In case of a double failure, the backup path might already be occupied, so that it should be restored like an unprotected connection then. In this study only single failures are assumed.

In case of 1+1 path protection, a backup path is predetermined and set up for each working connection. The backup capacity is dedicated to a certain backup path, which leads to more required capacity and therefore higher expenses in CapEx and OpEx. On the other hand, the cost to reroute the traffic becomes neglectable (*0* instead of *8* hours), as the traffic is sent over the backup path all the time. 1+1 path protection has an impact on the service provisioning cost as well. Indeed, when setting up a connection, we always need to set up both the working and the backup path. The cost of setting up a connection is therefore twice as big as in the other cases.



(a) dimensioning in terms of capacity



(b) dimensioning in terms of network equipment

Figure D.2: dimensioning results

resilience scheme	time to reroute traffic (h)
unprotected	8
1+1 protection	0
shared path protection	0.05

Table D.7: impact of resilience scheme on time to reroute traffic

D.5 Quantitative Results

D.5.1 Capital Expenditures

The first step in order to determine required CapEx and OpEx for the considered network and traffic, is to dimension the network, see the results of Figure D.2. Taking into account the equipment costs and the expected life time, this allows to calculate the yearly CapEx costs for the different resilience schemes, see Figure D.3. It is clear that the main difference is coming from the different amounts of transponders (line capacity) needed for the different resilience schemes. As an unprotected network has no overdimensioning, opposed to the other considered schemes, the CapEx cost for this scheme is the smallest. The total CapEx cost for the shared path protected case is *81%* bigger than in the unprotected case (mainly coming from the transponder cost which is *93%* bigger). The total CapEx for the 1+1 protected network is *131%* bigger than that for the unprotected one (*148%* when only considering transponders).

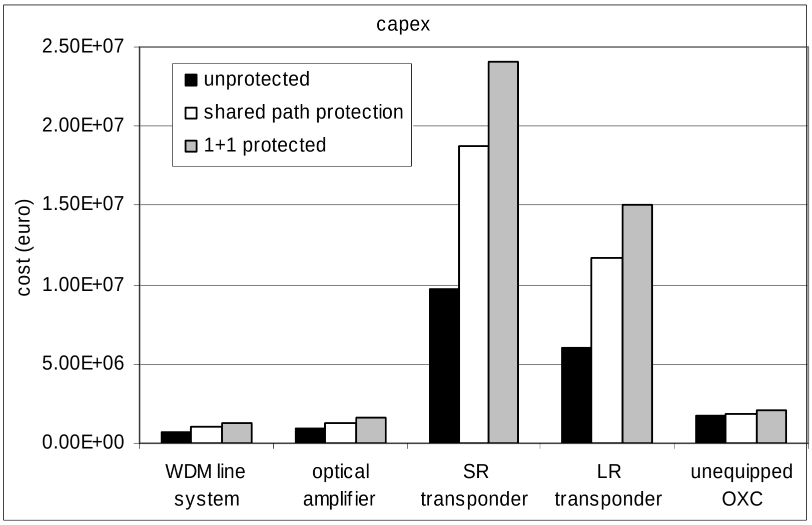


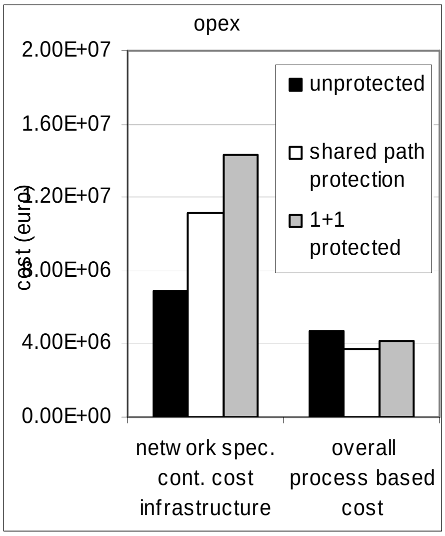
Figure D.3: impact of resilience schemes on CapEx

D.5.2 Operational Expenditures

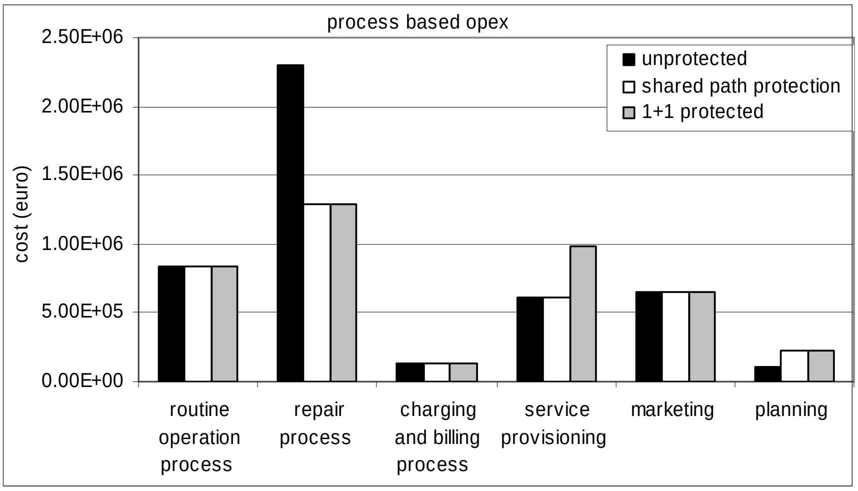
Concerning operational expenditures, the results are shown in Figure D.4. The continuous cost of infrastructure follows more or less the same trends as the CapEx costs. In case of shared path protection it is *164%* of that for the unprotected network, in case of a 1+1 protected network it is *209%*. The continuous cost of infrastructure is composed of two parts: energy consumption and floor space rental. With the assumptions made here, the cost for energy consumption is in the same order of magnitude as that for floor space rental. The continuous cost of infrastructure constitutes more than half of the total OpEx cost: *56%* in case of an unprotected network, *75%* for shared path protection and *78%* in case of 1+1 protection. The remainder of the OpEx is constituted by the process based costs. In this respect, we need to point out that our study only considered the OpEx costs for a network which is up and running. Also counting the operational expenses for first-time installation in the process-based costs probably would have changed the picture.

Having a closer look at the process based OpEx (network which is up and running), we notice that reparation is more expensive (almost twice as expensive) in case of an unprotected network, because of the additional effort to reroute the traffic in case of a failure. The cost for service provisioning is more than *1.5* time bigger in case of 1+1 protection than in the other cases, because the first approach requires to setup almost twice as many connections as the others cases. The costs for planning are smaller (half) for the unprotected network, because backup scenarios do not need to be planned for. Taking all processes together, the overall process based OpEx is cheapest in case of shared path protection, it is *10%* bigger for 1+1 protection and even *24%* bigger in case of an unprotected network.

When combing network specific continuous infrastructure costs with process based OpEx, we see that the cheapest solution in terms of OpEx is given by the unprotected network. A network using shared path protection is *30%* more expensive to operate, a network offering 1+1 protection even *60%*.



(a) impact on continuous cost of infrastructure versus process based cost



(b) impact on process based OpEx

Figure D.4: impact of resilience schemes on OpEx

D.5.3 Overall Costs

Bringing together the results of the two previous sections leads to the results of Figure D.5. It is clear that, with the considered assumptions, CapEx exceeds OpEx costs in all case. The ratio OpEx/CapEx is *60%* for an unprotected network, *43%* for shared path protection and *42%* for 1+1 protection. We remind the reader again that the operational expenses for first-time installation as well as the general expenses for non-telco specific administration and infrastructure are not counted. This can explain why we find that OpEx is smaller, on a yearly basis, than CapEx. However, we see significant differences between the resilience schemes under identical assumptions which may be interpreted as general trends for their influence on OpEx.

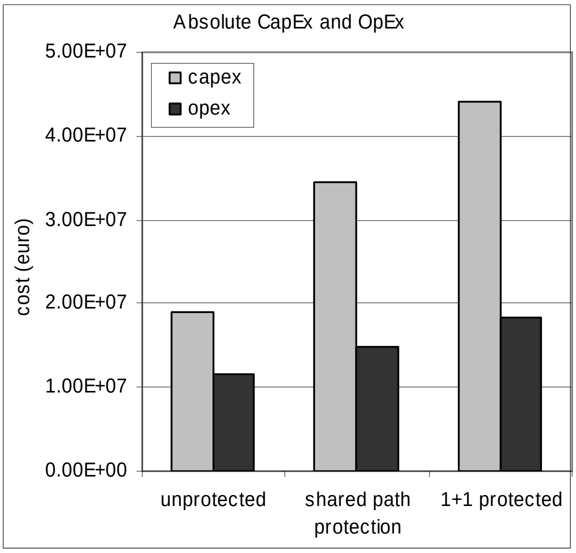


Figure D.5: impact of resilience schemes on overall costs

D.6 Conclusions and Future Work

In this paper, we have considered CapEx and OpEx costs for a backbone transport network and studied the impact of different resilience schemes on those costs. The first, obvious impact of the considered resilience scheme was observed in the dimensioning results. This has a direct effect on the CapEx costs and the OpEx part which is directly related to continuous costs of infrastructure (floor space, energy,…). Those costs are smallest for the unprotected network and grow with the needed required amount of backup capacity. A similar trend was seen for the costs of service provisioning, which is most expensive in case of 1+1 protection (more connections need to be set up). Also planning costs grow with the amount and complexity of failure scenarios that need to be planned for. Finally, also the reparation process is impacted by the dimensioning, because more equipment leads to more possible failures. On the other hand, the availability of backup capacity strongly reduces the time to get the network operational after the occurrence of a failure and therefore reduces this cost. Considering the overall picture, CapEx exceeds OpEx costs in all cases, but we note significant differences between the resilience schemes. The network using shared path protection is the cheapest to operate.

This paper reports preliminary results. Future work will focus on improving and validating the model. The estimations for the input data will be improved, by further questioning network operators. The OpEx and CapEx cost results obtained by the model will be compared to real expenses as described in telecom operators' year reports. The final goal of this work will be to come up with a useful decision support tool, which allows network operators to take OpEx costs into account in a straightforward way in their network evaluation studies.

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E

Influence of GMPLS on Network Providers' Operational Expenditures – A Quantitative Study

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Abstract

GMPLS is promoted as a major technology for the automation of network operations. It is often claimed to allow the reduction of Operational Expenses (OpEx). However, detailed analysis and quantitative evaluation of the changes induced by such technologies is very rare. In this paper we quantify the cost reduction potential of GMPLS. We present a detailed analysis and modelling of traditional operator processes. We also develop a model for the expected changed processes when using GMPLS and identify the differences quantitatively. Then, a survey with major telecom operators has been done and the process models have been verified and parameterized. This allowed quantitative evaluations of the OpEx changes with GMPLS. The results show that depending of the network operator's processes different impact can be expected. Anyway, as an overall result we could verify that a reduction in the order of 50% of the OpEx cost can be expected for most of the operational models.

Key words

GMPLS, OpEx, network management, network operations, business case

E.1 Introduction

During the last years the main focus of transport network evolution was on increasing transport capacities and on introducing data networking technologies and interfaces, e.g. Gigabit Ethernet. This evolution is complemented by ongoing initiatives to reduce the operational effort and accordingly the costs of network operations. Generalized Multiprotocol Label Switching (GMPLS) together with standardized interfaces like UNI/NNI automate the operation of telecom networks [E.1]. They allow to efficiently provide services and to improve the resilience of networks. For the service provisioning there is the new paradigm of user initiated service provisioning (also known as switched connections) where the client can setup connections without operator interaction. This does not only speed up the provisioning process, but also reduces effort for the network operator.

Currently the approach of using a distributed control plane for network functions like service provisioning, link management or failure restoration is followed by several initiatives and standardization bodies including ITU, OIF and IETF. In this paper we do not distinguish the details of these approaches but generally assume a control plane supporting automation of network operations. We use the term GMPLS to refer to any kind of control plane according to one or several of these standards.

The advantages of GMPLS have been described and discussed controversially in literature and conferences over the last years. However, all these discussions usually lack quantitative investigations of the impacts of such technologies. This results mainly from the difficulties to model operators' processes and to obtain quantitative information about the efforts and costs in these processes.

In this paper we evaluate how GMPLS technologies impact network operators’ processes, and provide a calculation of the expected OpEx savings. Based on surveys and interviews with several carriers we developed a generalized model of traditional network operation processes and potential changes with the introduction of GMPLS. In these surveys and interviews we also collected cost and effort figures for the current network operations and we extrapolated these to the new GMPLS process model.

In the remaining part of this paper we first explain our general approach for these investigations and then present the traditional and the new GMPLS-based process model. We then show and evaluate the results of the quantitative analysis. In the conclusion we summarize our findings and point out the overall expected OpEx improvements due to GMPLS.

E.2 Approach

The total expenditures of a company can be split in two parts: the capital expenditures and the operational expenditures. Capital expenditures (CapEx) contribute to the fixed infrastructure of the company and they are depreciated over time. They are needed to expand the services to the customers. Operational expenditures (OpEx) do not contribute to the infrastructure itself and consequently are not subject to depreciation [E.2]. They represent the cost to keep the company operational and include costs for technical and commercial operations, administration, etc.

This paper focuses on the impact of GMPLS on the OpEx in an operational network, i.e. one that is up and running [E.3]. We therefore don't consider the costs of the initial installation and those of network extensions. All infrastructures are counted as CapEx in our model, as suggested in [E.4].

For the traditional network, we assume that it provides end-to-end services. The GMPLS network additionally offers dynamic services.

Network operation comprises all the processes and functions needed to operate a network and deliver services to customers. That includes the sales and marketing processes, the various support functions, as well as provisioning and monitoring of the network and the corporate processes in general. By far, labour costs associated with all of these items account for the majority of a service provider's annual operating expenditures budget (besides other costs of infrastructure like energy, floor space etc). The significance that a reduction in operating expenditures can have cannot be downplayed.

In this study we want to perform a process-based quantitative analysis of the reductions in operational costs to be expected for network operators using GMPLS. The study is based on the OpEx model defined in [E.3]. Starting from this very comprehensive model, the idea is to evaluate which operations become more or less expensive when the used technology is GMPLS instead of the traditional static transport network. In extreme cases, some operations can even appear or disappear. Apart from the operations, particular attention has also to be paid to the processes' branches. The probability of each branch of the processes' flow has also to be extrapolated when considering the new technology.

Based on this qualitative modelling, quantitative results can be calculated. The normal cost of each operational step is the one assumed in the base OpEx model, for the traditional approach. Combining this cost and the qualitative variation, the new cost can be extrapolated. In this way the incremental costs/benefits from using GMPLS can be obtained.

E.3 Traditional Process Structure of Network Operators

In general, the introduction of GMPLS will influence the cost structure of network operators in many ways. The next sections describe the processes being affected.

E.3.1 Continuous and Recurring Processes

E.3.1.1 Continuous cost of infrastructure

The cost to keep the network operational in a failure free situation is the first important cost in this category. We call this the *telco specific continuous cost of infrastructure*. It includes the costs for floor space, power and cooling energy and leasing network equipment (e.g. fibre rental). Also right-of-ways, i.e. the privilege to put fibre on the property of someone else (e.g. along railways) is part of this cost.

E.3.1.2 Routine operations

It is the cost to maintain the network or to operate the network in case a failure can occur. The main actions performed here aim at monitoring the network and its services. Therefore, the actions involved include direct as well as indirect (requested by an alarm) polling of a component, logging status information, etc. Also stock management (keeping track of the available resources and order equipment if needed), software management (keeping track of software versions, and install updates), security management (keeping track of people trying to violate the system and block resources if needed), change management (keeping track of changes in the network, e.g. a certain component goes down) and preventive replacement are included.

E.3.1.3 Reparation

Reparation means actually repairing the failure in the network, if this cannot happen in routine operation. Reparation may lead to actual service interrupts, dependent on the used protection scheme. The actions involved in the reparation process are diagnosis and analysis, the technicians travelling to the place of the failure, the actual fixing of the failure and performing the needed tests to verify that the failure is actually repaired.

E.3.1.4 Operational network planning

We distinguish the ongoing network planning activity which we call *operational network planning*. It includes all planning performed in an existing network which is up and running, including day-to-day planning, re-optimization, planning upgrades.

E.3.1.5 Marketing

With marketing we mean acquiring new customers to a specific service of the network operator. The actions involved are promoting a new service, provide information concerning pricing, etc.

E.3.2 Service Management Processes

Due to the automation capabilities of GMPLS the service management will be affected to the greatest extent within the process structure of a network operator.

Thus, for our study we investigated the five most technology dependent processes within the traditional structure of network operators considering the interactions and operations of sales department (SD), administration (AM), project management (PM), network operation (NO) and external suppliers (ES), see also [E.5].

E.3.2.1 Service offer

The sales department negotiates the terms and conditions of the offer with the customer and does an inquiry whether the connection request can be handled by the standard mechanisms and infrastructure. In case of non-standard connection inquiries, separate projecting (PM) is triggered for the various domains (local, internal, external), and missing equipment (cards, fibres, etc.) is ordered, causing additional effort and delay. The projecting results then define the price calculation (SD), as well as the delay necessary to set up the service. Then the offer sent is to the customer.

E.3.2.2 Service provisioning

After the contract has been accepted the service delivery process starts (see Figure E.1). The sales department handles the contract administration and forwards it to the project management that splits it into work packages according to the network domains involved. After providing the connection, an end-to-end test is conducted (PM) and customer care, billing and alarm management are activated (AM). Finally, a delivery report is issued by the sales department to the customer.

E.3.2.3 Service cease

At the end of a contract or on cessation request by the customer the cease process triggers (via PM) the deactivation of the circuits (NO), followed by the recovery of equipment by field technicians (NO). SD is informed about the expected cessation and the final bill is sent out (AM).

E.3.2.4 Service move or change

Moving or changing a connection is the most complex task since it involves all three previous processes: Contract update, new connection setup and release of the previous connection. The customer’s request for change is handled by the sales department as a service offer process, checking again for the availability of resources. The sales department then generates orders for the service provisioning and cease process that are implemented through coordination from the Project Management department. In the same time the client is receiving updates on the new installation.

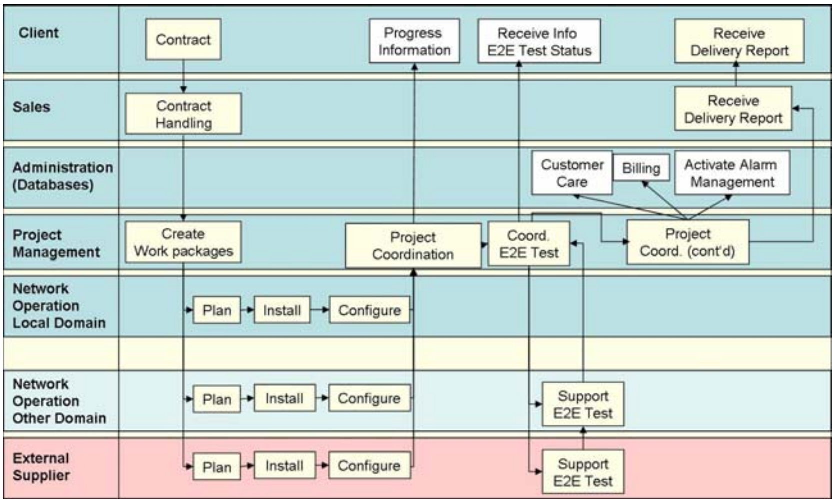

Figure E.1: typical service provisioning process

E.4 Impact of GMPLS on Operational Processes

From the main operational processes described above, several are impacted by the use of GMPLS.

E.4.1 Continuous and Recurring Processes

E.4.1.1 Continuous cost of infrastructure

The continuous cost of infrastructure will be impacted by the amount and the type of the network components used. With GMPLS the network usually allows mesh-based restoration, where less backup capacity is required, which in turn leads to less network components. The cost to power, cool and host this equipment will therefore also decrease.

E.4.1.2 Routine operations

The cost of the routine operation (maintenance cost) depends also on whether the network is automatically switched or not.

The use of GMPLS influences the routine operation costs because (re)configuration after replacement of equipment can happen faster. The replacements in the routine operation process are only those that can happen in the service window. The service window indicates the time (e.g. during the night) during which service interrupts are contractually not considered as downtime. As GMPLS enables faster reconfiguration, more operations can happen during the service window, so that the repair process needs to be triggered less often.

On the other hand, monitoring the software and the needed software upgrades becomes more expensive in case of GMPLS, because its complexity drastically increases due to the presence of the control plane. In general, we can expect the routine operation cost to increase a bit when GMPLS is used.

E.4.1.3 Reparation

As a result of using GMPLS more failures can be fixed from the NOC, which could have a beneficial impact on the reparation cost. On the other hand, GMPLS leads to more complex network operation, which might be an additional source of failures.

Rerouting of traffic happens faster: GMPLS allows for many fast and automated restoration and protection schemes. Isolating a fault gets cheaper when LMP's fault management procedure is available (but the link management protocol LMP is optional in GMPLS, [E.1]).

Overall, we expect the cost for the reparation process to decrease in case of GMPLS. [E.3] gives an overview of the repair process.

E.4.1.4 Operational network planning

Indirectly the used network technology will also influence the cost of planning, as more complex systems require a higher planning effort.

E.4.1.5 Marketing

As GMPLS technology allows to offer new services, which are initially unknown to the customers, additional marketing will be needed to inform the customers. This will lead to higher marketing costs. On the other hand, of course, it may also lead to higher revenues.

E.4.2 Services Management Processes

Finally, technologies automating some of the network operation allow to significantly reduce the cost for service provisioning, because the signalling can be done via standardized interfaces (User Network Interface UNI and Network to Network Interface NNI), without requiring manual intervention. This means that the cost for setting up a new connection decreases strongly.

In this case, the service offer process and provisioning process will be changed fundamentally [E.6]. Since the service delivery will now be automated and executed on the pure machine level, correct agreements and regulations have to be negotiated by the sales department, and implemented well before in the form of Service Level Agreements (SLAs). The use of GMPLS technologies and the possibility to offer dynamic services are strongly interconnected issues. The strongest impact of the dynamic services is on the pricing and billing process. Fixed price services, e.g. leased lines, will definitely be cheaper in pricing and billing than dynamic services. For dynamic services it is much more difficult (and thus more expensive) to correctly assign costs to customer accounts. Calculating a new price for a new service is more expensive than just applying a traditional pricing scheme. This is elaborated below as "negotiations" in the service provisioning process.

E.4.2.1 SLA negotiations

The process chain therefore starts with the SLA negotiation process. Before the single services are ordered and delivered, a contract framework specifies in detail all sections of a generic service template. Technical aspects like bandwidth (minimum, burst) and its granularity, service availability, quality of service are specified as well as legal and organizational questions (penalties for requirements not met, compensation, tracking and reporting, etc.). Within the network operator this is accompanied by forecasts (SD), Planning (PM), and adaptation of the infrastructure (NO).

E.4.2.2 Service provisioning

After this framework has been set up, the service delivery process can be simplified due to the introduction of standardized interfaces (Figure E.2). External signalling at the UNI is directly forwarded to the call control (PM) that splits it into RSVP signalling for each domain (NO). Manual intervention is necessary to set up the connection completely only if no positive responses were received. After database update (AM), customer care is informed, and billing and alarm management are activated. At the end of this process, the client receives the delivery report.

E.4.2.3 Service cessation

In the GMPLS case, the cessation request is also received via the UNI. The cease process then triggers the sales department to assess the cessation request and trigger the billing and confirmation of cessation to the client. On the physical side, the network operation centre is requested to cease the physical connection. Once the connection is released, this is confirmed to the project management and the order is closed.

E.4.2.4 Service move or change

The GMPLS-modified move and change process is initiated by the customer requesting a move and change. The availability of resources and the conformity of this request within the SLA contract are checked automatically. If both have been answered positively the corresponding cease and provisioning steps are handled directly via the control plane. Manual intervention is only necessary where additional resources have to be deployed in the network or if the request exceeds the SLA framework. Finally, the customer is informed about the results.

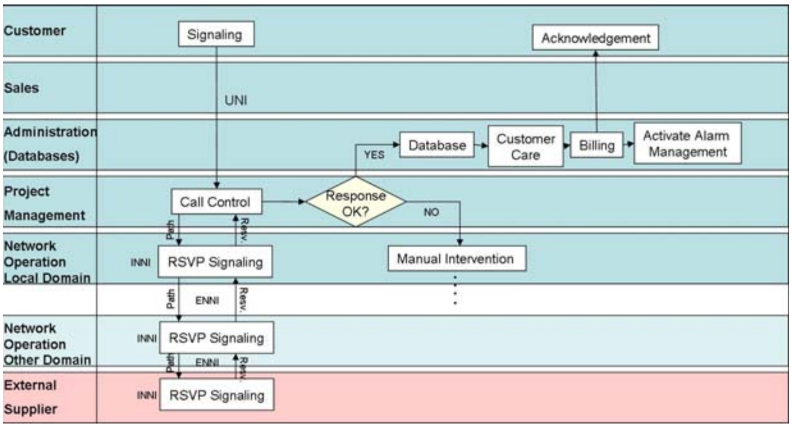

Figure E.2: service provisioning process with GMPLS

E.5 Quantitative Results

For each of the processes, costs have been assigned to the process steps (boxes in the figure) and a probability to the branches. We focused on labor costs, expressed in terms of hours required to carry out the task described in the box.

Then we calculated the hourly cost[9] of each kind of employee[10], and multiplied it by the number of hours. Summing up costs for all steps gives then an upper bound estimate of the overall cost of a given process.

The figures on which we based our calculations were obtained by means of interviews and surveys of several network operators[11]. A first analysis of these figures revealed two main types of operators. Indeed, some operators had high number of hours for the sales, administration and project management departments. On the other hand, another group of operators presented lower figures for these departments, whereas the figures for the other departments remained in the same range. We refer to the first type of operators as *incumbent* since they have usually heavier administrative procedures involving a bigger number of employees. By contrast, the second type is referred to as *new entrant*, having less administrative overhead and simpler project management procedures.

E.5.1 Incumbent

In the case of a typical incumbent operator (Figure E.3), the service offer process involves expensive sales and availability checks operations. In the end it is nearly as expensive as the service provisioning itself. The cease process involves nearly no work from project management and network operations centre, which explains why it is much cheaper. The move and change process is the combination of service offer, provisioning and cease (in principle, it is a little more expensive since it requires some more coordination).

Looking at the GMPLS-modified processes, we first notice that SLA negotiations are more expensive than the typical service offer. This is normal since the former includes some operations that are usually carried out in the service provisioning process (plan, install and configure equipment boxes). For a fair comparison, one needs to compare the combination of service offer and provisioning. In the case where GMPLS is used, project management and sales are involved only once - when the SLA is setup - leading to substantial savings. Another advantage is that the same SLA can serve for several services. So once the SLA is in place, provisioning several services with GMPLS costs much less.

[9] Costs for the company, not only the wages, as suggested in [E.7].

[10] Each department involved in the processes is composed of one type of employee except the Network Operations Center, where engineers, technicians and field technicians have been considered [E.7].

[11] For confidentiality reasons the company names of these operators are not disclosed in this paper.

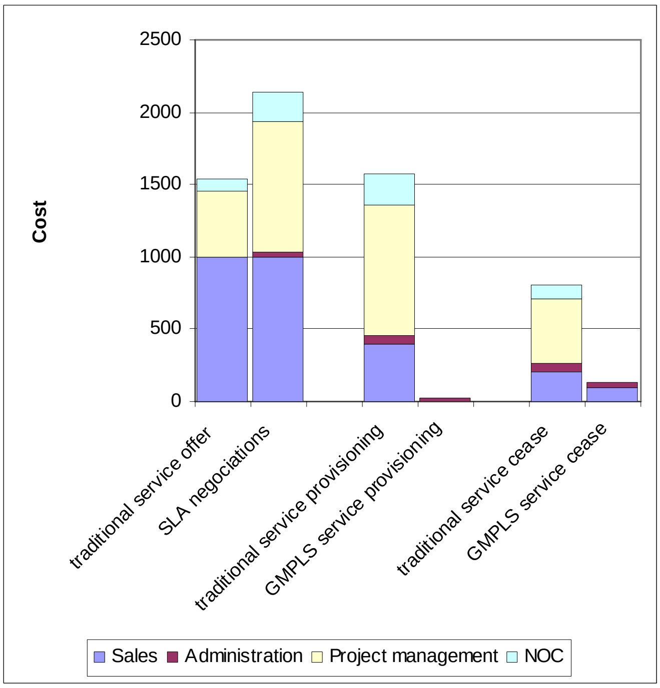

Figure E.3: cost comparison for incumbent

E.5.2 New Entrant

For new entrants (Figure E.4), we first see that typical processes are cheaper. This is normal since less administrative procedures and project management are involved. But we should not forget that this type of operator certainly owns less equipment and infrastructure and thus probably doesn't provide as many different types of services as an incumbent. Moreover, outsourcing parts of a connection to an external supplier is more frequent, e.g. access lines from a city carrier. In Figure E.3 and Figure E.4, the costs displayed do not include the cost of having part of a service going through an external supplier, since this can vary widely and depends on many parameters. But one has to keep in mind that the additional costs it induces (renting, more testing required at interconnection points, etc.) will certainly reduce the cost difference between incumbents and new entrants.

In any case, we see that also for new entrants GMPLS modified processes are cheaper and in the same proportion as for the incumbent.

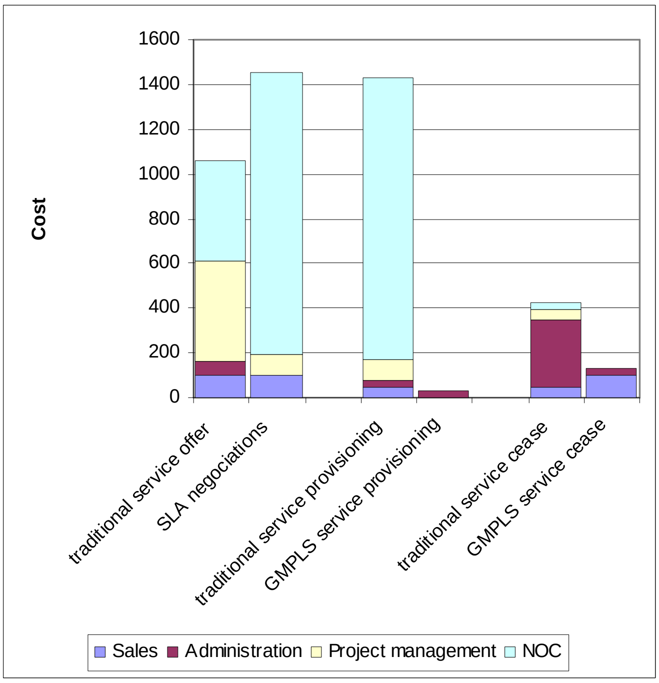

Figure E.4: cost comparison for new entrant

E.6 Summary and Conclusion

The investigations for this paper include a considerable high effort for surveys and interviews with multiple carriers. This allows going one step beyond the general claims of advantages of GMPLS. Quantitatively substantiated conclusions can be drawn, critically evaluating the real OpEx benefits of GMPLS.

Our studies show that most network operators' processes are similar and can be modelled quite generically. When looking at the typical efforts for these processes, there are major differences between incumbent operators and so called new entrants, which have much lighter business processes but also more complex technical processes since they have to resort to external partners more often. This is also the reason why new entrants are very often focusing on large customers and project business, where customized solutions with more technical efforts are required anyway. Incumbents in contrary have lean technical processes that allow providing standard services more easily.

However, interestingly for both types of operators OpEx effort and cost reductions in the order of 50% compared to traditional operations can be identified when introducing GMPLS.

Based on these results the introduction of GMPLS can generally be recommended to significantly reduce OpEx. This advantage can even be improved, if all network domains and all network layers support interworking GMPLS control planes and hereby also reduce the operational cost for end-to-end connections across multiple operators' domains.

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Regulation for Interconnection between Network Operators in a Liberalized Market

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Abstract

Interconnection between network operators in a liberalised market is essential for delivering services to end users. As the incumbent has a strong advantage compared to the new entrants, regulation is necessary for making sure that a competitive market can be established. Interconnection tariffs are used for protecting market shares by the incumbent and therefore have to be regulated by the national regulatory instance (NRI). Several cost models have been formulated for making sure that the tariffs reflect the real costs made by the operators for connecting the calls. In this paper, the legal framework formed by the EU and the Belgian government is explained, as well as the cost models that the NRIs have constructed. The most important part of this paper deals with the modelling of the market interaction between an incumbent and two new entrants, a cable operator and an alternative operator who is using the carrier select service of the incumbent, and this for situations with and without regulation. Our model

allows confirming that the use of cost models leads to lower interconnection tariffs for network operators as well as lower telephony prices for the end users.

Key words

interconnection tariffs, liberalization, regulation, cost models, telecom market

F.1 Introduction

Until the eighties most European telecom networks were owned by their government. The advantage of the incumbents is that they have already rolled out a complete network, covering a large area. Therefore, it is very difficult for new telecom players to enter the market. Large investments for a new network must be carried out and justified, and costs and inconveniences for the society such as breaking up the streets must be avoided. It would be easier if some of the existing infrastructure that the incumbent owns could be reused [F.1].

Interconnection is the physical linking of a carrier's network with equipment or facilities not belonging to that network. This is most common between two or more carriers who want to connect their customers with customers of the other carrier(s).

F.2 Legal Framework

To facilitate the entry of new network operators, the EU decided to introduce a framework for regulation [F.2] which describes a set of policies and directives the national regulatory instances (NRI) in the EU member countries should implement. In the Framework Directive, the competences and responsibilities of the NRIs, as well as the obligations of carriers with significant market power (SMP) are described. The latter are defined as: *"An undertaking shall be deemed to have SMP if, either individually or jointly with others, it enjoys a position equivalent to dominance, that is to say a position of economic strength affording it the power to behave to an appreciable extent independently of competitors, customers and ultimately consumers."* These obligations contain transparency, non-discrimination, accounting separation, access to, and use of, specific network facilities, price control and cost accounting obligations, further explained in the Access Directive. The Non-Discrimination Directive encloses the obligation to offer services and information to the other carriers at the same conditions as to its own partners or subsidiaries. Cost accounting obligations ensure that the incumbent cannot set its prices freely. These must be based on costs, raised with a fair investment return. This will be explained in the next section The Authorisation Directive describes how an internal market can be established for electronic communication networks and services. This must facilitate the entrance of new players on the telecom market. The Universal Service Directive ensures a liberalised market where a minimum number of services must be offered to all end users at a reasonable price.

In Belgium, Belgacom is the incumbent and only market player with SMP in fixed lines services. Belgacom is obliged to make reference offers with tariffs the other carriers must pay for services offered by the incumbent. The BRIO reference offer [F.3], approved every year by the BIPT (the Belgian NRI) encloses several interconnection services offered by Belgacom. *Terminating Access Services:* Phone calls from carriers' end users to Belgacom customers are handled in the access points and terminated in the Belgacom network. *Collecting Access Services:* Belgacom end users could make use of services of other carriers. The conversion is put through on the other carriers' network in the closest access point and terminated in this network or put through again on the Belgacom network. Examples of this service are carrier pre-selection and carrier selection. In the first case, all conversations will be redirected automatically to the alternative operator's network. In the latter case, the end user can choose to make a connection via the alternative operator's network through a code. If the user does not use the code, Belgacom will terminate the call. *Transit Service:* Belgacom will transit a call, originating in the network of operator A, over its own core network and passes through the call to the network of operator B, e.g. termination of international calls.

F.3 Cost Model

The European Directives have dictated that the NRIs must work out cost models by which the network operator(s) with SMP must justify that the interconnection tariffs they are asking to the other operators are reflecting the true costs made for offering this service. A cost model is made up of two parts: cost modelling and cost allocation. Several approaches are followed by the different NRIs: top-down (TD) versus bottom-up (BU) cost modelling [F.4]. Two important cost allocation schemes are Fully Distributed Cost allocation and Incremental Cost allocation. The Fully Distributed Cost (FDC) method allocates all costs to all services. Direct costs are immediately attributed to each cost consuming service, shared/joint and common costs are attributed through the use of allocation keys. The hardest part when using this cost-base is to find the right allocation key for all costs. The tariff for a service thus includes all the incurred costs by this service [F.1]. The Long Run (Average) Incremental Cost (LR(A)IC) method only measures the change in total costs when a substantial and discrete increment or decrement in output is generated [F.5]. Long run means that capital investments or disinvestments are possible. Average means that the fixed cost is averaged over the total of all increments. This allocates the direct, shared and common costs to the various services depending on used definition of an increment. Economies of scale will be playing an important role in the allocation of shared/joint cost, resulting in a smaller part of attributed costs than in FDC. The LR(A)IC method is mainly used in the bottom-up approach (e.g. introduction of a new service or an increase in output of one service).Finally, also the manner in which the tariffs are deduced from the model is also important. Is the model developed by the incumbent and audited by the NRI or is it directly developed by the NRI.

In Belgium, the NRI develops a TD FDC model in collaboration with the incumbent as well as a BU LRAIC model. The TD model, adjusted by the results of the bottom-up model, is used to determine interconnection tariffs [F.6]. Another method is used in Denmark where the incumbent must develop a top-down model and the entrant a bottom-up model, both LRAIC based [F.5]. Although in both countries the market share of the incumbent is the same, Denmark has far lower interconnection tariffs [F.7].

F.4 General Market Interaction Model

In the next parts, we will aim to model the influence of regulation on market share and profit of network operators in a fictitious telecom market. Based on the described market situation, the model will be elaborated, starting from the model described in [F.8]. Some assumptions had to be made for defining the fictitious market: all operators are offering only one product (telephony service over fixed lines), the market is homogeneous (only the residential market), price discrimination will not be applied by the operators, demand is inelastic, consumers will choose the operator with the lowest price, and telephone behaviour of the customer is random (no network preference). Three players are interacting in a simplified market. The incumbent (*I*) owns a PSTN/ISDN network and holds a position of SMP in the considered market. Two new players are entering the incumbent's market. A cable operator (*C*) owns a complete cable network, which has the same functionalities, quality and range as the incumbent's network, and can reach all end users on its own. The alternative operator (*A*) only possesses a core network and uses the carrier select services of the incumbent to reach its end users. Two services are offered within the model, a termination service and a carrier select service. Only the cost of the access network is taken into account. Fixed cost includes the equipment and network costs. Variable costs are a weighted average of all the recurring operational and capital costs the operator has. In our model only the termination and network costs are relevant.

I has the largest costs due to the historic (less efficient) dimensioning of the network. We assume that the access network of *C* is more efficient which results in lower costs. *A* has no fixed cost as it is using the incumbent's access network. *A* is also the most efficient player resulting in the lowest network costs, but its termination costs will depend on the interconnection costs that are asked by the other operators. The total cost for an end user is the fixed cost plus (cost per minute multiplied by number of minutes) and can be viewed in Figure F.1 for the incumbent where the fixed cost equals the subscription cost, and the variable costs are related to the number of minutes called. However the cost function of the new entrants must be raised with a stickiness coefficient (z) that represents the extra costs a client must pay for switching from the incumbent to another operator (Figure F.2). These contain real costs (e.g. switching subscription from *I* to *C* or *A*) as well as perceived costs (e.g. lack of reputation, quality). This factor will decrease when more customers have switched operator and perceived quality and trust have increased.

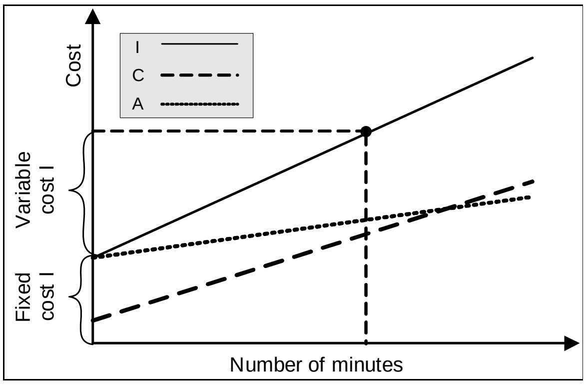

Figure F.1: cost for customer without stickiness coefficient

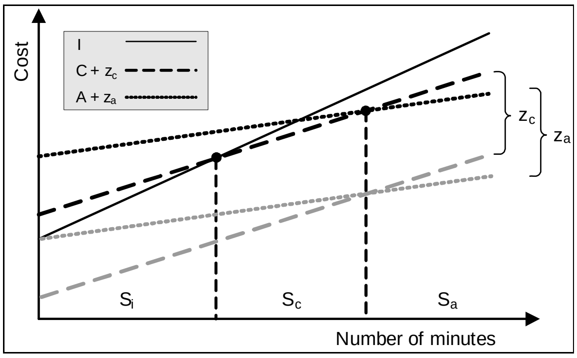

Figure F.2: total cost for customer & market shares for operators I, A and C

An operator's market share is that part of the market where he can offer the lowest total price to the end user, determined by his subscription cost and cost per minute. The market share for each operator can be deducted from the intersections between the different total cost curves (Figure F.2). The real profit for *I*, *C* and *A* consists of the profit margin on subscription, profit on the difference between the amount of people calling over the network minus the interconnection costs for calls that terminate in another operator's network, and profit at the expense of other operators for people calling to the network in addition to which interconnection costs can be asked. For *I*, extra revenues are generated by *A* which uses its carrier select service.

F.5 Market Interaction without Regulation

Without regulation, *I* determines the termination and collecting tariffs. When I sets this latter tariff very high, *A* will not be able to gain market share because *I* has direct influence on the fixed cost of *A* (A_1 to A_2 in Figure F.3), which results in a complete control of the market by *I*. For *C*, the variable costs will be high due to the high tariffs *I* imposes on the other operators for interconnection, ensuring that the market share of *C* will be limited (C_1 to C_2 in Figure F.4). *C* can only create a customer base by adjusting its fixed cost, and this by asking no or little subscription cost to the customer and only charging per minute (C_2 to C_3 in Figure F.4). *C* will have to focus on end users who are calling few minutes for enlarging its customer base, by which the stickiness coefficient will decrease and the operator will be able to lower its cost function below this of *I.*

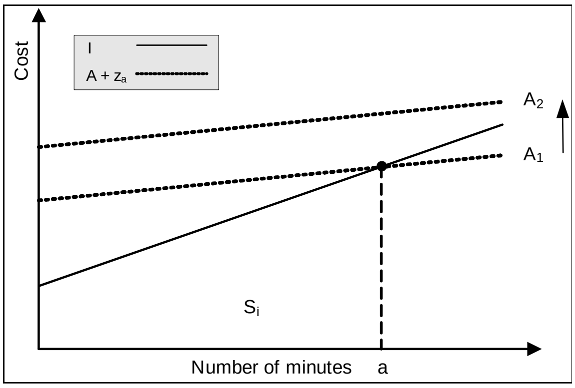

Figure F.3: alternative operator A's market share without regulation

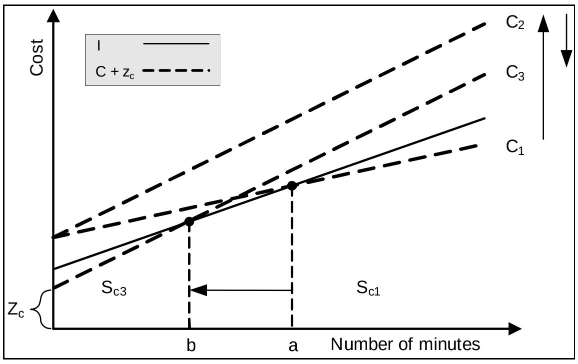

Figure F.4: C's market share without regulation

F.6 Market Interaction with Regulation

Regulation is thus necessary to ensure that a competitive market can be created. Two different scenarios will be discussed: a market where new players are entering and a more mature market where these new players have gained a reasonable market share.

In the first case, interconnection costs are calculated by *I* via the FDC allocation method. In this case the carrier select tariff equals the fixed cost of the incumbent. The fixed cost of *C* is still lower than that of *I*. The total interconnection cost *A* must pay to *I* and *C* will be higher than the revenues it receives from calls terminating on its network. This is also the case for *C* but due to its enlarging customer base, this gap will be decreasing whereby its cost function will lower. The best strategy *A* can implement is to lower its cost per minute by which it will gain market share for customers who are calling much. *C* will set its subscription cost equal to the cost for its fixed cost plus a profit margin. The variable costs will be lower than *I*'s because its network is more efficient (Figure F.5). Profit for *I* will only be generated by its own operations, not at the expense of other operators as interconnection tariffs are based on real costs. *C* can make profits at the expense of other operators like *I* and *A* because it can set its own termination cost based on its real costs, which can be higher than *I*'s. The regulator can also impose LR(A)IC as regulatory cost allocation method. The interconnection costs will only be a fraction of the costs charged with FDC regulation. The carrier select cost will decrease, leading to a lower fixed cost for the alternative operator. The fixed cost for *C* remains the same. The interconnection tariff will also decrease, leading to a less steep slope in the cost functions of *C* and *A*. If both operators implement the strategies discussed for FDC, both will gain market share at the expense of *I*. *A* could also decrease the subscription cost by which its customer base will grow larger (Figure F.6).

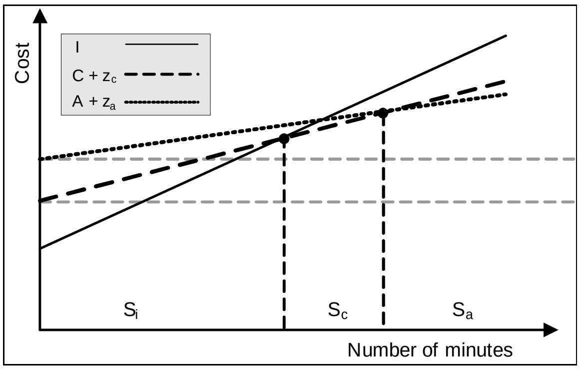

Figure F.5: FDC regulation

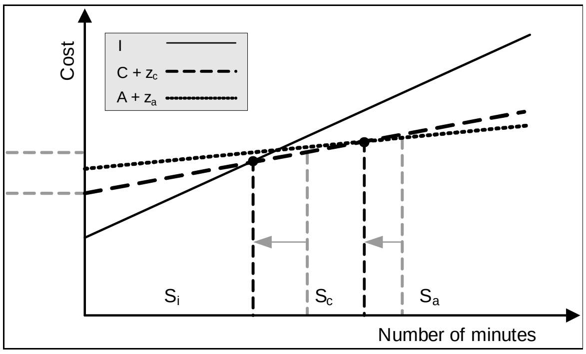

Figure F.6: LRIC regulation

As time passes, the entrants have built up a customer base and market reputation, which results in a decline of their perceived extra costs. More market share can be acquired, which forces the incumbent to take action. Figure F.7 shows the decreasing cost functions of *C* and *A* and loss in market share for *I*. At first *I* will give up its monopolistic profits and when this is not enough, it will be forced to reduce costs. This can be on three fronts. If *I* lowers the termination costs, *C* and *A* will benefit because they could lower their cost per minute they charge their customers. If *I* lowers its fixed cost, *A* will benefit because a lower collecting cost will be paid. *I* will only gain by decreasing its network costs because this has only effect on its cost function without advantages for the other players. This will result in the preservation of its market share (Figure F.8).

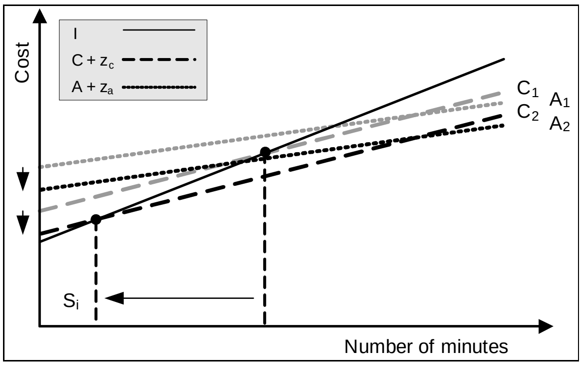

Figure F.7.: decrease in stickiness coefficient for cable operator C and alternative operator A

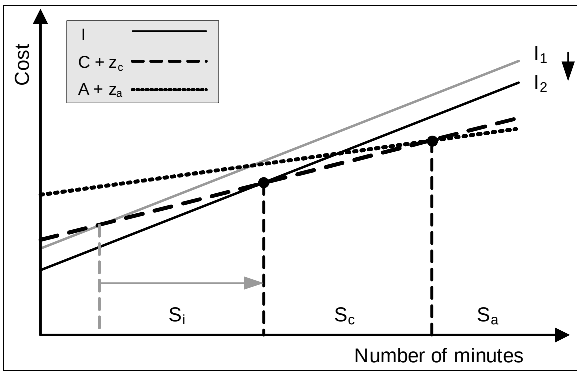

Figure F.8: incumbent I lowering profits and costs

F.7 Conclusion

In this paper, we have presented a model for studying the effects of terminating and collecting tariffs in a telecom market with three players. Most models in literature only deal with two players, e.g. [F.9]. Our model allows to indicate in a straightforward way that regulation is essential in the telecom market. Without regulation, an incumbent is likely to boycott any new entrant. A cost model is imposed by the NRI's for calculating interconnection tariffs based on the real costs. LRIC cost allocation leads to lower tariffs as it doesn't take into account the incumbent's network inefficiencies, opposed to the case of FDC. Lower interconnection tariffs will increase competition. The entrance of new players forces the incumbent to analyze and reduce its inefficient costs, leading to lower tariffs and lower prices for all end users.

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