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TRANSMISSION INVESTMENTS: CONCEPTS FOR EUROPEAN COLLABORATION IN PLANNING AND FINANCING

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Transmission investments:
Concepts for European collaboration in planning and financing

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Abstract

European transmission grids face a huge challenge over the next decades. Driven by European energy policy goals aiming at sustainability, competitiveness and security of supply, massive investments in the transmission grids are required to enable these goals and fulfill its tasks at the heart of the European power system. This challenge clearly plays at a larger level than the traditional national scale requiring stronger regional or European collaboration in planning and financing of investments.

This thesis firstly performs an assessment of the current framework and analyzes how the European interest is integrated in the current investment planning, financing and decision-making process. It is observed that the national level remains crucial and the incorporation of European goals is limited. Hence, an area of tension exists between both levels.

Next, a formal framework is developed for investigating this wedge. Three collaboration concepts are defined. They differ in the assumed level of collaboration between the national decision-makers and in the assumed incorporation of European goals. The three concepts are modelled mathematically as quadratic programs, mathematical programs with equilibrium constraints or equilibrium problems with equilibrium constraints and tested on small examples using standard solution methods. All models assume a static treatment of the time horizon, no uncertainties and a reactive planning approach with respect to generation investments. A perfectly competitive market with nodal pricing using a DC load flow approximation for modelling the network flows is explicitly modeled in each concept. In the objective function only economic welfare is maximized. Comparison of the concepts allows drawing conclusions on how different forms of collaboration influence the ultimate investment outcome.

Samenvatting

Het Europese hoogspanningsnet staat voor enorme uitdagingen de komende decennia. Gedreven door Europese energiedoelstellingen inzake duurzaamheid, interne markt en bevoorradingszekerheid, zijn gigantische investeringen in het netwerk noodzakelijk om het elektriciteitssysteem, waarin het een centrale plaats inneemt, toe te laten die doelen te verwezenlijken en de opgelegde taken te vervullen. Deze uitdagingen overstijgen duidelijk het klassieke nationale niveau en vereisen een sterkere regionale en Europese samenwerking inzake planning en financiering van investeringen.

Vooreerst wordt in deze verhandeling het huidige kader gewikt en gewogen en wordt geanalyseerd hoe vandaag het Europese belang in rekening wordt gebracht bij de planning en financiering van investeringen en tijdens het beslissingsproces. Dit leidt tot de vaststelling dat het nationale niveau een cruciale rol blijft spelen en dat Europese doelstellingen slechts in beperkte mate doorwegen. Er is bijgevolg een spanningsveld tussen deze twee niveaus.

Vervolgens wordt een formeel kader ontwikkeld dat toelaat deze wig te onderzoeken. Drie concepten voor samenwerking worden gedefinieerd. Zij verschillen in de veronderstelde mate van samenwerking tussen nationale beslissingsnemers en hoe de Europese doelen in rekening worden gebracht. De drie concepten worden wiskundig gemodelleerd als kwadratische programma's, mathematische programma's met evenwichtsvoorwaarden of evenwichtsproblemen met evenwichtsvoorwaarden en geïllustreerd aan de hand van kleine voorbeelden die worden opgelost gebruikmakend van standaard oplossingsmethoden. Alle modellen veronderstellen een statische behandeling van de tijdshorizon, geen onzekerheden en een reactieve benadering ten op zichte van investeringen aan de productiezijde. Een markt met perfecte concurrentie en een knooppuntgebaseerd prijsmechanisme wordt voorop gesteld waarbij de vermogenstromen in het net gemodelleerd worden via een DC load flow benadering. In de objectieffunctie wordt enkel de economische welvaart gemaximaliseerd. Op basis van vergelijking van de concepten kunnen conclusies getrokken worden aangaande hoe verschillende vormen van samenwerking de uiteindelijke investeringen kunnen beïnvloeden.

Voorwoord

Na ruim vijf jaar ligt dit boekje dan eindelijk op tafel. De volgende hoofdstukken zijn het resultaat van het gevoerde onderzoek en geven in zekere mate ook het afgelegde parcours weer. Er is echter een groot hiaat: het menselijke luik. Velen hebben me de voorbije jaren steeds gesteund en geholpen. Hoog tijd dus om te zorgen dat dit boekje een volwaardig verslag van de voorbije tijd kan zijn en om wat menselijke gezelligheid en warmte toe te voegen aan de veeleer droge analyses en resultaten.

Alles begon in de Leuvense binnenstad met hoorcolleges over energie die mijn interesse wekten. De reden voor die interesse, zo ontdekte ik later, is de combinatie van een honger naar iets meer techniek en een voorliefde voor netwerkeconomie. Uiteindelijk belandde ik in een groepje van handelsingenieurs op Electa, een bastion van ingenieurs. De spil in dit hele verhaal is Ronnie. Hij heeft me niet enkel de kans gegeven om op Electa te werken. Gedurende vijf jaar heeft hij tal van kansen gegeven: de kans om met interessante partners samen te werken, de kans om een stukje van de wereld te zien (incl. de Vurige Stede), de kans om fouten te mogen maken en natuurlijk ook de kans om met hem als promotor aan dit doctoraat te kunnen werken. Ik heb op die manier veel kunnen leren en niet enkel over het energievraagstuk, maar bijvoorbeeld ook dat vele problemen een menselijke kant hebben (tot zover de illusie van het rationele individu) en dat ingenieurs best een gezellig volkje zijn. Bedankt voor alle kansen! Ik wacht enkel nog op de kans om ooit in een Duffels bioscoopcomplex een film op het witte doek te zien, maar ja...

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ook met veel warmte, begrip, steun en interesse. Het geluk staat niet enkel aan mijn zijde, ik ben omsingeld. Bedankt mama, papa en Linde om gedurende al die jaren interesse te tonen en mij op alle mogelijke manieren te steunen.

Op het onderzoeksfront kwam warmte en gezelligheid vooral van lotgenoten, de collega's. Enkele tassen zijn weliswaar gesneuveld, maar de goede sfeer bracht ons vaak aan de koffiemachine. Miko is er - geheel onterecht - wel bij gevaren en ook de producent van de soldatenkoek heeft geen recessie gekend de voorbije jaren. De groep koffiedrinkers en de locatie zijn doorheen de tijd weliswaar veranderd, maar aan de gezelligheid (en de frequentie) is nooit geraakt.

Enkele collega's hebben zeker hun stempel gedrukt op mijn Electa-tijd. In de eerste plaats zijn er mijn bureaugenoten. Door enkele stoelendansen heb ik het plezier gehad met velen een bureau te delen, maar Leen en Cedric zijn vaste waarden en vaste discussiepartners over alles wat wel en niet met energie of beroemd en bizar te maken heeft. Het was aangenaam toeven op ons bureau. Verder wil ik ook David bedanken als partner in crime. Zijn inbreng in mijn doctoraat is groot, onder andere dankzij de modelling Fridays en de bijhorende partyschotels en ijsjes in de Lodge. Maar ook de organisatie van de quiz zo nu en dan, het bezoek aan RTE en de droppings samen met Valentijn waren toppers. Ook alle andere collega's zijn stuk voor stuk fijne mensen om plezier mee te beleven tijdens een voetbalmatch, in Londen aan zee en in Limburg, op vrijgezellenweekend, op een activiteit van Guy Ener, op YEEES, op conferentie, op café... Ook van de samenwerking in de powergroep of in het labo heb ik enorm genoten. Het was een fijne tijd op Electa.

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Een welgemeende dankuwel!

Patrik

Mechelen
22 december 2011

List of symbols and abbreviations

Symbols

$\blacksquare^{max}$	Maximum	
$\blacksquare^{init}$	Initial	
$\blacksquare^{*}$	Optimal	
p	Period index	
n, b	Node index	
t	Generation technology index	
l	Line, corridor index	
z	Zone index	
Ω^P	Set of periods	
Ω^N	Set of nodes	
Ω^T	Set of generation technologies	
Ω^L	Set of lines	
Ω^Z	Set of zones	
T_{XY}	Transmission link between nodes X and Y	
T_p	Duration of period p	[h]
$A_{n,p}$	Intercept demand function in node n for period p	[€]
$B_{n,p}$	Slope demand function in node n for period p	[€/MW^2]
$d_{n,p}$	Demand in node n in period p	[MW]
$C_{n,t,p}$	Intercept generation cost function in node n for technology t in period p	[€]
$D_{n,t,p}$	Slope generation cost function in node n for technology t in period p	[€/MW^2]
$g_{n,t,p}$	Generation in node n for technology t in period p	[MW]
CL_l	Annual line cost for line l	[€/(MW.km.year)]
LN_l	Length of line l	[km]
x_l	Invested capacity in line l	[MW]
θ_n	Voltage angle in node n	
INC	Network incidence matrix with rows indicating lines and columns indicating nodes	
H_l	Susceptance of line l	[S]

$f_{l,p}$	Flow on line l in period p	[MW]
F_l^{max}	Flow limit for line l	[MW]
$G_{n,t,p}^{max}$	Maximal generation output in node n with technology t in period p	[MW]
$\Lambda_{n,p}$	Long run nodal price in node n in period p	[€/MWh]
$\lambda_{n,p}$	Short run nodal price in node n in period p	[€/MWh]
NC_l	Number of circuits in corridor l	
y_l	Dummy variable indicating wether line l is built or not	
CC_l	Annual cost of building line l	[€/year]
WF_z	Welfare in zone z	[€/year]

Abbreviations

AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
BEMIP	Baltic Energy Market Interconnection Plan
CR	Congestion Revenues
CS	Consumer Surplus
DC	Direct Current
DCOPF	Direct Current Optimal Power Flow
Dena	Deutsche Energie-Agentur GmbH
EC	European Commission
EEA	European Economic Area
EERP	European Economic Recovery Plan
EIP	Energy Infrastructure Package
ENTSO-E	European Network of Transmission System Operators for Electricity
EPEC	Equilibrium Problem with Equilibrium Constraints
ERGEG	European Regulators Group for Electricity and Gas
ETSO	European Transmission System Operators
EU	European Union
GA	Genetic Algorithm
GNEP	Generalized Nash Equilibrium Problem
ISO	Independent system Operator
ITC	Inter-TSO Compensation mechanism
KKT	Karush-Kuhn-Tucker
LMP	Locational Marginal Price
LP	Linear Program
MIP	Mixed-Integer Program
MIQP	Mixed-Integer Quadratic Program
MPEC	Mathematical Program with Equilibrium Constraints

NEC	Net Export Curve
NLP	Non-Linear Program
OPF	Optimal Power Flow
Pareto CA	Pareto-planner with Cost Allocation
Pareto w/o CA	Pareto-planner without Cost Allocation
PIP	Priority Interconnection Plan
PS	Producer Suplus
QP	Quadratic Program
RTD	Research and Technology Development
TEN-E	Trans-European Energy Networks
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UCTE	Union for the Coordination of the Transmission of Electricity

General remarks

- The capitals used to indicate points in a figure in chapters 3 and 5 are not listed above. It should be clear from the text that it are not the symbols above which are referred to in these cases. Referral only occurs within a single section and not throughout the text.
- Greek symbols always indicate dual variables. They are not specifically listed in the symbol list, except for θ, λ and Λ which are used to indicate voltage angles and short and long run nodal prices.

Contents

1

Introduction

This introductory chapter intends to familiarize the reader with the topic investigated, explain how the research materialized over the previous years and how the text is structured. A brief description of the context and the motivation of the performed research is given in section 1.1. The road towards this thesis is described in section 1.2. Section 1.3 provides a guide to the reader by unfolding the structure of the thesis.

1.1 Context and motivation

This thesis deals with electricity transmission investment planning and financing in Europe. On the one hand Europe (and in particular continental Europe) is characterized by a single interconnected transmission network connecting generation facilities and demand centres. It serves as a backbone for the entire power system and combines multiple tasks ranging from keeping the lights on over accomodating a sustainable and low-carbon energy mix to facilitating international trade. On the other hand it should not be overlooked that this interconnected network is a patchwork of different national systems. Those systems are built and financed nationally. Many assets still date from an era when a European vision was limited to mutual help in case of difficulties in generation. Although there have always been clear benefits to interconnect different national grids (e.g. higher reliability, better economic mix), the call for a better integrated European network has never been heard louder than today.

Indeed, the transmission network faces a huge investment challenge for the next decades. Not only are there several assets that approach the end of their lifetime and need to be replaced[1], but also how the network is planned, what it is planned for and how it will be financed and used is undergoing drastic changes. Whereas in the previous years the national level used to play the central (if not the only) role, the regional and European levels are more and more coming into the picture. Recent developments in European legislation and a renewed intrest in overlay grid concepts and 'European electricity highways' are visible manifestations of this trend.

This transition from a nationally oriented approach to network investment planning and financing to an approach inspired by European-wide goals and challenges is not straightforward. The historical frameworks and decision processes are not fully adapted to this new context and need to be redesigned. This redesign and the question how different national decision-makers can collaborate in a European context, is the main motivation for this thesis. This thesis and its results can feed the debate with solid arguments. In particular in the field of transmission investments, a momentum is reached with the Third Package going live and a new infrastructure package on the drawing board. This research can provide policy-makers with appropriate guidance for future choices.

1.2 Road towards this thesis

Transmission investments have been a hot topic over the last years. The number of research projects in this area is significant, both from an academic and industrial point view. Several projects have given shape to this thesis. Especially the research question itself, but also the ideas for how to approach the question originate from such projects.

A first project dealing with cross-border investments took place in collaboration with a merchant transmission investor. Besides the pecularities arising from the merchant nature of a project (e.g. specific European legislation, competition assessments and the issue of determining the 'optimal' investment capacity), it allowed a close look at the potential of congestion revenues in the European context. Obviously, financing, risk and profit are very important for a third party merchant

[1] Ageing assets and replacement investments are not dealt with in this thesis as this is considered 'business as usual' and not linked to the specific European context of interconnected national grids.

investor. Additionally, this collaboration was also an early introduction to today's topic concerning overlay and offshore grids.

A second project in collaboration with a European transmission system operator (TSO) focused in particular on the inter-TSO compensation (ITC) mechanism and how it could (or could not) contribute to investments. Here the issue of incentives for regulated transmission system operators came into play. Apart from a detailed analysis of the ITC mechanism this project also served as a first eye-opener on the misalignment of investment incentives.

This issue was further deepened in a third project with the same TSO where the broader cross-border framework was analyzed and in particular the impact of the Third Legislative Package was investigated. The results of this project are at the root of chapter 2 and the research questions formulated at the end of that chapter.

In addition, several other research projects done by the research group Electa at K.U.Leuven on the increasing European impact served as source for inspiration. In particular research on market coupling, the coordination of power flow controlling devices and the design and integration of balancing markets in a European context helped in setting the scene [1–3].

1.3 Thesis overview

The thesis is structured around one central theme: collaboration of different transmission planners in a single interconnected network.

In *chapter 2* it is analysed why this topic is relevant and how the current European framework performs. Building further on the short motivation of section 1.1, it sets the scene, describes flaws in the current framework and distilles concrete research questions. Whereas chapter 2 adopted a policy viewpoint for determining research questions, *chapter 3* is used to set up a formal framework allowing an in-depth analysis of the research questions in the following chapters. The framework enables the identification of three concrete collaboration concepts.

Before entering into the concrete modelling of the different collaboration concepts defined in chapter 3, a literature overview on transmission planning models is provided in *chapter 4*. Not only does this chapter identify several general design options for transmission planning models, it also investigates the state-of-the-art on how a situation with multiple transmission planners is dealt with in the academic literature. Finally, the literature review allows determining an appropriate set of general assumptions for all models presented in the following three chapters.

Backed up by the literature review and assumptions made in chapter 4, the three collaboration concepts defined in chapter 3 are described, modelled and illustrated in *chapters 5, 6 and 7.* The internal structure of these chapters is identical. The sequence of these chapters is chosen in such way that the mathematical complexity increases and is presented in a logical way in order to facilitate a more easy access for readers who are not familiar with concepts from operations research. Additionally, a decreasing degree of collaboration can be noted when moving from chapter 5 to chapter 7.

Comparison of the three different models allows answering the research questions. The answers are formulated throughout the different chapters whenever they occur as a result of the performed analysis. They are recapitulated in *chapter 8* emphasizing the link with the policy analysis in chapter 2. In addition, recommendations for further research are made.

2

European transmission investment framework: ready for the challenge?

This chapter positions this thesis in the European energy infrastructure debate. Starting from the ongoing policy debate and a reality check, the research questions are distilled.

In section 2.1 it is argued that there is a clear electricity transmission investment challenge. Moreover, it is illustrated that this challenge is a direct consequence of European energy policy. Additionally, it is suggested that the challenge goes beyond the typical national level of decision-making. After these observations, it is analysed in section 2.2 whether the current European framework for cross-border investments is able to cope with this challenge or not. For planning, regulatory oversight and financing, it is checked whether or not the European nature of the challenge is adequately incorporated. Based on the findings of the first two sections conclusions are drawn in section 2.3 and from these conclusions relevant research questions are distilled. These questions are tackled in this thesis.

2.1 European transmission investment challenge

The purpose of this section is twofold. Firstly, in section 2.1.1 the aim is to indicate the origin and scale of the transmission investment challenge Europe is facing. It is argued that European policy is clearly at the root of the challenge and that it goes beyond national borders and historical network boundaries. Secondly, the challenge is given a face by providing a brief look into the results of two recent studies. It is important to gauge the size of the challenge before further analyzing it and tackling underlying problems. This is pursued in section 2.1.2.

2.1.1 Policy-driven investment needs

Since 2007 the European Union (EU)[1] by the voice of the European Council, the European Commission and the European Parliament has repeatedly expressed clear goals with respect to energy policy. A triangular vision is endorsed. Sustainability, security of supply and a competitive and affordable energy supply are put forward [4]. This general threefold goal heavily relies on adequate energy infrastructure, including electricity transmission networks [5]. Transmission networks are considered the backbone of the energy infrastructure and prerequisite for meeting the goals. Although the three goals are intertwined, for each of them it is highlighted how it poses a challenge for the transmission network.

- A sustainable energy future is strived for by reducing or even eliminating the emission of greenhouse gasses. The electricity sector is considered key for delivering on this goal. Europe set a 20% target for renewable energy by 2020. This implies that a share of more than 30% of electrical energy should be produced from renewable energy sources [6].[2] Wind energy is already a major contributor and its share in the energy mix is thought to further increase. Locations with favourable conditions for developing wind energy are often remotely located and not equally spread over Europe. Offshore and coastal areas around the North Seas and the Baltic Sea are best suited to host wind farms. However, these areas should be connected to the transmission grid in order to bring the energy to the demand centres. An extra challenge is

[1] Although the European Union does not cover all countries in Europe and is limited to its 27 Member States, in this thesis no further distinction is made. The geographic scope is not always the same when different legislative texts, frameworks and associations are considered. For instance, the EU covers a different area than the European Economic Area (EEA) or than European Network of Transmission System Operators for Electricity (ENTSO-E). The differences and implications coming from this patchwork are not studied in this thesis and the presented analysis remains valid without distinguishing between them.

[2] The debate concerning the role of nuclear energy in a low-carbon future is not touched upon in this thesis but is obviously an important element in the discussion of a sustainable energy future.

put on the transmission network due to the variable output profile of wind energy and other renewable energy sources as e.g. photovoltaics. When no wind is available, other generation facilities should ensure the balance with demand for electrical energy. Substantial investments in new connections and reinforcements are required. For instance, a study focussing on the German context identified the need for a tremendous amount of new transmission investments required to accomodate further wind power development [7]. The challenge for the transmission network when wind energy is massively integrated is studied at European scale by [8]. In particular, a strong focus was put on the interconnections between the different countries. A similar result emphasising the need for transmission investments is reported.

- Aiming for a secure energy supply is a goal playing at different fronts. Firstly, there is the long-term energy mix and the dependence on primary energy supplies. Diversification in the energy mix with the aim of lowering the dependence of natural gas from outside Europe is a good example. The development of renewable energy based on locally available resources is another route followed in this process for diversification. The electricity transmission grid again plays a central role. On the one hand there obviously is the challenge of connecting the newly developed renewable energy plants, but on the other hand at larger scale an adequate electricity transmission grid can increase the possibilities for solidarity between different countries. The burden for diversification can be shared by tapping into the best suited locations. Secondly, as already hinted upon in the previous paragraph, the transmission grid is the backbone for ensuring a short-term secure and reliable electricity supply. Balancing demand and supply at European scale requires sufficient interconnection capacity between the different national grids [3].

- The third goal pursues the establishment of a single European energy market with the purpose of ensuring a competitive and affordable energy supply. Electricity sector reforms taking off in the nineties introduced significant changes with this goal in mind. The results of the Sector Inquiry published by the European Commission in 2007 identified several obstacles impeding a genuine European electricity market to become a reality [9]. A lack of investments in the transmission network was one of the elements. Persistent congestion on several interconnections resulting in diverging prices between various national markets should be alleviated by transmission investments. In general, by investing in the network and increasing available transmission capacity for commercial transactions, a level playing field is created and new entrants can more easily access the market. More fundamentally, a better interconnected network allows benefitting to the full extent of the cheapest electricity generation resources and avoids the use of expensive power plants in congested areas.

Not only are the goals formulated at the European level, their nature suggests that a European or at least coordinated approach is required for attaining them in a cost-effective manner (e.g. [10]). Several of the challenges identified above such as accomodating massive wind power development, balancing demand and generation, long-term solidarity and interconnecting markets go beyond the national level. Although this level used to be (and still is) the main level for decision-making and the subsidiarity principle should not be questioned, it at least appears beneficial to take the challenge to a level with a larger geographic scope and to install a framework for this collobaration with solid instutions and correct incentives for all parties involved. This issue is further explored in this thesis with respect to planning and financing of transmission investments.

2.1.2 Gauging the challenge

In the previous section it is discussed that all three European energy policy goals require a strong grid and therefore new investments in it. The aim of this section is to sketch an image of the size of the challenge. Results of two recent studies are referred to for providing an indication of the technical and financial challenge.

It is already highlighted that Germany requires significant transmission investments in order to fulfill its needs with respect to wind power for the year 2020. A study conducted by Dena[3] found that in Germany alone about 1700 km of additional routes in the transmission grid are required when state-of-the-art technologies[4] are applied and about 3600 km without these technologies [7]. The latter amount is more than the total number of kilometers installed in Belgium in 2010 at 150, 220 and 380 kV (cables and overhead lines).[5] Preparing the German network would require 1.617 billion € per year until 2020 for the case with state-of-the-art technologies and 0.946 billion € per year until 2020 without these technologies.[6]

For Europe as a whole the challenge is obviously larger. In 2010 ENTSO-E published a first pilot Ten-Year Network Development Plan (TYNDP). In this plan the European-wide transmission investments needs are assessed. A total length of 35300 km of new connections are identified. Additionally the upgrade of 6900 km of existing connections is considered necessary. Financially this boils down to an investment challenge during the next five years of 23 to 28 billion €. Note that the TYNDP only looks ten years ahead. Hence, on the longer term the investment challenge is even greater. For instance, offshore networks like a North Seas grid are not yet taken into account.

[3] The Deutsche Energie-Agentur GmbH (Dena) is the German Energy Agency. It is the second time in five years that Dena investigated the transmission impact of German wind power.

[4] In particular high temperature conductors are assumed [7].

[5] According to [11] 891, 297 and 2435 km are installed at respectively 380, 220 and 150 kV.

[6] The financial numbers are annuities assuming typical asset lifetimes for Germany [7].

From these two examples it should be clear that the investment challenge is huge, not only in terms of lines to be built but also when the price tag is taken into account.

2.2 Analysis of the current European framework

In this section the European framework dealing with transmission investments is analysed. The focus lies on all cross-border aspects. Purely national issues (e.g. national tariff design) are not discussed. The current framework is by large the result of the Third Legislative Package (further called 'Third Package'). With respect to electricity, three documents are of particular importance: Regulation (EC) No 713/2009, Regulation (EC) No 714/2009, and Directive 2009/72/EC [12–14]. They are taken as a starting point for the analysis. Other elements of the European framework like the Transeuropean Energy Networks (TEN-E), the inter-TSO compenstion (ITC) mechanism and the European Economic Recovery Plan (EERP) are also part of the analysis.

Additionally, the legislative proposals recently launched by the European Commission on trans-European energy infrastructure are investigated. After a blueprint for an integrated European energy network published in November 2010 [5], an infrastructure package including proposals for a new European Regulation on trans-European energy infrastructure [15] and a more general Regulation on network infrastructure (incl. broadband, transport. . .) [16] is published on 19 October 2011 (further called 'Energy Infrastructure Package (EIP)'). Note, however, that these proposals are not yet final and currently only reflect the European Commission's viewpoint.[7] The Member States and the European Parliament can have different opinions and the ultimate outcome is uncertain. As a consequence, these proposals should be carefully dealt with.

The analysis is split in three parts: planning, regulatory oversight and financing.

2.2.1 Planning

The Third Package takes important steps towards a better integration of European policy goals into future grid development. Firstly, two new European-wide institutions are given a crucial role. Regulation (EC) No 714/2009 creates the European Network of Transmission System Operators for Electricity (ENTSO-E) bringing together all TSOs that until now have been cooperating on a voluntary basis only within for instance UCTE, ETSO and Nordel. Also, European Regulation

[7] The current timeline foresees entry into force on 1 January 2013.

(EC) No 713/2009 establishes the Agency for the Cooperation of Energy Regulators (ACER) and bundles all energy regulators.

Whereas there used to be no European-wide transmission development plan, Art. 8(3) of Regulation (EC) No 714/2009 gives ENTSO-E the task to publish each two year a non-binding Community-wide 10-year network development plan (TYNDP) including a European generation adequacy outlook up to 15 years ahead. According to the Regulation the TYNDP has to build on the yearly published 10-year national investment plans, i.e. a bottom-up approach is envisaged. Art. 22 of Directive 2009/72/EC provides further details on these national plans. It has to take into account regional investment plans. Although not said with that many words in the Third Package itself, ENTSO-E considers the regional level and their development plans as the working horses for the Community-wide plan.

Furthermore, the TYNDP has to incorporate supranational aspects, so-called Community aspects via a top-down approach. Explicit referral is made to the guidelines for the Trans-European Energy Networks (TEN-E). The latter guidelines including the TEN-E project lists and the Priority Interconnection Plan (PIP) can be considered as the most concrete realization of the supranational viewpoint (see also section 2.2.3). Cross-border investments or the lack thereof should also be given sufficient attention in the TYNDP. It is clear that the bottom-up approach based on the national development plans is flavoured by national aspirations and the top-down approach based on the Community needs is supranationally oriented. The TYNDP combines both and is complemented with public consultations. An important question is whether both planning approaches can converge or not and whether they both have sufficient impact on the resulting plan and, ultimately, on the investments really done or not. Note that the TYNDP by itself is non-binding. Proper regulatory oversight at different levels is key. This is further discussed in the next section.

In March 2010 a Pilot TYNDP is published by ENTSO-E. This version only takes into account the bottom-up approach, i.e. it is based on national development plans and does not fully incorporate a European viewpoint yet. This pilot intends to open the debate and start the loop of public consultations and consecutive publications of bi-annual TYNDPs also including the top-down approach.

In the EIP planning is explicitly dealt with. In particular a planning process based on regional clusters is proposed with the aim of identifying Projects of European Interest. The project lists resulting from the different regional clusters are then pooled into a unified European list. This list serves as an input to the TYNDP drafted by ENTSO-E. As for the TYNDPs this process is repeatedly undertaken and closely follows the loop of the TYNDPs. Via these projects of European Interest the European viewpoint should be more actively pursued and incorporated in the TYNDP [5].

Another long-term element is introduced in the blueprint of the EIP: European

Electricity Highways. Their purpose is threefold: (a) accomodating increasing levels of renewable generation throughout Europe, (b) connecting these new hubs with major storage facilities based on hydropower and large demand centres and (c) coping with more flexible and decentralised demand and supply [5]. Although the first projects of this kind should be commissioned by 2020, its scope clearly goes beyond 2020 and the ten-year ahead viewpoint of the TYNDP. The proposed EIP Regulation sets up a framework to identify bi-annually projects of common interest (cfr. infra) within regional groups. After an opinion of ACER, the Commission decides on adoption of the list projects. These projects should become an integral part of the regional investment plans and national ten-year network development plans.

Finally, it is interesting to note that throughout Europe different forms of voluntary cooperation are being established aiming at a regional approach of cross-border investments. There is an increased awareness of regional challenges.

In Scandinavia there is a longer tradition of cooperation in this field with grid master plans [17]. The process is long and remains nationally inspired. More recently a Baltic Energy Market Interconnection Plan (BEMIP) was agreed upon among the different countries in the region. The development of electricity interconnectors is part of the plan. Another recent example can be found in the North Seas region. Nine countries around the North Seas signed in December 2009 a political declaration concerning the development of an offshore grid in the North and Irish Seas. These cooperations are an important step into the good direction, but based on voluntary cooperation it cannot be expected from the participants to leave their own national interests when they do not match with the best solution from a European perspective.

2.2.2 Regulatory oversight

Regulatory oversight with respect to the TYNDP is mainly a task of ACER. In Regulation (EC) No 714/2009 it is stipulated that ACER has to give its opinion on both the TYNDP (Art. 9(2)) and national development plans (Art. 8(11)). The latter opinion should assess to which extent there are inconsistencies between the national plans and the TYNDP. ACER can recommend amendments to the national plans which then have to find their way to the national regulators. At the same time the national regulators have to examine the national development plans and check their consistency with the TYNDP. Although it appears there is a lot of oversight on the development plans, it remains to be seen whether the struggle between the bottom-up and top-down approaches converges to a result that is acceptable for both national and European parties. Indeed, national regulators still play a central role, even in the incorporation of higher-level viewpoints. Do they have sufficient incentives to do so?

Moreover, will ACER truly act as a European regulator and will it be as powerful as required to fulfill Community needs? According to Art. 2 of Regulation (EC) No 713/2009, ACER consists of four entities: an Administrative Board, a Board of Regulators, a Director and a Board of Appeal. The Board of Regulators and the Director are responsible for the opinions, recommendations and decisions of ACER. These entities should make the difference in adopting the European viewpoint. The Board of Regulators copies the structure of ERGEG , i.e. one representative of the national regulator per Member State and one non-voting member of the European Commission. Art. 13(5) of Regulation (EC) No 713/2009 requires that this board should act fully independently and should not be influenced by (among others) the Member States. It remains to be seen how well this structure works. The members of this board are still clearly linked to the national regulators and the question is whether they will defend their national interest or draw the European card. This opens the door towards a more multilateral nature where everyone separately has to benefit in order to progress. However, the Board of Regulators acts by a 2/3 majority (Art. 13(3)). Abandoning unanimous decision-making is an important step towards a supranational ACER. Backed up by sufficient incentives for national regulatory authorithies to think across borders, this framework might work. In the next section on the financing framework, these incentives are analyzed from a financing point of view.

Although the EIP does not propose concrete measures to incent national regulatory authorithies to think more in line with European needs, the EIP at least proposes a toolbox facilitating cross-border approval procedures such as the one-stop-shop principle and limitations on the duration of the approval procedure. The one-stop-shop principle entails a better integrated and coordinated scheme for obtaining all necessary approval decisions. Nevertheless, member states still keep their full decision-making and approval competences [5, 15]. Note that when a project of common interest is undertaken a cost-benefit analysis is used to allocate investment cost. National regulatory authorithies have to reach an agreement on the allocation key. If they disagree, ACER is given the decision-power for cost allocation.

2.2.3 Financing

In European energy policy, funding of energy networks has always been based on self-financing by private partners, i.e. mainly the different TSOs in their respective regions. This proved to be a successful way of working in a time without substantial and fluctuating international power flows. The new challenges cause an increase in geographic scale and force the cross-border investment framework to move from a bilateral context to a regional or even European context. The financing framework has not kept pace with this evolution.

Supportive financing mechanisms for cross-border investments have been set up since the nineties, but until now they more served as a market fix. In fact, they have never been able to change the true nature of European network funding: nationally oriented self-financing via national transmission tariffs charged upon national grid users. Cost allocation across borders or direct funding from the European level has been limited. Two frameworks exist with a special focus on the cross-border context: the (almost abondonned) TEN-E program and the Inter-TSO Compensation (ITC) mechanism. Although no clear framework is present today congestion revenues also have the potential to play a role on the cross-border scene. Additionally, a European Economic Recovery Program (EERP), being part of the program to overcome the recent economic crisis, provides a one-time opportunity for financing a limited number of projects.

A brief discussion of these four elements is given, high-lighting why they are not fully adapted to the new cross-border context and why they rather facilitate a nationally oriented multilateral cooperation instead of a supranationally inspired grid development. The recent proposals of the EIP are linked to these four elements, although it sometimes clearly goes beyond the existing framework.

TEN-E program

The TEN-E program was launched in 1995 to promote transmission investments enabling a European internal energy market, strengthening security of supply and improving economic and social cohesion throughout Europe [18, 19]. Together with the Priority Interconnection Plan (PIP) of 2007 [20], mainly consisting of a subset of the TEN-E project list, it has been the most concrete framework inspired by Europe for transmission investments for a long time.[8]

The merits of TEN-E with respect to financing have been limited. Although published at the European level, the TEN-E framework did not include funding for entire projects. Financial support was mainly limited to financing feasibility studies. Although several barriers were encountered for the different projects, the lack of European funding or an adequate cost sharing mechanism might have contributed to the slow progress.

In November 2008 a Green Paper [22] reconsidering the role of TEN-E was published by the EC which resulted in the Energy Infrastructure Package in 2010 [5]. Whereas network policy used to 'plug gaps' and foster 'missing links', a renewed energy infrastructure policy should be fully aligned with the new challenges and proactively promote network investments supporting security of supply, sustainability and competitiveness. The TEN-E framework's visibility and impact should be altered to be more compatible with the overall energy policy and to increase its efficiency.

[8] Reference [21] provides a historical overview of how the European interconnected network is created. European-wide plans are not new, but it is the first time that they are explicitly embedded in any form of legislation.

Note that the TEN-E and PIP project lists do not entail any binding commitment on the EU Member States.

The Green Paper's bottom-line for financing energy network investments remains self-financing by TSOs. The proposed improvements for financing investments are two-fold. Firstly, an increased TEN-E budget is put forward. It should especially facilitate non-commercial investments, e.g. driven by security of supply. Secondly, TEN-E should be better aligned with other forms of EU funding, like the Structural and Cohesion Funds and RTD Framework Programmes. Further coordination between TEN-E and the European Investment Bank and the European Bank for Reconstruction and Development should be explored. The World Bank Accelerated Programmatic Loan is also considered as a potential partner.

It is clearly stated that self-financing remains the main driver for energy network investments. Most attention in the Green Paper goes to the surrounding framework. No proposals are made to enhance the self-financing frameworks themselves, although it remains the core revenue stream. There is, however, one reference to the problem of financing cross-border investments by different Member States. In the context of TEN-E projects it is stated in the Green Paper that [22]: 'Member States who benefit may also be expected to contribute.' This indeed addresses the root of the problem, but how it should be organized remains an open question.

The EIP goes further than the 2008 Green Paper. Not only the TEN-E framework is replaced by a more powerful framework, but also an ex ante cost-benefit analysis and cost allocation is introduced (see next section on ITC). The TEN-E era is de facto finished and a proposal is made to alter the framework. No lists with concrete projects are proposed, rather a set of criteria is determined against which all projects within four predefined priority corridors[9] can be tested. This can result in projects being labelled as Project of Common Interest. Such a framework is believed to be more flexible than the rigid TEN-E project lists. With respect to financing, the EIP goes significantly further than the TEN-E framework. Not only feasibility studies are eligible for grants, but also works themselves can be eligible if the necessary conditions are met. Moreover, not only grants are available, also other financial instruments are defined. In particular, project bonds and possibly even equity funding are possible. Both instruments should help investors to have better access to capital and capital markets in general. Finally, the EIP introduces the possibility to provide extra incentives (extra return on investment, treatment of anticipatory costs…) for projects of common interest if required by the risks incurred. However, these extra incentives can only be given by the national regulatory authorithy. Summarized, the EIP provides an elaborate toolbox both for permitting and approval and for financing, but the national level remains crucial.

[9]The corridors are: Northern Seas Offshore Grid, North-South electricity interconnections in South-Western Europe, North-South electricity interconnections in Central Eastern Europe and South Eastern Europe and the Baltic Energy Market Interconnection Plan in electricity.

Inter-TSO Compensation (ITC) mechanism

The ITC mechanism stems from the beginning of European market integration and went online for the first time in 2002. It has been created so that countries receive compensation if their assets are used by TSOs that do not contribute to their financing. Participation by national TSOs in the mechanism used to be voluntary. It replaced tolling mechanisms at the different borders (often referred to as pancaking[10]) and thereby enabled international trade. The mechanism allows introducing an international element in the different non-harmonized national tariffs [25].

According to ETSO[11] there are three mechanisms dealing with costs originating from the cross-border context [25]. Firstly, there is an ITC mechanism for compensating costs caused by network losses. Secondly, new investments and costs linked to firmness are to be covered by congestion revenues. Finally, there is an extra ITC fund providing any necessary additional compensation.[12] Network losses are not considered in this thesis. Congestion revenues are discussed in the next section. In the remaining part of this section this additional ITC fund is treated.

This ITC mechanism has been the subject of a lot of debate and the algorithms used for determining who pays and who receives money changed several times over the last decade. Several of them were fundamentally flawed [26, 27]. They draw on a yearly ex post calculation based on energy-based measures. However, ex ante securing financing is crucial for investment decisions involving large sunk costs. Cost distributions should be agreed upon upfront. Transmission investment decisions are more often capacity-based (MW) rather than energy-based (MWh). Moreover, the size of the fund also varied over time rendering it a less reliable source of funding. Recently it was reduced to 100 M€, whereas it used to be about 350 M€ [25]. This may change once a new mechanism is installed [28].

Although the intention of the ITC is laudable as it introduces a cost-sharing mechanism across borders and as it was successful in removing the pancaking of tariffs at different borders, it has been found inadequate for fostering new investments and providing good incentives to TSOs.

[10]The pancaking refers to the problem of double marginalization [23]. Applied to the context of international electricity trade, this refers to the practice where in each zone or country along a contract path the monopolist network operator charges the transaction for the use of the network and extracts a monopoly rent from it. The price paid for the transaction then depends on the number of political borders crossed. An accumulative 'pancaked' tariff is paid, rather than a tariff that would occur under a single-zone paradigm (see [24], p. 246). The European reforms removed this pancaking. The ITC-mechanism brought this transfer to the TSO level. Grid users now only have to deal with the congestion management mechanisms, such as explicit and implicit capacity auctions.

[11]ETSO, the association bundling several European Transmission System Operators, ceased to exist. Its activities are now taken over by ENTSO-E.

[12]It should be noted that the ITC mechanism for infrastructure was not conceived as a mechanism aiming at supporting new investments, its focus is on existing infrastructure.

The Third Package called for a long-term mechanism in which all TSOs participate and instructed the formulation of guidelines for such mechanism. The guidelines were published in September 2010 [28]. The current mechanism dwells on the calculation of transit flows. Nevertherless, ACER is instructed to propose a new mechanism by the end of 2012 based on long-run average incremental costs and standard-costing methodologies [28].

The EIP acknowledges the difficult situation created by the current framework for financing large cross-border projects. In particular when benefits and costs of investments are unequally distributed over different countries, projects are not likely to be financed by nationally regulated private TSOs. A new ex ante cost allocation mechanism is proposed and is thought to resolve the cost-benefit distribution issue. Not only those countries hosting the infrastructure, but all involved and/or affected countries are part of the mechanism in order to better address externalities. Cost are said to be allocated proportionate to benefits. The current proposals, however, seems to only focus on investment cost allocation only.[13] Compensations for negatively affected parties are not mentioned.

Congestion revenues

In Europe congestion revenues are mainly collected via auctioning transmission capacity at borders between different countries (and sometimes between different zones within a country). Within a country, uniform pricing is applied.[14] As a consequence, congestion revenues are a direct result of international trade and the link with cross-border transmission infrastructure is easily made. Using these revenues as funding for cross-border investments seems an attractive solution.[15]

Before the Third Package, it was stipulated in Art. 6(6) of Regulation (EC) No 1228/2003 that congestion revenues could be used for three purposes: (a) guaranteeing the actual availability of the allocated capacity, (b) network investments maintaining or increasing interconnection capacities and (c) as income to be taken into account when approving transmission tariffs. It was not defined which option should be prioritised. The last option, reducing national transmission tariffs, has been frequently enforced by regulators [9].

[13]See, for instance, the presentations given by representatives of the European Commission in the Working group for offshore and onshore grid development (North Sea, Baltic Sea) (the so-called Adamowitsch working group)

[14]Except for Norway, Denmark and Italy where different price zones exist. In Poland a nodal pricing scheme is announced.

[15]Only congestion revenues on regulated transmission links are considered. A minority of (mainly DC) cross-border connections are developped under the so-called merchant scheme (e.g. Estlink, BritNed). This implies they are exempted from several requirements stipulated in the European regulations, including those dealing with the use of congestion revenues. Merchant investors are rewarded with the congestion revenues collected on their link to finance the investment.

In Art. 16(6) of Regulation (EC) No 714/2009 the formulation is changed. Option (a) envisaging firmness of interconnection capacity has been retained; the wording of option (b) is altered in order to better emphasize new interconnection investments. The new wording ensures that congestion revenues have to be used to either ensure or increase interconnection capacity. Only if congestion revenues cannot be efficiently used for options (a) and (b), they can be used to lower tariffs (the former option (c)). Therefore, implicitly a priority list for the use of congestion revenues is now enforced. This is clearly an improvement.

Although more capital should now be available for investments in cross-border transmission capacity, the regional or European viewpoint is not captured here. Congestion revenues are still kept by the national TSOs and they decide, after approval by the national regulator, on how to use them. The Third Package gives also no hints on the distribution of the congestion revenues over different countries or how they can be used to foster interconnections that go beyond the bilateral cooperation between adjacent countries and serve the new investment challenges. Also in the EIP this issue remains untouched.

European Economic Recovery Plan

On the March 2009 Spring Summit of the European Council a proposal for the European Economic Recovery Plan (EERP) has been adopted [29]. Investments in energy infrastructure are financially supported. Several millions of euros are assigned to specific projects for interconnectors for gas (1440 M€) and electricity (910 M€), offshore wind projects (565 M€) and carbon capture and storage (1050 M€). This commitment will be spread over two years, i.e. 2009 and 2010. The list of selected interconnection projects is inspired by the PIP.[16]

With respect to electricity interconnectors the proposed amount is significant. For instance, for the envisaged link in Germany between Halle/Saale and Schweinfurt 100 M€ is budgeted. This is more than 50% of the required budget according to estimated costs in the 2007 Priority Interconnection Plan [20, 29].

Although the extra money for interconnectors is welcome and can contribute substantially, this injection is a one-time opportunity for a limited set of projects. It does not change TSOs' investment incentives and it remains to be seen whether all supported projects will be operational in due time and not blocked at national levels due to different interests.

Although the EIP does not create a permanent source for European funding, it aims at increasing access to public funding (e.g. from the European Investment Bank) for projects of common interest. Also, these projects should be able to

[16] In total, at least about 700 km of subsea HVDC connections and 640 km of AC connections are supported.

benefit from different, flexible financial mechanisms tailored for mitigating the specific risks encountered (e.g loan guarantees, project bonds, grants).

2.3 Conclusion: policy-oriented research questions

In this chapter it is argued that for the next decades to come there is a clear investment challenge for electricity transmission networks. Several thousands of kilometers of new lines have to be built and billions of euros are required to make it happen. Moreover, not only is the investment challenge inspired by European policy goals, the geographic scope is larger than the traditional level of decision-making.

The consequences of the connection of massive amounts of renewable energy sources to the existing power system for the transmission network cannot be captured by a single country. As networks are interconnected and a reliable service is required both in the short and the long run, countries cannot be isolated from each other when solidarity, diversity of supply and balancing of load and generation are considered. Increasing cross-border trade opportunities and lowering persistent congestion in order to achieve a single internal electricity market requires investments in internal and cross-border transmission links. It should be clear that the national level alone is unlikely to take up this task in a cost-effective way. An adapted framework fostering collaboration and providing correct incentives is required.

Given this call for an adequate framework and incentives, this chapter provided an analysis of the current framework. The Third Package clearly introduced a European flavour in transmission investments. The creation of ENTSO-E and ACER are important milestones. The TYNDPs have the potential to become powerful tools for meeting the challenge. However, it should also be clear that the Third Package does not go far enough to ensure that European goals will be met. An area of tension between the national and the European level remains. The national level of decision-making remains very strong and lacks incentives to truly incorporate the European goals in its decision-making. Planning, regulatory oversight and financing are not fully adapted to the investment challenge.

The upcoming EIP again takes significant steps forward with the introduction of a cost-benefit allocation mechanism and a new financial toolbox, but is unlikely to fix all remaining loopholes. Although the investment process for projects of common interest becomes better streamlined and more financing tools become available, the root of the area of tension is not addressed. The national level does not receive sufficient incentives to fully align their interests with European policy goals.

Given the investment challenge and the identified flaws in the current framework, a fundamental question can be raised:

> What outcome can be expected when the national level of decision-making remains strong without incentives to really take into account the European goals?

Given the above question, the call for incentives and the proposals done by the European Commission in the EIP to foster an investment cost allocation scheme in order to resolve the cost-benefit distribution problem, a second question can be identified:

> Is investment cost allocation a sufficient tool to align European and national goals?

Both questions are relevant for the ongoing developments and answering them can feed the debate on the design of a good framework with solid arguments. In the remaining chapters, this thesis addresses both. The structure of the thesis is built around the first question, considered the main contribution of this thesis. The approach includes the setup of a formal framework, the definition and comparison of three collaboration concepts and testing them on how they behave on small examples. The second question is dealt with throughout the different chapters.

It is important to realise that both research questions do not address the specific design of any financing mechanism. It only looks at the outcome, i.e. which investments have to be done and whether or not a cost allocation mechanism is an appropriate tool. Different designs of such tool are not investigated, nor is dicussed how different outcomes should be translated into end-user transmission tariffs.

3

Concepts for transmission investment collaboration

Departing from the area of tension described, this chapter outlines different ways for collaboration in transmission investments. In essence, three planning collaboration concepts are developed: supranational, Pareto-optimal and non-cooperative planning.

The aim is to provide a single framework based on welfare economics enabling a comparison of the different concepts. It sheds a light on the underlying principles and interrelations. By doing so this chapter serves as a guide to the reader and an intuitive introduction to the models presented in chapters 5, 6 and 7 without going into mathematical details. It refines the research question and translates it from a general policy-oriented formulation towards a more concrete problem that can be addressed by the use of specific models.

Firstly, section 3.1 develops the framework, introduces planning concepts and outlines further issues after intuitively discussing a two-node example. Next, section 3.2 makes the link with game theory. This is followed by a further refinement of this thesis' research question in section 3.3. Section 3.4 concludes this chapter.

3.1 Framework based on welfare economics

From the previous chapter it is concluded that the current regulatory context can drive a wedge between what is striven for by a common European energy infrastructure policy and by the individual member states. The objectives are not always aligned. An insightful framework to analyze this problem relies on welfare economics. Firstly, the necessary basics of welfare economics are briefly mentioned. Secondly, a more formal framework is presented and three planning concepts are developed. Thirdly, the concepts are applied on an intuitive two-node example. Starting from this example several other relevant issues are highlighted.

3.1.1 Basic welfare economics

In welfare economics the economy is studied from a general equilibrium point of view. It analyzes economic efficiency and how the economy can be organized. This is strongly related to public-choice theory, i.e. the domain in economics studying how governments take decisions [30]. As clarified throughout the following sections, especially the organization and decision-making of transmission planning is a key element in analysing the area of tension in transmission planning impacting the further outline of this thesis.

In Fig. 3.1 a basic representation with two zones A and B is given. The vertical and horizontal axes reflect respectively zone A's and B's utility, in this case called welfare. The curve going from $A^{\max}$ to $B^{\max}$ is called the Utility Possibility Frontier or Pareto-front.[1] An outcome is said to be Pareto-efficient or Pareto-optimal if there is no other outcome that makes every player at least as well off and at least one player strictly better off. Stated otherwise, a Pareto-optimal outcome cannot be improved upon without hurting at least one player. Given the available inputs, all outcomes on the frontier are Pareto-efficient outcomes.[2] All points to the southwest from this curve are sub-optimal. Outcomes located northeast from this curve are not reachable with the given set of inputs.

Assume now an initial situation U with initial welfare A^{init} and B^{init} for zones A and B. As U is located to the southwest from the Pareto-front, there clearly is some inefficiency in the economy. For instance, this can be due to market failures like externalities or imperfect competition. In the context of this thesis the lack of transmission planning collaboration can be the cause of such inefficiency.

The area of sub-optimal outcomes can be split in four smaller areas:

[1] This goes back to the first theorem of welfare economics stating that in a perfectly competitive general equilibrium, the system is Pareto-efficient[30].

[2] According to the second theorem of welfare economics it possible to switch between different efficient outcomes by changing the initial welfare distribution and allowing competition to work.

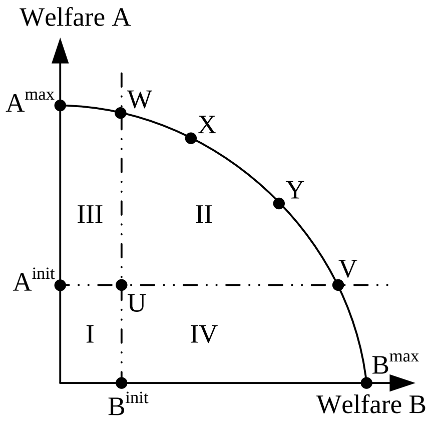

Fig. 3.1: Pareto-optimality and initial welfare distribution (adapted from [30])

- Area I groups all outcomes with a strict lower welfare for both zones.
- Area II includes all outcomes with a higher or equal welfare for both zones. These outcomes are Pareto-improving.
- Area III gathers all outcomes with a strict lower welfare for zone B, but a higher or equal welfare for zone A.
- Area VI groups all outcomes with a strict lower welfare for zone A, but a higher or equal welfare for zone B.

Note, however, that even within area II significant differences exist in how welfare is distributed. The fact that a particular outcome like V, W, X or Y is Pareto-optimal, does not imply that welfare is evenly distributed among the different zones. V and W are two extremes. Point V denotes the Pareto-optimal outcome with the highest welfare for zone B without decreasing zone A's welfare. Point W is the equivalent for zone A. In X and Y both zones benefit compared to U, but not with the same intensity.

3.1.2 General framework for collaboration concepts

Based on the above notions of welfare economics, a framework formalizing the different objectives regarding transmission investments is presented. The focus lies on how transmission planning and decision-making is organized.

Assume that zones A and B are connected and their welfare depends on investments in the interconnecting network. In U, the initial situation, there is a clear inefficiency caused by a lack of coordination and investments in this network. By investing it is possible to alter the welfare in both zones. The effect of investing is illustrated in Fig. 3.2 for two cases. Due to investments total welfare can change according to the parallel movement of the straight line from t^{init} to t^*. It is assumed that total welfare increases in the direction of the arrow. Welfare does not necessarily change in an equal way for both zones. For instance, an investment can cause a huge welfare increase for one zone, whereas the other zone benefits only moderately. This is reflected in the angle of the straight line. An angle of 45 degrees implies that both zones benefit equally (case (a) of Fig. 3.2).

In case (a) of Fig. 3.2 the solution with the highest welfare is found in X, i.e. at the intersection of the tangent t^* and the efficiency frontier. Moving from U to X implies a welfare increase for both zones. In terms of Fig. 3.1 point X lies in area II.

The situation is different for case (b). Here both zones benefit with a different intensity from the transmission investment. Zone A profits more from the capacity increase. This can be caused by different characteristics of both zones with respect to generation portfolio, demand elasticity, etc. Contrary to case (a), the total

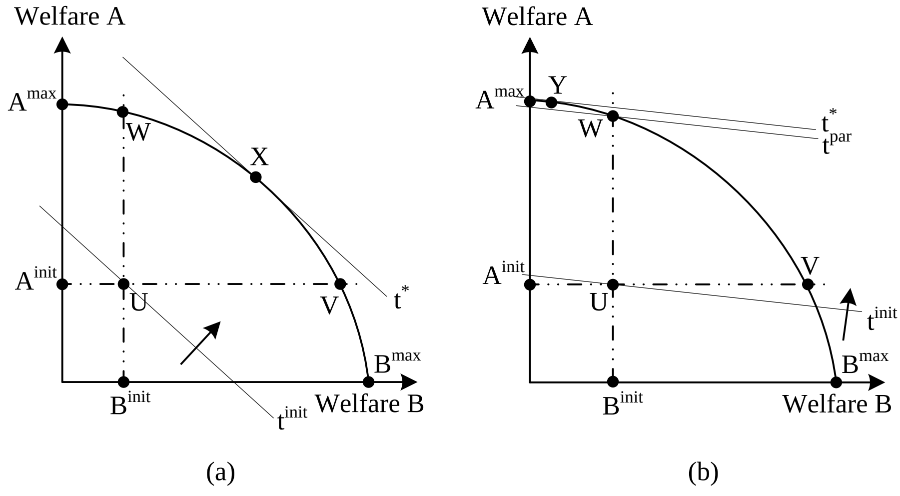

Fig. 3.2: Impact of investments on the Pareto-optimal solution: two cases (adapted from [30])

welfare maximising solution, i.e. point Y, is now located in area III implying a negative welfare impact on zone B. Although zone B looses in this situation, from an overall welfare point of view this is counterbalanced by the welfare gains of zone A. As a consequence, an overall welfare maximizing transmission planner would invest until point Y is reached and then organize a lump-sum payment from zone A to B to compensate for zone B's welfare loss.

Returning to the analysis of chapter 2 solutions X and Y can be classified as the desired outcomes of European policy makers for cases (a) and (b) in Fig. 3.2. However, as discussed in chapter 2, today there is no adequate compensation mechanism in place in Europe. Welfare transfers are not possible. Together with the fact that investment decisions are mostly decided at the zonal level, it is unlikely that zone B accepts moving to point Y in case (b). Without compensations only Pareto-improving solutions, i.e. solutions in area II of Fig. 3.1, are realistic. For case (b), the solution with the highest welfare within reach is point W. Based on the above analysis two planning collaboration concepts are defined.

Collaboration concept 1. *Supranational planner: The supranational planner maximizes overall welfare, i.e. the sum of welfare created in all zones minus transmission investment costs, by deciding on transmission investments in the entire interconnected grid as if it is one single zone.*

Collaboration concept 2. *Pareto-planner: The Pareto-planner maximizes overall welfare, i.e. the sum of welfare created in all zones minus transmission investment costs, by deciding on transmission investments in the entire interconnected grid as if it is one single zone, but constrained by the initial welfare distribution. No zone can loose welfare.*

An alternative interpretation of a compensation mechanism is making the supranational results binding for the involved zones, i.e. they have to implement the results even if this negatively affects them. This would of course require a strong regulatory framework. This alternative is not further considered in this thesis.

The above two concepts both start from the objective to maximize overall welfare. This is in line with policy goals defined at the European level. Whereas for the supranational planner the distributional effects and welfare transfers are not important (i.e. a compensation mechanism is assumed), the Pareto-planner looks for the welfare-maximizing solution which is still Pareto-improving, i.e. situated in area II of Fig. 3.1. The supranational planner can also consider solutions within areas III and IV. Due to this larger solution space the supranational planner always outperforms the Pareto-planner or, at best, they come to the same solution. Stated otherwise, both planners are solving the same problem but the Pareto-planner is bounded by more constraints and is therefore never able to attain a higher overall welfare than the supranational planner.

A third planning collaboration concept takes a different starting point. It does not assume a single planner maximizing overall welfare. Different zonal planners maximizing zonal welfare are together playing a game. Of course, those different planners influence each others decisions as they all act on the same interconnected network.

Collaboration concept 3. *Non-cooperative planning game: Game between zonal planners maximizing zonal welfare minus investment costs by deciding upon transmission investments in their zone. A solution or equilibrium is found when no planner can increase its zonal welfare given the decisions of the other players.*

Although it can always be plotted on the same graph, in general the outcome of this game is not easily intuitively determined in terms of Fig. 3.1.[3] The result can be anywhere on or southwest from the Pareto-front. Furthermore, it can even coincide with the supranational and/or the Pareto-planner's solution. It is even possible that the game has no solution. The outcome depends on the reactions of the different planners on the actions of the other planners. A solution or equilibrium is characterized by the fact that in the given situation no planner can increase its zonal welfare given the actions taken by the other players.

3.1.3 Application on a two-node example

In this section the above framework and concepts are illustrated on a two-node example. Without going into any technical details or specific modelling assumptions the different solutions are intuitively deduced. Starting from this example several other relevant issues are identified in the next section.

Consider the two-node example of Fig. 3.3. Each node represents a zone. Both zones are linked with a single transmission link $\mathrm{T_{AB}}$ consisting of two parts $\mathrm{T_{AF}}$ and $\mathrm{T_{BF}}$. Each zone hosts one part of the link. F denotes the frontier between zones A and B. In the initial situation there is already some trade, but the transmission capacity is fully used, i.e. the link is congested. Changes in welfare are directly related to increased trade over this link. Depending on the characteristics of each zone, welfare can change in various ways with increased interconnection capacity.

In Fig. 3.4 three possible trajectories are illustrated.[4] The solutions for the different

[3]For specific cases it is possible to derive a solution based on a graphical intuitive analysis (see section 3.1.3).

[4]Note that by limiting the options to move away from U to a single variable, i.e. increasing transmission capacity on a single link, the area of possible improvements is limited to a single line. The graphical representation is slightly abused as now not all points southeast from or on the Pareto-frontier are reachable. The Pareto-frontier is only shown to illustrate the link with the more general framework and some further comments made at a later stage in this section.

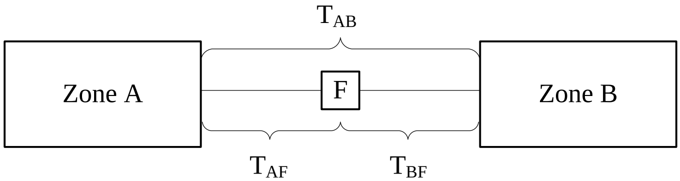

Fig. 3.3: Two-node example: network structure

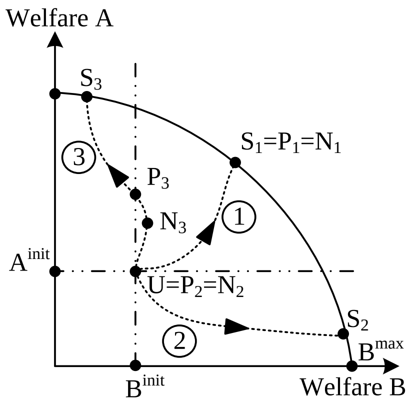

Fig. 3.4: Two-node example: impact of transmission investment on welfare

planning concepts are directly related to this trajectory. S_1, S_2 and S_3 are the outcomes of the supranational planner for each possibility. The first trajectory remains in the Pareto-improving area. S_1 is therefore also the outcome of the Pareto-planner. As both zones gain with every capacity increase, this is also the outcome for the non-cooperative planning game.

On the entire second trajectory a negative impact for zone A is observed. Whereas the supranational optimum is S_2, the Pareto-planner's solution (P_2) is to remain in U and not to invest in a capacity increase. As both zones can influence the capacity on the entire link $\mathrm{T_{AB}}$[5], the non-cooperative game also ends in U. Whatever the action is of zone B, zone A always blocks the capacity increase from its side.

[5]The minimum capacity of $\mathrm{T_{AF}}$ and $\mathrm{T_{FB}}$ determines the capacity of $\mathrm{T_{AB}}$. In theory they can only differ in the non-cooperative planning game when both zones would decide on another capacity to be installed.

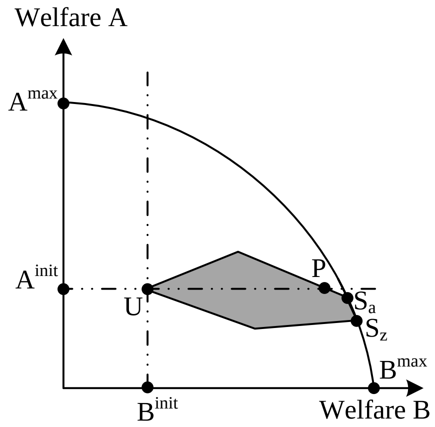

Fig. 3.5: Multiple investment options creating a solution area

The third trajectory is more complicated. The first part of the trajectory going from U to P_3 is Pareto-improving. This changes at P_3, where zone B's welfare equals its initial level. The second part from P_3 to S_3 is only beneficial for zone A. Therefore, P_3 is the solution for the Pareto-planner. On the supposition that both zones can influence the capacity to the same extent, the outcome of the non-cooperative planning game is N_3. Here zone B's welfare reaches its maximum value along the trajectory.

3.1.4 Further considerations

The two-node example presented in the previous section illustrates well the planning collaboration concepts. However, the very simple setup hides several underlying difficulties which need to be addressed when more realistic examples are dealt with.

- The transmission segments $\mathrm{T_{AF}}$ and $\mathrm{T_{FB}}$ in Fig. 3.3 are complimentary in a sense that a limited capacity on one segment also limits the capacity on the other even if the latter segment is designed for a higher capacity. In meshed transmission networks this is not always the case. Transmission links can also work supplementary to other links. This can obviously change the games played. Moreover, when there is more than just a single link to invest in, the trajectories of Fig. 3.4 can expand towards areas as for instance depicted in Fig. 3.5.

- It can also happen that for the Pareto- and supranational planners the same level of overall welfare can be reached by different sets of investments. As mentioned in section 3.1.1, those solutions can significantly differ in the zonal welfare distribution. This is illustrated in Fig. 3.5 by section S_a to S_z which is a subset of the Pareto-frontier. Also the non-cooperative planning game can have several solutions. The question arises which solution is preferred and whether some solutions are more likely to materialise than others?

- In case of a larger network it is better to address investments in the entire network at once, rather than applying the concepts on each link separately. The effects can often not be isolated. Due to complementarity and supplementarity, a new investment is likely to change the effects produced by previous projects. This also increases the solution space of a Pareto-planner as negative and positive effects can cancel out when investments are considered together. Now more investments are allowed than only those benefiting to all parties when looked at individually.

- A final so far unaddressed issue is to define in more detail who finances the investments. For the non-cooperative planning concept the situation is clear. The lack of any form of collaboration directly implies that investments have to be borne by the zones deciding upon and hosting the infrastructure. Also for the supranational planning concept this issue is implicitly covered by the assumptions. When solving the planning problem itself, the investment costs are part of the welfare maximizing objective function and it looks like they are financed at the supranational level, e.g. via direct European funding. However, the supranational planner decides on investments assuming that there is a compensation mechanism in place correcting the welfare distribution. Such a mechanism can also cover the investment costs.[6]

  For the Pareto-planner, however, the underlying financing mechanism can cause subtle differences in the solutions found. Two possible mechanisms can intuitively illustrate this. Firstly, assume a strict interpretation of the Pareto-planning concept and suppose that there is no possible way to allocate costs nor benefits among different zones. In such a context each zone has to finance all investments hosted on its territory. This implies that the Pareto-planner's zonal welfare constraints have to include those costs. Secondly, assume a more relaxed Pareto-planner. Although there is no compensation mechanism for redistributing welfare as in the case of the supranational planner, a mechanism limited to investment cost allocation only can diminish the potential gap between the Pareto- and supranational planner. In such a relaxed context the zonal welfare constraints include welfare without infrastructure costs.

[6]The European Inter-TSO Compensation Mechanism (ITC) is set up for this purpose. It has as a goal to allocate infrastructure costs among different European TSOs. However, it is limited to cost allocation only and does not consider an overall welfare redistribution.

The latter are taken into account in the overall welfare maximizing objective function and are ex post allocated to the different zones.

The above issues are further discussed in the chapters 5, 6 and 7 dealing with the specific planning concepts in more detail.

3.2 Links with game theory

Although this thesis is not rooted in game theoretical research it is interesting to note that the three defined concepts have close ties with game theory. For the third planning concept this is obvious as it is directly defined as a game, but both other concepts can also be considered as a game.

In game theory, two large groups of games can be identified: cooperative and non-cooperative games. Whereas in non-cooperative games all players act individually in line with their own interest, in cooperative games coalitions can be formed. Coalitions take joint actions and the consequences for the group rather than the individual members are at stake. The cooperative games can be further split into two groups according to the possibility of transferring utility (or welfare) or not. The ability to transfer utility among members of a coalition, e.g. by means of monetary side payments, can change the outcome of the game. Cooperative games go back to the theories developed in [31]. The fundamentals of non-cooperative games are laid by Nash [32]. A basic understanding and overview of the theory can however be found in most textbooks on game theory [33].

For linking the three planning concepts to game theory, a last notion is required: the grand coalition. In general, coalitions do not necessarily include all players. For instance, in a game with three players, a coalition can exist of two players playing against the third. The coalition gathering all players is called the grand coalition.

As mentioned earlier, the third concept is classified as a non-cooperative game among zonal transmission planners trying to maximize zonal welfare while taking into account the other planners' actions. The supranational and Pareto-planners are closely related to cooperative games. They both look for the best possible solution for the grand coalition. They maximize overall welfare, i.e. the sum of zonal welfare of each zone. The major difference lies in the transferability of welfare among the members of the (grand) coalition. Whereas the supranational planner assumes that it is possible to transfer or redistribute welfare among all zones, the Pareto-planner considers welfare as non-transferable or limited to investment costs only.

3.3 Research question and further outline

The research question as defined in chapter 2 is policy-driven. Given today's investment planning and financing framework it is observed that it is not straightforward that policy objectives set at a higher level and requiring significant support for well interconnected transmission networks are met in a context where investment planning and decision-making is undertaken at a lower level. The potential mismatch of interests between both levels causing different preferences in transmission investments is to be investigated.

In section 3.1.2 three collaboration concepts are defined. These concepts allow to further refine this thesis' research question. The impact on preferred transmission investments is analyzed via the three concepts. The concepts differ in the assumed level of collaboration among the different zonal planners. These differences are suitable for linking them to the policy-driven research question.

The supranational planner corresponds to the European level where policy goals are set impacting all zones. The non-cooperative planning game represents another extreme, i.e. the situation where all zonal planners act out of their own interest without caring about European policy. The Pareto-planner is situated in between both extremes. It presents a way to reconcile European objectives with zonal interests.

Explicit mathematical modelling of each collaboration concept and comparison of their outcomes for concrete examples allows providing profound techno-economic background and proof when addressing the problems addressed in chapter 2. Keeping this goal in mind, the three defined collaboration concepts give shape to the structure of the remainder of this thesis.

Chapter 5 deals with the supranational planner. The Pareto-planner is considered in chapter 6 and the non-cooperative planning game in chapter 7. As depicted in Fig. 3.6, these three chapters not only differ in the degree of the assumed level of collaboration, but also in the degree of the mathematical complexity of formulating the different collaboration concepts as explicit models. Whereas the degree of assumed collaboration has already been addressed in this chapter, mathematical complexity is discussed throughout the following chapters. The further elaboration of these models is preceded by chapter 4 where the general characteristics of transmission planning models are discussed and choices are made for the subsequent models.

Although the next chapters could also be organized the other way around, i.e. with increasing degrees of collaboration and decreasing degrees of mathematical complexity, there are additional reasons for the choice made:

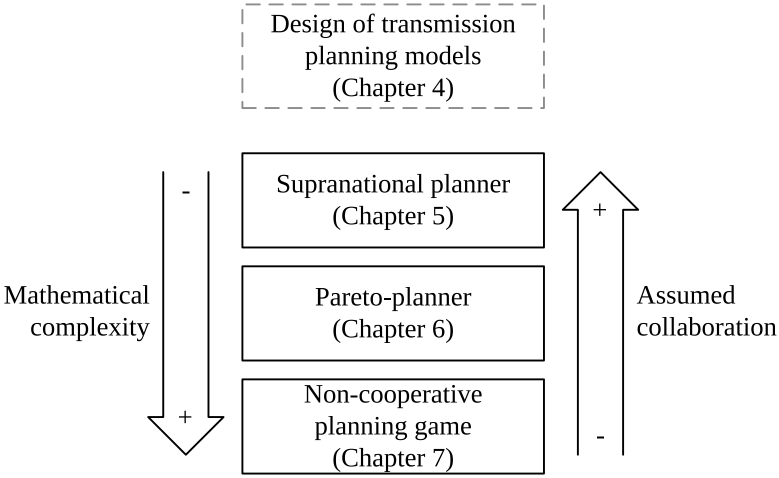

Fig. 3.6: Relation between further thesis outline and collaboration concepts

- The supranational planner most closely follows existing academic literature on transmission planning. Starting from these existing models the Pareto-planner can be considered as a logic expansion of known models. Although there is a close link with both other concepts, the non-cooperative planning game has less ties with existing transmission planning literature and is more than an expansion of existing models.
- The mathematical complexity increases in the proposed structure. Each next chapter can build further on the foundations laid in the previous chapters, thereby avoiding unnecessary repetition and guaranteeing a gradual approach. This should help the reader in grasping a better understanding of the problem.

3.4 Conclusions

The seams issues described in chapter 2 and the resulting research question can be captured in a more formal economic framework based on welfare economics. There is also a close link with game theory. Intuitively, the framework already allows indicating the relevance of an adequate compensation mechanism when the policy goals set at the European level are to be met with consent of the zonal level. Furthermore, it suggests that depending on the level of collaboration, a different outcome can be reached and there is no guarantee that in all cases European objectives are always met.

In order to assess this wedge, three collaboration concepts are defined. A first concept, the supranational planner, assumes that an adequate compensation mechanism is in place (or that zones can be forced to invest against their own benefit) and maximizes European welfare irrespective of the distributional effects.

Pareto-improvements are the prerequisite in convincing the zonal level without an adequate compensation mechanism covering for possible zonal welfare losses. Otherwise no zone is willing to accommodate projects lowering their own welfare even if they are increasing overall welfare. The second collaboration concept, the Pareto-planner, starts from this assumption. It looks for an investment plan maximizing overall welfare on the supposition that no compensations are made. The distributional effects are accounted for by adding the initial welfare level as a lower bound to the problem, i.e. it has to be Pareto-improving. Additionally, it is argued that a relaxed interpretation of the zonal welfare constraints can help closing the gap with the supranational planner.

A last concept is more difficult to capture in the general framework as it depends on specific characteristics of the different zones involved. Assuming no collaboration at all between different zonal planners and no commitment to act in line with the European policy goals, zonal welfare maximizing planners play a non-cooperative planning game, i.e. the third collaboration concept.

The three collaboration concepts serve as a story line for the remainder of this thesis. Their relationships in terms of degree of assumed collaboration and mathematical complexity, but also their ties to the academic literature on transmission planning play a decisive role for the further structure. However, before addressing the three planning collaboration concepts themselves, the general design of transmission planning models is discussed.

4

Design of transmission planning models

After having defined and further refined this thesis' research question in chapters 2 and 3, this and the following chapters deal with transmission planning models. Whereas chapters 5, 6 and 7 consider specific models linked to the earlier defined planning concepts, this chapters describes the main contours of those models. The main building blocks of the models used are determined and supported by a thorough literature review on transmission planning models.

Firstly, section 4.1 discusses the literature on transmission planning models. The discussion is structured by the use of common design building blocks. Each model consists of a combination of different features brought together to serve a particular research question. A building block can relate to the scope of a model or to a basic assumption. Here, only major constituting elements are discussed. Often also more specific assumptions are made as discussed in chapters 5, 6 and 7 when the specific models are described. Secondly, the model design choices are presented and argued in section 4.2.

Note that the presented overview of building blocks focuses on models only, not on how they are solved. Solution methods are considered to be chosen after the model is properly designed. Taking into account that this thesis does not focus on solution methods but rather on the models themselves and the comparison of their outcomes, they are merely considered as a tool and therefore discussed separately for each planning concept in the following chapters.

4.1 Transmission planning model building blocks

In the literature several fruitful attempts for classifying transmission planning models have been undertaken. A large number of publications is classified in [34] according to three main building blocks: solution methods, treatment of the planning horizon and consideration of the electricity sector. Whereas in [34] the intention is to really classify publications on transmission planning with electricity sector considerations as just another building block, this particular block is used in [35] to structure its overview. Starting from planning in vertically integrated utilities, changes and new requirements for transmission planning in a market context are defined. Nevertheless, the treatment of the planning horizon and solution methods are used as building blocks at a lower level to differentiate between different publications.

An alternative building block is extensively discussed in [36] where the distinction is made between deterministic and non-deterministic transmission planning approaches. The importance of this building block is linked to the changed market context which introduced increased uncertainty for transmission planners, but also changed the transmission planning objectives. In both [34] and [35] these aspects are mentioned but not put forward as true building blocks. They are rather considered as consequences of a changed market context. It is however argued by [36] that not all uncertainties are related to the market and some are inherent to the transmission planning problem, e.g. the random nature of load or unplanned outages.

Furthermore, the changed interrelationship between transmission and generation investments as a consequence of market context changes not only increases uncertainty but also gives rise to a more fundamental question in planning. Who takes the lead: transmission or generation planners? The choice between proactive or reactive transmission planning is not always explicitly recognized as a separate building block, but can significantly influence a transmission planning model design [37, 38].

As the market is (at least partly) responsible for determining the dispatch of load and generation and consequently for the flow patterns, it is a major driver for transmission investments. There are different approaches possible for taking this into account in a transmission planning model. Either the market can be separated from the planning model and serve as an exogeneous input or it can explicitly be part of the model. Market modelling itself is therefore an important building block for transmission planning models.

A last building block is driven by the research question of this thesis and addresses the way neighbouring grids and the international context are taken into account. In the literature this is not identified as a critical issue and has been overlooked so far.

Based on the analysis of the overview papers and the above argumentation, several building blocks cosntitute a model's design. It is clear that the generally formulated building block of electricity sector considerations or changed market context can be covered by several more specific blocks as its impact on transmission planning model design is diverse.

The following building blocks are shortlisted for further exploration in this section:

- Treatment of the planning horizon
- Uncertainty incorporation
- Transmission planning objectives
- Market incorporation
- Link with generation investment planning
- Multi-area awareness

4.1.1 Treatment of the planning horizon

Transmission investment planning deals with investments to be done in future. It is important how this time period is addressed. In general, there are two options: a static or dynamic planning approach [34, 35].

A static approach plans for a single moment in time, e.g. a specific year. A static transmission planning determines how the network has to look like at a future moment in time. According to [35] it answers questions like *what* and *where*, but not *when*. It does not make any consideration on the timing of the investments or the sequence in which investments have to be done. The path followed from now until the considered moment in time is not specified.

In contrast, a dynamic approach explicitly answers the *when* question. Instead of statically determining the network for a future moment in time, it defines which investments have to be undertaken in the period starting now until a specified later moment. It provides an investment strategy and can lead to better results. In [38] the superiority of the dynamic approach is illustrated in a context with lumpy investments and returns to scale. Obviously, the quality of the result depends on how detailed the modeled time period is and at how many moments during that period actions can be undertaken.

Dynamic models outperform static ones in the quality of output, but they are significantly larger, more complex and more difficult to solve. Therefore, mostly static models are used in literature. However, a third approach identified in [34] reconciles the more easy to solve static and qualitatively better dynamic models to a certain extent: pseudodynamic models. This kind of models solves a sequence of static models for different subsequent moments in time in an attempt to approximate the dynamic approach.

Recent examples of static transmission planning models can be found in [39–43]. Dynamic planning models are less common. In [44] a dynamic investment planning model involving both generation and transmission investments is presented. Another example is found in [45] where the advantages of being able to act on different moments in time in the dynamic approach are exploited by allowing flexible grid operation and thereby alter investment needs. In [46] both a static and a dynamic model are solved. A more extensive list of examples for both approaches is provided in [34, 35].

4.1.2 Uncertainty incorporation

In general, there are two groups to be distinguished in this category: deterministic and non-deterministic models. The former differs from the latter by not taking into account the probability of occurrence or degree of importance of an event [36]. An interesting example to illustrate the difference is the way reliability is dealt with. For instance, N-1 rules are deterministic as each possible outage is given the same probability of occurrence and the system has to withstand each such event [47].

According to [36] there are several kinds of uncertainties transmission planning has to deal with. They all put different requirements on planning models. Infrastructure availability, actual load, wind power output, generation expansions and closures, future market rules,... all create uncertainties.

General approaches to deal with uncertainties are based on scenario techniques and decision analysis [36]. In the former different scenarios are identified, each with a specified weight reflecting its importance or probability of occurrence. An investment plan is then determined according to a decision rule like expected cost, minimax regret or Pareto-optimal. Decision analysis is based on an event tree and looks for a flexible plan able to adapt quickly to emanating events. This kind of approaches is for instance used in [41, 44, 48–50] to take into account different states of the system or different market outcomes (e.g. peak and off-peak demand, wind power output, unexpected outages). For specific types of uncertainties, e.g.

actual load or wind power output, models using statistical approaches (e.g. chance constraints, time series models, etc.) can be used [47, 51–53].

4.1.3 Transmission planning objectives

Transmission planning is a complex problem and the network has to serve multiple goals simultaneously. This is reflected in the different kinds of objective functions put forward in the literature. Historically, transmission investment cost minimization and reliability-driven planning received a lot of attention, but since the emergence of electricity sector restructuring more and more attention goes to market-oriented and even sustainable objectives.

Several models only address transmission investment costs in the objective function sometimes supplemented with costs due to losses. Such models minimize these costs subject to constraints for ensuring a feasible power flow given power injections and withdrawals or maintaining a specified reliability level [54].

Reliability can also serve as an objective rather than as a constraint. A typical example is the trade-off between investment costs and reliability gains [55–57]. In [58] the choice between different investment options is based on the minimization of estimated costs related to a lack of reliability. The vulnerability of the transmission network to terrorist attacks is minimized in [59, 60].

Market-oriented objectives are modelled in various ways. Whereas some publications explicitly focus on minimizing congestion costs emphasizing the market facilitation function of the transmission network [61–63], other publications define different kinds of welfare functions to be maximized. Sometimes welfare is calculated based on a market outcome and consists of functions of consumer and producer surplus [41, 64, 65]. In other cases an approach minimizing a total cost function including investments costs, losses, congestion costs and costs related to not supplied energy is adopted [66]. In [63] this is done in a multi-objective framework.

In [67] an illustration of a model including a sustainable objective function is provided. A common welfare maximizing transmission planning model including economic dispatch and transmission investment costs is extended with the costs related to CO_2 emissions. An alternative approach considering sustainable criteria is found in [68], where land use is minimized.

Furthermore, combining several (incompatible) goals in a multi-objective framework is being extensively investigated [63, 68–71]. Often an assessment of objectives is required as they not always point in the same direction. Also the European energy policy objectives aiming at security of supply, competitiveness and sustainability are sometimes incompatible and require trade-offs [72].

Note that not optimizing for a particular goal via the objective function, does not mean it is not at all accounted for in a model. For instance, market-oriented objective functions can still be constrained by reliability considerations. A popular approach is to add N-1 constraints to the problem [44, 50, 54, 69].

4.1.4 Market incorporation

Especially in a changed context with generation and load levels determined via the market and the transmission planner acting as facilitator of that market, it is important to analyze how the market is incorporated in transmission planning models. In the end, the market determines which generators inject power in the network and how much is withdrawn at different demand locations. Put differently, the market is responsible for the flow patterns observed in the network and it is the transmission planner's task to invest efficiently in order to accommodate these patterns.

Several models explicitly incorporate the market as a separate problem within the transmission planning model and thereby make the transmission investment decision dependent on the market outcome and vice versa.[1] This is especially true for models focusing on economic issues. Most of the time a DC Optimal Power Flow (OPF) is used maximizing welfare subject to network constraints [41, 44, 45, 48, 64, 67, 73]. A DCOPF can be used to represent a perfectly competitive market ran by an ISO when it is assumed that all participants bid their true costs. Alternatively, it can be considered as a pool-based market clearing bids from all participants. The dual variables in a DCOPF[2] can be interpreted as locational marginal prices (LMP) or nodal prices [74]. However, also other market representations are possible. For instance, in [75] an oligopolistic market is used as underlying market determining load and generation levels.

Instead of setting the generation and load levels within the transmission planning model, some models start from ex ante determined levels. Note, however, that these values can still originate from a market outcome. However, the reciprocity between transmission investments and market outcome is lost. Examples can be found in [70, 76, 77]. Especially in models focusing on reliability issues this simplification is used [54, 55, 58].

Note that most models use a DC (optimal) power flow representation for modeling the power flows in the network.[3] Especially for economic analyses DC power flow is considered as sufficient and it is not required to rely on the more accurate but also more complex AC power flow representation [49, 78].

[1] See also chapter 5 for a more elaborate discussion on this matter.

[2] In particular, the dual variables linked to the nodal balance equations can be interpreted as nodal prices. They indicate the marginal cost of supplying an extra unit of energy in a particular node.

[3] The specific DC power flow assumptions are given in section 5.2.1.

Additionally, it is important to realise that in all market models implying the (implicit) auctioning of transmission capacity, such as all models relying on a DCOPF, the investor is not able to set prices for access to or use of its investment. The transmission planner only decides on the transmission capacity and the market determines the level of congestion revenues. No explicit tolling mechanisms are possible. This assumption is in line with European (and beyond) reality where tolls for transit flows have been abolished since market reforms took off (see also chapter 2).[4]

4.1.5 Link with generation investment planning

Market reforms changed the way transmission and generation are organized and their interrelation. The impact on investment planning is significant. Whereas it were mostly vertically integrated utilities covering both generation and transmission within one company, generation and transmission are now unbundled. They are now managed - and in many cases also owned - by different entities. Whereas generation and transmission used to be part of a single planning process, they are now planned separately with limited (if any) information exchange. Nevertheless, the one can never be planned without knowledge or assumptions about the other. The question then rises who comes first?

From the perspective of transmission planning they are two options. Either transmission planning is proactive and by investing it provides signals towards generation investments or a reactive approach is adopted where transmission is planned given actual and anticipated generation expansions. This fundamental difference and its welfare implications are studied in [37, 38, 81].

Although theoretically the proactive planner leads to ideal investments and a higher welfare level, it is argued in [38] that the reactive planner is probably the most realistic assumption.[5] Transmission planners are said not to be willing to take the risk to end up with stranded investments. It is not the economic consequence that prevents them from acting in an optimal proactive way, it is rather the embarrassment of taking wrong investment decisions that drives planners to a reactive approach.[6]

[4] In the more general non-cooperative pricing and investment literature, this would be considered as an unconventional assumption. Often a two-stage game is developed where in the first stage the investment capacities are determined and the second stage the prices for using the infrastructure [79, 80].

[5] In [38] the reactive planning policy is called the practical planning policy.

[6] It should, however, be noted that reality is often more complex and for different generation technologies a different approach could be applied. For instance, the lead time to develop a new high voltage line is nowadays longer than for the construction of gas-fired power plant. The opposite holds when nuclear power plants are considered. This distinction is not further taken into account.

Although many publications start from the assumption of a reactive transmission planner, i.e. with a given (future) generation park, strategic investment decisions at the generation side impacting transmission investments are also modelled. Recent examples of the former group include [41, 46, 48, 61, 66], the latter approach is applied by [73, 82]. Despite a changed market context, several publications develop planning models under the old paradigm of an integrated or coordinated planning of generation and transmission investments with the purpose of being used as references for regulatory authorities or for markets without restructuring [44, 83]. Another coordinated but market-based approach for investments is found in [84, 85]. They model an ISO governing a coordinated capacity planning process involving both generation expansions and merchant transmission investment proposals.

4.1.6 Multi-area awareness

Keeping in mind the research question addressed it is relevant to investigate how transmission planning models deal with an international or multi-area context, i.e. a context with neighbouring networks, cross-border energy exchanges and other planners.

Although it is generally acknowledged as something to take into account [86, 87], it is interesting to note that only very few papers presenting a modeling approach take this context into consideration. Almost all papers design transmission planning models as if the transmission planner covers the entire network. The network is considered as a single zone. This can be interpreted in two ways: (i) either there are no neighbouring networks or their existence is neglected or (ii) the transmission planner decides for the entire network, including the neighbouring zones. The latter interpretation corresponds to the supranational planning concept defined in section 3.1.2. For instance, in [88] multi-area generation and transmission planning is addressed but the adopted viewpoint fits into the supranational planning concept. Similarly, a single zone viewpoint for interregional planning in Europe is applied in [89].

Although generally overlooked in the transmission planning literature, there are a number of publications touching on a situation with multiple transmission investors. They link the problem to game theory. In [90] the followed investment rationale is based on merchant investors maximizing own profit rather than welfare. Although no quantitative analysis is provided, it is clearly indicated that merchant investors are participating in a non-cooperative planning game and their interactions should not be neglected. As further discussed in chapter 7, the non-cooperative planning game concept has a close connection with this problem.

Whereas a non-cooperative game is assumed in [90], a multi-agent approach embedded in cooperative game theory is followed in [91–94]. The focus is on finding a fair cost allocation convincing involved parties or regions to cooperate.

In [91] no attention is given to the planning problem itself and the analysis starts from a given set of possible coalitions and their potential gains.[7] Similarly, in [92, 93] potential transmission investors, namely loads, generators and third party investors, try to find a coalition in order to maximize their benefit via bilateral negotiations. Although multiple agents interacting in a game are modeled, no areas are defined. As a consequence, the analysis is not fully applicable on the European situation where transmission infrastructure is always hosted by a particular country which itself is a player in the game. In contrast, in [94] countries are specifically addressed. Although the planning part is underdeveloped in [91–94], their discussion is obviously linked to the topic discussed in this thesis as it addresses the potential of compensation mechanisms.[8]

Not only compensation mechanisms are dealt with in literature, but also related multi-area issues are discussed. Several papers address investment cost allocation in a multi-area context. In particular the European situation is discussed [26, 27]. Other topics include operational issues like multi-area optimal power flow calculation [95] and phase-shifting transformer coordination [96], power exchanges covering multiple zones [97], cross-border balancing [3] and organization of transmission operators and regulatory authorities across boundaries [98].

4.2 Design choices

For the three planning collaboration concepts defined in chapter 3 to be comparable, they should all be modelled according to same design choices. Based on the above analysis, this section presents the choices made for the specific models discussed in the following chapters. The set of model design properties should be such that it is possible to address the research question. The differences in planning concepts should become clear. Nevertheless, it is preferred not to make the models too complex in order to keep results more tractable and intuitively understandable.

The following choices are made for each building block:

- *Treatment of the planning horizon:* A static planning approach provides a picture of how the grid should look like at a specific moment in time. A static transmission planning model already allows differentiating between the three planning concepts. They differ mostly in objective functions and constraints and timing is not a primary concern in the concepts. As a consequence, a dynamic planning setup leading to larger and more complex models is not required.

[7] Moreover, it is unclear from the paper whether only transmission or also generation investments are part of the cooperation.

[8] Note that the compensation mechanisms addressed in the mentioned publications discuss an allocation of benefits and are not limited to cost allocation only.

Note, however, that it is argued in [90] that a dynamic approach can reveal additional interaction between different national planners in the non-cooperative planning game. It is illustrated how merchant investors can suffer from pre-emption and a war-of-attrition game. This is not further explored.

- *Uncertainty incorporation:* A deterministic approach is opted for. This keeps the models less complex and still allows to address the research question. Additionally, the deterministic approach can define several scenarios that can be taken into account and properly weighted. For instance, transmission planning can be done taking into account multiple load levels representing peak and off-peak periods.

- *Transmission planning objectives:* Although in a European context there are several objectives in play, the analysis in this thesis is limited to changes in economic welfare.[9] This is clearly linked to the objective of competitiveness or affordability of energy supply. Although it is theoretically possible to extend the models towards other objectives, sustainability and security of supply are not addressed. These objectives are also not covered by the constraints. This implies, for instance, that no N-1 requirements are enforced. Although it is technically possible to implement such extra constraints, it would render models more complex and results less tractable. Moreover, as long as other elements can be expressed in monetary terms (e.g. the cost related to the visual impact of new lines or crossing a nature reserve) they can be easily incorporated within an economic welfare oriented objective function.

- *Market incorporation:* An explicit market formulation as a part of the transmission planning models is chosen. Although this makes the models more complex, this is required to enable the analysis of the effects of transmission investments on prices and dispatched generation and load. The interplay between market and transmission network is considered as crucial. Additionally, the choice for an economic planning objective, i.e. maximizing economic welfare, also calls for an explicit market modeling.

  Furthermore, a DCOPF assuming marginal cost bidding and maximizing overall economic welfare is chosen as network and market model as it can be used to represent a perfectly competitive market. It is assumed that all loads and generators place bids according to their true costs. Locational marginal pricing is used to determine energy prices and to take into account the effect of congestion on prices.

- *Link with generation investment planning:* As argued in section 4.1.5 the reactive planner is likely to be the most realistic assumption. Moreover, a reactive planning model is less complex. Consequently, the models in this thesis start from an ex ante known and fixed generation park.

[9] In chapter 5 economic welfare is further defined.

- *Multi-area awareness:* Given this thesis' research question, multi-area awareness is crucial. The different planning concepts vary in the way how the different areas or zones are dealt with. Whereas in the supranational concept a single zone viewpoint is adopted, the Pareto-planner and the non-cooperative planning game differentiate between various zones. For the Pareto-planner this is limited to putting constraints on the zonal welfare distribution only. The non-cooperative planning game goes a step further and also considers transmission investments as a zonal decision variable.

  With respect to the market incorporation it is assumed for all planning collaboration concepts that an integrated market is present. This implies that all generators and loads participate in a single market covering all zones and that one set of prices and quantities clears the market for all players. This viewpoint matches with the European goal of a single internal electricity market.

The above outlined set of design choices give shape to the models presented in the next chapters and ensure that they are consistent and comparable. Sometimes extra assumptions are required for a specific model as discussed for each model separately.

4.3 Conclusions

In this chapter transmission planning models are anatomized according to different building blocks defining a model design. Based on the transmission planning literature and the research question addressed in this thesis a total of six building blocks are identified: treatment of the planning horizon, uncertainty incorporation, transmission planning objectives, market incorporation, link with generation investment planning and multi-area awareness.

It is observed in the literature that planning models differ significantly in their design choices. Driven by a particular research question complexity is added in one building block in order to have a more subtle representation of the planning problem. Other building blocks are dealt with in a lighter way in order to keep models simpler and results more tractable.

For all building blocks a range of design choices is possible and examples covering this spectrum can be found throughout the literature. Only for the building block concerning multi-area awareness, there is an observed lack of publications addressing this issue in concrete planning models. This thesis is an attempt to contribute in this research field.

Based on the analysis of the different design building blocks for transmission planning models, a choice of design options is made for the models presented in the next chapters. A static, deterministic transmission planning model with the aim of maximizing economic welfare is opted for. A perfectly competitive market determining locational marginal prices and the generation and load dispatch covering all zones is assumed to interact with the planning problem and is explicitly modelled as a part of the planning problem. Furthermore, a reactive planning philosophy with respect to generation expansions is adhered. The treatment of multiple areas or countries is dealt with in different ways for the different planning concepts and is a part of the addressed research question.

5

Supranational planner

In this chapter the first planning collaboration concept is further elaborated. Firstly, the intuition and structure of the supranational planning concept is discussed in section 5.1. Based on this structure a mathematical formulation is proposed in section 5.2. It is further refined in order to come to a setup which still has the required complexity for dealing with the supranational planning concept, but is as simple as possible in order to be easily implementable. The necessary assumptions are highlighted. Next, the solution methods are briefly described in section 5.3. The last section of this chapter (section 5.4) introduces four examples which allow illustrating various aspects of the collaboration concepts and providing an insight in the model's sensitivities. The same examples are also used in the next chapters.

5.1 Model intuition and structure

As defined in section 3.1.2 the supranational planner maximizes overall welfare by deciding on transmission investments in the entire interconnected grid as if it is one single zone. Hence, the supranational planner can decide on any investment anywhere in grid even when it causes effects elsewhere in the network, e.g. in another zone than the zone hosting the infrastructure. Or stated in terms of the building block of multi-area awareness as discussed in section 4.1.6, the supranational planner acts as if he is not aware of the fact that the addressed network covers multiple zones.

In his objective function the supranational planner makes a trade-off between welfare and transmission investment costs. He invests until the marginal benefit of an extra unit of transmission infrastructure, i.e. a marginal increase in overall welfare, equals the marginal cost of investing more in infrastructure. This trade-off is not trivial and implies that in the optimum there can still be congestion. Hence, any objective function aiming at reducing congestion entirely and obtaining a so-called copper plate is fundamentally flawed [38].

By investing in transmission infrastructure, the planner can influence the level of welfare attained. The crucial link between both is the market. By providing the market with a better transmission grid more trade opportunities can be realised and more welfare created. However, the market itself is out of direct control of the transmission planner. It is a separate problem that acts as a set of constraints for the transmission planner. As indicated in Fig. 5.1 this reciprocal relationship between the transmission planner and the market can be captured by a bilevel structure. From a structural point of view, the market problem constrains the transmission planner in a similar way as direct constraints of the planning problem itself. In Fig. 5.1 the latter is indicated by the so-called investment constraints.

Such a bilevel problem structure is well known in economics as well as operations research theory. In the former such structure is found in Stackelberg games. In this type of game there are two players: a leader and a follower. The leader has the advantage of first deciding on his output. When taking his decision the leader already anticipates the response of the follower on his decision. He determines the best-response curve of the follower which he takes into account when maximizing his own objective function. The follower then decides given the decision of the

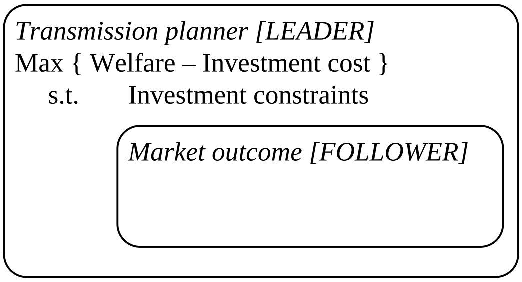

Fig. 5.1: Bilevel structure of the supranational planning concept

leader. In the context of the supranational planning concept, the transmission planner is obviously the leader whose decisions are then used as an input for the market problem. Hence, the planner decides on optimal investments taking into account the market's best response to his investment decisions.

A mathematical classification of a bilevel problem is found in operations research theory. An optimisation problem with another problem in the constraints is called a Mathematical Program with Equilibrium Constraints (MPEC). The equilibrium constraints refer to the underlying problem. The best response of the underlying problem given the decision of the upper level problem can be written as a set of equilibrium constraints.[1] MPECs are further discussed in chapter 6.

5.2 Mathematical formulation

After highlighting several assumptions, this section provides a mathematical formulation of the supranational planner based on the bilevel structure. Next, it is argued that, under the given assumptions, this structure can be simplified towards a single-level structure. This proves to have significant advantages with respect to finding solutions for the supranational problem. Finally, several assumptions are relaxed and the model is again reformulated with the aim of accommodating lumpy investment decisions using discrete variables instead of a continuous representation.

5.2.1 Assumptions

Before providing a mathematical formulation of the supranational planner, necessary assumptions are outlined and clarified. Major assumptions are already covered by the selection of design options in chapter 4. They include:

- Static treatment of the time horizon.
- Deterministic planning with the possibility of using scenarios covering different situations.
- Economic welfare is to be maximized. Security of supply, sustainability or other objectives are not accounted for in the objective function nor in the constraints.
- The market is explicitly represented in the planning models via a DCOPF.
- A reactive planning approach starting from a fixed and known generation park is modelled.

[1] For an optimisation problem the equilibrium conditions are the Karush-Kuhn-Tucker (KKT) conditions.

- The supranational planner acts as a single zone planner treating all countries together as one zone.

Although not changing the basic nature of the model, several other assumptions are required concerning the following issues:

- Possible investments,
- Network representation,
- Shape of demand, generation and transmission cost functions,
- Overall welfare definition.

Possible investments

modelling transmission infrastructure investments requires a strict definition of what exactly the investment options or decision variables of the planner are. Firstly, in this thesis it is assumed that the planner can invest in extra transmission capacity on each existing or ex-ante defined transmission corridor. This implies that the transmission investor is bounded by an ex-ante network topology.[2] Hence, the planning models never suggest connections between nodes that are not linked before the model is run. If new links should be explored by the model, they have to be already added to the network incidence matrix on beforehand. Stated otherwise, the possible investments are capacity upgrades of existing transmission corridors or at least ex-ante determined corridors. It is not further specified which technology is used for this upgrade, e.g. increasing the voltage level or adding an extra circuit. Investments are expessed in MW, i.e. in terms of extra transmission capacity.

Secondly, it is assumed that a capacity upgrade of any corridor is possible. This assumption is used in, for instance, [48, 49, 62]. The set of possible investments is not ex-ante limited to a shortlist of possible projects. When planning problems become larger in scope or when there are other constraints which are not modelled limiting investment options (e.g. environmental or urban planning constraints), it might be appropriate to start from a limited set. This contributes to a reduced model size and calculation times. A predefined limited set of investment options is used in, for instance, [60, 76, 99].

Thirdly, investments can be modelled in a continuous or discrete way. Whereas a continuous representation allows a capacity increase of any size, a discrete treatment assumes that capacity increases are lumpy and only steps of e.g. 100 or 500 MW are possible. The step size depends on the available technologies. A discrete

[2]Network topology is defined as the network defined by nodes and connections between them. It can be represented by a network incidence matrix.

representation is more realistic. Unfortunately, by introducing discrete variables the model complexity increases significantly. Whereas the model is first developed using continuous variables, in section 5.2.4 a discrete representation of investment options is provided. Throughout this thesis both approaches are used depending on the concept or example considered. However, unless clearly stated otherwise, continuous variables are assumed.

Network representation

As already briefly mentioned in section 4.1.4 a DCOPF is used to model the market and consequently also the power flows in the network. A DC load flow is a linear approximation of the AC power flow equations based on the following assumptions [78]:

- Voltage angle differences are small,
- Line resistance is negligible,
- Flat voltage profile over the entire network.

It is generally accepted that the DC approximation can be used for economic applications [49]. As discussed earlier it has been widely applied in transmission planning literature.[3] In [78] it is argued that under certain conditions a DC representation is sufficiently accurate. In [100] this is validated for the UCTE network. In this thesis it is assumed that these conditions are met. As a consequence of using a DC representation losses and reactive power issues cannot be analysed in this thesis.[4]

Investments in the network are likely to have an impact on the technical characteristics determining the load flow. However, for the sake of simplicity it is assumed that reactances - the only characteristic taken into account in a DC load flow - do not change when increasing the transmission capacity. By doing so, the linear nature of the load flow equations does not change after introducing investment variables. In this thesis this assumption is only used for the continuous representation of investments.[5] It corresponds to assuming fixed Power Transfer Distribution Matrices as modelled in [49] and applied in [50]. In section 5.2.4 this simplification is removed and discrete capacity increases affecting the total reactance of a corridor are modelled.

[3] See section 4.1.4.

[4] Note, however, that methods have been developed to extend the DC method with (an approximation) of losses, e.g., in [101].

[5] Note, however, that it is possible to use a continuous representation and at the same time alter the electrical characteristics. One option is to make the reactance of a line a function of the decided investment level. The formulation becomes non-linear is such a case. An example can be found in [102].

Shape of demand, generation and transmission cost functions

Demand is considered elastic and linearly decreasing with the price. Generation costs are assumed to be linearly increasing with the output. In some examples constant generation costs are assumed. Non-convexities like minimum run levels and start-up costs are not taken into account. Only variable generation costs linked to fuel costs are taken into account. Other cost increasing factors like ramping requirements are also ignored. By assuming generation cost functions, abstraction is made from a specific underlying generation mix. The generation cost function can be understood as a merit order with increasing marginal costs.

Transmission costs are assumed to be linearly increasing with the transmission capacity. No economies of scale are assumed.[6]

Overall welfare definition

As discussed in section 4.2, a purely economic objective function maximizing welfare is opted for. Several measures for economic welfare exist. In [41] social welfare, merchandising surplus, consumer and producer surplus (CS and PS) are proposed as metrics for measuring the economic effects of transmission investments. In this thesis overall welfare is defined as the sum of net consumer and net producer surplus and congestion revenues (CR). They are all valued equally. This implies that CS is considered as important as PS or CR. As a consequence, it is possible that welfare transfers occur from consumers to producers and vice versa. The planners are assumed to be indifferent to this matter. This is a rather strong assumption. It is not unreasonable to think that from a zonal perspective PS is not valued equally with CS and CR because generation facilities are often owned and operated by international companies. Generation profits (i.e. PS) is hence not necessarily linked to a particular zones. This issue is particularly relevant in the remaining two concepts, where zonal welfare is explicitly calculated (see also Appendix B).

Net consumer surplus is defined as the quantity consumed in a node multiplied by the difference between the willingness to pay of the load and the price paid in that node. This boils down to the area below the demand function minus the area corresponding to the payments made. Net producer surplus is the profit

[6]For electricity transmission infrastructure economies of scale exist. Assuming economies of scale has as a consequence that in the optimal outcome it is for investors no longer possible to rely on congestion rents only to finance the investment cost. Extra side-payments are then required. In the electricity transmission sector this is covered by transmission tariffs charged upon grid users. These tariffs are often a function of the energy withdrawn from or injected on the network. Not only economies of scale, but also other elements (e.g. reliability constraints) make such tariffs a necessity to cover the enitre network cost. This issue is addressed by [103] for transmission infrastructure.

at generation side calculated as the revenues received minus the costs made. Congestion revenues are calculated as the price difference between the nodes at both side of a link multiplied by the flow over that link.

The supranational planner maximizes overall welfare and therefore sums net CS, net PS and CR over the entire network. An aggregated calculation is more straightforward. Overall welfare is then defined as the aggregated gross consumption surplus, i.e. the area below the aggregated demand function[7], minus total generation costs. CR are inherently included in this way of calculating overall welfare. Formulating overall welfare in this way only uses variables concerning generation and load levels and thereby avoids a formulation requiring the prices in each node.[8]

5.2.2 Bilevel supranational planning model

Under the assumptions outlined above, the supranational planning concept can be mathematically formulated as follows:

Maximize

$$\sum_p \sum_n T_p \left(A_{n,p}\, d_{n,p} - \frac{1}{2} B_{n,p}\, d_{n,p}^2 \right) \tag{5.1a}$$

$$- \sum_p \sum_n \sum_t T_p \left(C_{n,t,p}\, g_{n,t,p} + \frac{1}{2}\, D_{n,t,p}\, g_{n,t,p}^2 \right) \tag{5.1b}$$

$$- \sum_l \left(CL_l\, LN_l\, x_l \right) \tag{5.1c}$$

subject to:

$$\forall l \qquad x_l \geq 0 \qquad [\alpha_l] \tag{5.2}$$

[7]The aggregated demand function is the horizontal sum of the demand functions in each node.

[8]As further discussed when the supranational planner and the Pareto-planner are mathematically formulated, nodal prices are obtained from the dual variables of the planning optimisation. Demand and generation levels are primal variables. A less complex model is obtained when everything can be formulated in either primal or dual variables, rather than when both sets are used together.

$$\text{where} \quad \forall p: \qquad d_{n,p}, \theta_{n,p}, \theta_{n_s,p}, g_{n,t,p} \in arg: \quad Maximize$$

$$\sum_{n} \left(A_{n,p}\, d_{n,p} - \frac{1}{2} B_{n,p}\, d^2_{n,p} \right) \tag{5.3a}$$

$$- \sum_{n} \sum_{t \in \Omega^T} \left(C_{n,t,p}\, g_{n,t,p} + \frac{1}{2}\, D_{n,t,p}\, g^2_{n,t,p} \right) \tag{5.3b}$$

subject to:

$$\forall n,p \quad \sum_{t} g_{n,t,p} - d_{n,p} - \sum_{l} \left(INC_{l,n} H_l \sum_{b} (INC_{l,b} \theta_{b,p}) \right) = 0 \quad [\lambda_{n,p}] \tag{5.4a}$$

$$\forall l,p \qquad -F^{max}_l - x_l \leq H_l \sum_{n} (INC_{l,n}\, \theta_{n,p}) \qquad \left[\mu^a_{l,p}\right] \tag{5.4b}$$

$$\forall l,p \qquad H_l \sum_{n} (INC_{l,n}\, \theta_{n,p}) \leq F^{max}_l + x_l \qquad \left[\mu^b_{l,p}\right] \tag{5.4c}$$

$$\theta_{n_{s,p}} = 0 \qquad [\xi_p] \tag{5.4d}$$

$$\forall n,t,p \qquad g_{n,t,p} \leq G^{max}_{n,t,p} \qquad [\nu_{n,t,p}] \tag{5.4e}$$

$$\forall n,t,p \qquad g_{n,t,p} \geq 0 \qquad [\rho_{n,t,p}] \tag{5.4f}$$

$$\forall n,p \qquad d_{n,p} \geq 0 \qquad [\kappa_{n,p}] \tag{5.4g}$$

The bilevel structure is clearly visible. The leader's objective function is given by (5.1). It is constrained by (5.2) and by the follower's problem. The objective function of the following market problem, i.e. the DCOPF, is found in (5.3). The equations in (5.4) are the market-related constraints. Note that the above problem has a convex quadratic objective function (both in the leader and follower's problem) and linear constraints. The remaining part of this section discusses the different levels of the above problem formulation in more detail.

Transmission planner's objective function and constraints (Leader)

The transmission planner's objective function in (5.1) consists of three terms. The first term (5.1a) represents the gross CS or the area below the aggregated demand function. In (5.1b) the total generation costs are calculated. Both terms are weighted by T_p representing the number of hours in period p. The sum of T_p for all p has to equal 8760 hours in order to be comparable with the annual transmission investment cost.[9] Note that these two terms are fully determined by $d_{n,p}$, demand in each node in each period, and $g_{n,t,p}$, generation in each node for each technology in each period. These two sets of variables are determined in the underlying market problem. Hence, welfare is clearly determined by the market outcome.

The transmission investments costs in (5.1c) are proportional with the length LN_l of the line, a unit cost CL_l per MW.km.year and the added capacity x_l. This assumes that there are no economies of scale in transmission investments.

The transmission planner is directly constrained by limitations on the feasible transmission investments. As discussed in section 5.2.1 it is assumed that only capacity increases on existing transmission corridors are possible. This is expressed by constraint (5.2).

Underlying market (Follower)

The transmission planner is also bound by the underlying market outcome, here modelled via a DCOPF. As for each period a different market outcome is possible, for each period p a DCOPF has to be added as a follower to the transmission planner's problem. These different DCOPFs are independent from each other.

As a DCOPF is an optimisation problem itself, it has an objective function and constraints. The objective function for a single period is given by (5.3). As again economic welfare is maximized over the entire network at once, gross CS minus total generation costs is maximized. The constraints in (5.4) represent network, generation and demand limitations and can be interpreted as follows:

- Kirchhoff constraints are enforced using (5.4a)-(5.4d). Nodal energy balances are maintained via the equality constraints in (5.4a). Constraints (5.4b) and (5.4c) ensure that flows are within their limits. Note that the transmission investment variable x_l is determining these limits and added to the already existing transmission capacity. The voltage angle in the slack bus is fixed by constraint (5.4d).
- Generation is bounded by its generation capacity and has to be positive according to constraints (5.4e) and (5.4f).[10]

[9] The annual transmission investment cost should be understood as the yearly amount to be paid when all costs of the asset during its lifetime and the investment cost are taken together and then recalculated to a yearly cost using an annuity [104]. Note that in the planning model described in this section existing infrastructure constitutes a sunk cost. Hence, it does not appear in the objective function. Only new investments are influencing the objective function value.

[10] Pumped storage is not taken into account.

- Demand has to be positive due to constraint (5.4g).

The Greek variables after each constraint denote the dual variables. Of particular interest is $\lambda_{n,p}$, which is the nodal price in node n in period p. It indicates the cost of supplying an extra unit of demand in the node and period considered.

5.2.3 Single-level supranational planning model

The bilevel supranational planning model from the previous section can be reformulated as a single-level problem. This is advantageous as it can enable the use of less complex solution methods. In this case, the crucial element for the simplification to be possible is the model chosen for the underlying market. As here a DCOPF is opted for, it turns out that the follower's objective function in (5.3) is already covered by the leader's objective function in (5.1).[11] As argued in [48] and implicitly assumed in [49] the constraints of the follower can simply be added as normal constraints to the leader's problem at the same level as constraint (5.2) on the feasible investment options. This avoids the necessity of looking for the (more complex) equilibrium conditions of the follower's problem and using those as constraints to the leader's problem. As a consequence, the bilevel formulation of section 5.2.2 can be simplified to a conventional QP formulation:

Maximize

$$\sum_{p} \sum_{n} T_p \left(A_{n,p}\, d_{n,p} - \frac{1}{2} B_{n,p}\, d_{n,p}^2 \right) \tag{5.5a}$$

$$- \sum_{p} \sum_{n} \sum_{t} T_p \left(C_{n,t,p}\, g_{n,t,p} + \frac{1}{2}\, D_{n,t,p}\, g_{n,t,p}^2 \right) \tag{5.5b}$$

$$- \sum_{l} \left(CL_l\, LN_l\, x_l \right) \tag{5.5c}$$

subject to:

[11] In [48] this is formulated as follows: *"... the objective function of the upper-level problem and the objective functions of all lower-level problems 'point to the same direction', i.e., all these objective functions align pursuing their respective targets."*

$$\forall n,p \quad \sum_t g_{n,t,p} - d_{n,p} - \sum_l \left(INC_{l,n} H_l \sum_b (INC_{l,b} \theta_{b,p}) \right) = 0 \quad [\Lambda_{n,p}] \tag{5.6a}$$

$$\forall l,p \quad -F_l^{max} - x_l \leq H_l \sum_n (INC_{l,n}\ \theta_{n,p}) \quad \left[\mu_{l,p}^a\right] \tag{5.6b}$$

$$\forall l,p \quad H_l \sum_n (INC_{l,n}\ \theta_{n,p}) \leq F_l^{max} + x_l \quad \left[\mu_{l,p}^b\right] \tag{5.6c}$$

$$\theta_{n_{s,p}} = 0 \quad [\xi_p] \tag{5.6d}$$

$$\forall n,t,p \quad g_{n,t,p} \leq G_{n,t,p}^{max} \quad [\nu_{n,t,p}] \tag{5.6e}$$

$$\forall n,t,p \quad g_{n,t,p} \geq 0 \quad [\rho_{n,t,p}] \tag{5.6f}$$

$$\forall n,p \quad d_{n,p} \geq 0 \quad [\kappa_{n,p}] \tag{5.6g}$$

$$\forall l \quad x_l \geq 0 \quad [\alpha_l] \tag{5.6h}$$

The interpretation of the different constraints remains unchanged. Note, however, that the meaning of the dual variables has slightly changed compared to the bilevel formulation. For instance, in constraint (5.4a) $\lambda_{n,p}$ was linked to the objective function of the DCOPF. Now, $\Lambda_{n,p}$ is linked to the transmission planner's objective which not only includes gross CS and generation costs, but also transmission investment costs.[12] This nodal price still indicates the cost of supplying an extra unit of demand in node n in period p, but now also transmission investments are possibly determining this cost and not only increased generation. Therefore, $\Lambda_{n,p}$ can be seen as a long-term nodal price as for instance studied in [66], whereas $\lambda_{n,p}$ is the commonly known (short-term) nodal price.

5.2.4 Planning model with discrete investments

As outlined in the assumptions in section 5.2.1 and seen from the bilevel and single-level formulations of the supranational planner, transmission investments are modelled as continuous variables representing a capacity increase on existing connections. The size of the increase can take any value higher than zero.[13]

[12] Also the interpretation of the other dual variables has slightly changed. Unlike for $\lambda_{n,p}$ no new symbol is assigned to them because they are not further used in the text.

[13] Of course, an upper bound can be imposed on the capacity increase.

Furthermore, it is assumed that the electrical characteristics of the network do not change due to the increased transmission capacity. In this section these assumptions are relaxed and discrete transmission investment variables are introduced. This allows representing lumpy transmission investments, i.e. in fixed steps of several hundreds of megawatts, the addition of extra circuits in an existing corridor and the development of new corridors. However, the resulting model becomes more complex.

In the transmission planning literature discrete transmission investment representations are well-known. In general, two approaches are observed. The first introduces integer variables indicating the number of circuits. The second uses binary variables to decide on whether to accept an ex-ante defined candidate project or not.

Integer approach

Capacity increases can be modelled by the possibility of adding circuits parallel to existing circuits or on a newly defined corridor [43, 46, 63]. When extra circuits are added in parallel to a particular corridor l, the flow in a circuit l can be calculated as:

$$\mathrm{f}_{l,p} = \left(NC_l^{init} + NC_l\right)\ H_l \sum_n \left(INC_{l,n}\, \theta_{n,p}\right) \tag{5.7}$$

where NC_l^{init} and NC_l are integers respectively indicating the number of initial and extra circuits on transmission corridor l and H_l is the susceptance of a single circuit.[14] Whereas NC_l^{init} is a parameter known ex-ante, NC_l is the decision variable for the transmission planner. Note that when $NC_l^{init} = 0$ deciding on $NC_l \geq 0$ is equivalent to developing a new transmission corridor between two nodes which are not linked in the initial situation.[15] The formulation has become non-linear due to the bi-linear terms created by the multiplication of NC_l and $\theta_{n,p}$. This makes the problem more complex and may require more sophisticated solution methods.

[14]Note that the index l now rather indicates corridors which can contain multiple circuits than a particular line. In the remainder of this thesis l represents single connections or circuits, i.e. when there are more circuits in a corridor they are represented by as many instances of l as there are circuits.

[15]As discussed earlier it is important to notice that this possibility has to be provided to the model ex-ante as the model itself does not propose new corridors.

Binary approach

Another approach allows the model to choose between candidate investments which are ex ante defined [44, 48, 66]. Although the difference is subtle, there is a clear difference in how they are implemented. Whereas in the previous approach there is a single integer variable indicating the number of parallel circuits in a particular corridor, in this approach a binary variable is assigned to each candidate circuit. In fact, each new circuit is regarded as a new connection and is represented by a separate row in the network incidence matrix. Note that a candidate circuit can be parallel to an existing one or the first one in a new corridor. The flow on a circuit l is defined as:

$$\text{flow}_{l,p} = y_l \; H_l \sum_n \left(INC_{l,n} \; \theta_{n,p} \right) \tag{5.8}$$

where y_l is a binary variable indicating whether circuit l is built or not and $INC_{l,n}$ is the row of the network incidence matrix corresponding to the candidate investment. Also in this case the formulation is no longer linear due to the multiplication of y_l and $\theta_{n,p}$.

Linearisation of the binary approach

In this thesis the binary approach is used in transmission planning models as it can be easily reformulated as a set of linear equations without compromising the discrete nature of investment decisions. Also in the literature this approach has been followed. A number of publications applying such linearisation deals with switching in transmission grids and tries to optimise reliability or generation dispatch by also considering changes in the network topology.

Especially the work presented in [105–107] is interesting. Switching on or off transmission lines is there applied within a DCOPF and the objective function is therefore similar to the one of the supranational transmission planner. The only difference lies in the transmission investment costs. Whereas in the switching application no costs are assigned to switching lines on or off, in transmission planning an investment cost is assigned to the switching variable. Investing in a candidate line is equivalent to switching that line on at a certain cost. Of course, when multiple periods are considered an investment remains, whereas in the switching application the line can be turned off again when the generation and load dispatch changes. This switching approach for discrete investment decisions is applied in [41, 48]. A mixture of both approaches is found in [45] where transmission investment planning is investigated with an underlying DCOPF allowing switching to improve dispatch costs and possibly avoid transmission investments.

Mathematically, the single-level supranational transmission investment problem can be formulated as:

Maximize

$$\sum_{p}\sum_{n} T_p \left(A_{n,p}\ d_{n,p} - \frac{1}{2} B_{n,p}\ d^2_{n,p} \right) \tag{5.9a}$$

$$-\sum_{p}\sum_{n}\sum_{t} T_p \left(C_{n,t,p}\ g_{n,t,p} + \frac{1}{2}\ D_{n,t,p}\ g^2_{n,t,p} \right) \tag{5.9b}$$

$$-\sum_{l} \left(CC_l\ LN_l\ y_l \right) \tag{5.9c}$$

subject to:

$$\forall n,p \qquad \sum_{t} g_{n,t,p} - d_{n,p} - \sum_{l} \left(INC_{l,n} \mathrm{Flow}_{l,p} \right) = 0 \tag{5.10a}$$

$$\forall l,p \qquad -F^{max}_l y_l \leq \mathrm{Flow}_{l,p} \tag{5.10b}$$

$$\forall l,p \qquad \mathrm{Flow}_{l,p} \leq y_l F^{max}_l \tag{5.10c}$$

$$\forall l,p \qquad H_l \sum_{n} \left(INC_{l,n}\ \theta_{n,p} \right) - \mathrm{Flow}_{l,p} + M\left(1 - y_l\right) \geq 0 \tag{5.10d}$$

$$\forall l,p \qquad H_l \sum_{n} \left(INC_{l,n}\ \theta_{n,p} \right) - \mathrm{Flow}_{l,p} - M\left(1 - y_l\right) \leq 0 \tag{5.10e}$$

$$\theta_{n_{s,p}} = 0 \tag{5.10f}$$

$$\forall n,t,p \qquad g_{n,t,p} \leq G^{max}_{n,t,p} \tag{5.10g}$$

$$\forall n,t,p \qquad g_{n,t,p} \geq 0 \tag{5.10h}$$

$$\forall n,p \qquad d_{n,p} \geq 0 \tag{5.10i}$$

$$\forall l \in \Omega^L \qquad y_l \in \{0,1\} \tag{5.10j}$$

$$\forall l \in \Omega^L_{init} \qquad y_l = 1 \tag{5.10k}$$

The above formulation closely follows [48]. The intuition behind the linearisation is explained in [48, 107]. In constraints (5.10d) and (5.10e) M is a sufficiently large number. When $y_l = 1$ and the line is built, the term containing M becomes zero. Both constraints together then ensure that the flow through line l is correctly calculated. When $y_l = 0$ and the line is not built, the term containing M is dominating the other terms in (5.10d) and (5.10e) and thereby ensures that the constraints are met. The flow itself is brought to zero by constraints (5.10b) and (5.10c) as the maximum flow through the line becomes zero.

The part of the objective function concerning transmission investment costs has slightly changed to accommodate discrete investment decisions. The costs are now calculated using CC_l, a single annual total cost figure for the entire line l, and not a cost per MW installed. The cost for existing lines is assumed to be zero and does not influence the objective function value.

Constraints (5.10j) and (5.10k) respectively define y_l as a binary variable and ensure that already existing lines are active.

The supranational transmission planning problem in (5.9)-(5.10) has a quadratic objective function and linear constraints. It consists of both continuous and discrete variables. Therefore, it can be classified as a Mixed Integer Quadratic Program (MIQP).

5.3 Solution methods

The continuous single-level supranational planning model is a convex QP and the discrete model can be written as a convex MIQP. For both model types proven optimal solutions can be determined. Both problems are well known and can be solved easily using commercially available solvers. For this thesis the models have been implemented in GAMS using the CPLEX solver.[16]

When the problems become larger, the calculation time for the MIQP can become unacceptably high and other solution methods have to be used. As discussed in chapter 6 heuristics like genetic algorithms can provide near-optimal solutions in such cases.

[16]The General Algebraic modelling System (GAMS) is a high-level modelling system for mathematical programming and optimisation. CPLEX is a high-performance LP/MIP solver from IBM. (`http://www.gams.com`)

5.4 Examples and sensitivity analysis

After having introduced a mathematical optimisation model for the supranational planning concept in the previous sections, the remainder of this chapter introduces several examples. They are used to illustrate the basic principles of the model and to get grips on the true meaning of the supranational planning concepts. A simple example is also used to illustrate important sensitivities inherent to the model. The same examples are also used in the next chapters when the other planning concepts are modelled and compared.[17]

The examples and numerical data are chosen in function of the research question at hand. The selection is made with the purpose of illustrating potential differences between the different planning concepts. There is no guarantee that these differences occur in each situation.

The discrepancy between the different collaboration concepts only occurs when the involved zones have different characteristics. When the zones are entirely symmetric with respect to demand and generation cost functions, there is obviously no reason to trade and no rationale to develop the transmission link.[18]

Firstly, a simple two-zone example with each zone consisting of one node is introduced. It is used to outline the basic principles and to test the model with respect to a number of sensitivities. Next, two three-zone examples with each zone consisting of one node are given. They differ in network topology. Whereas the first three-zone example has a radial topology, the second has a meshed triangular network. In the three-zone examples especially the effects of a transit zone are interesting. Finally, a more complicated 14-node network with three zones is used to illustrate the effect when a single zone consists of multiple nodes. Additionally, the results obtained in the examples are linked to real European transmission systems.

For each example a description of the network and connected network users is given as well as the data used to obtain the presented results. All results are found using CPLEX in GAMS.

5.4.1 Two-zone example

A simple two-zone example is presented to explain how the supranational planning concept works. Also a detailed graphical analysis of the welfare effects is provided.

[17]This is true for all examples, except for the 14-node, three-zone example. The latter won't be used for the non-cooperative planning game.

[18]Except for reliability purposes, which are not analysed in this thesis.

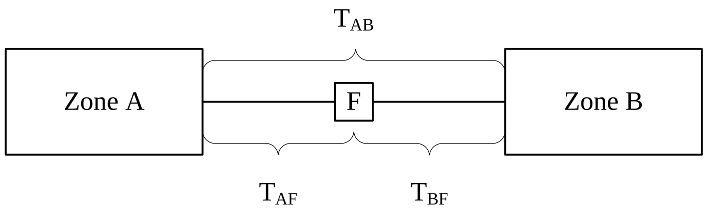

Figure 5.2: Two-zone example: network structure

Data

Assume two zones A and B each consisting of a single node and interconnected via a single transmission link T_{AB}. In figure 5.2, the auxiliary node F indicates the frontier between A and B. The transmission link can be split into two parts T_{AF} and T_{BF} respectively linking A and B to F.[19] Both segments are identical and have an arbitrarily chosen length of 100 km. Transmission investments come at an annual cost of 50 €/(MW.km.year). This cost corresponds approximately to a typical investment cost of a double circuit 380 kV line as calculated in [104]. The order of magnitude is the same as found in other studies like [108] and values retrieved from Transmission System Operators (TSO).[20]

In each zone there is available generation capacity and price-elastic demand.[21] It is assumed that generation capacity is abundantly available meaning that in each zone sufficient generation capacity is installed allowing it to be autarkic. Hence, maximum generation output levels do not constrain this example. The demand and generation cost functions are given in figures 5.3(a) and 5.3(b). Only one period is assumed meaning that generation and demand levels are equal in each hour during a year.[22]

[19] This split of T_{AB} in T_{AF} and T_{BF} is not particularly relevant for this chapter, but this example is referred to when the other collaboration concepts are discussed and illustrated in the next chapters.

[20] Private communication with a European TSO and UK values in [109].

[21] It is possible to do the analysis with price-inelastic demand. Although this would simplify the problem, it makes the examples less useful with respect to the other planning concepts presented in the next chapters.

[22] In terms of the mathematical formulations in section 5.2, there is only one element p in the set of periods.

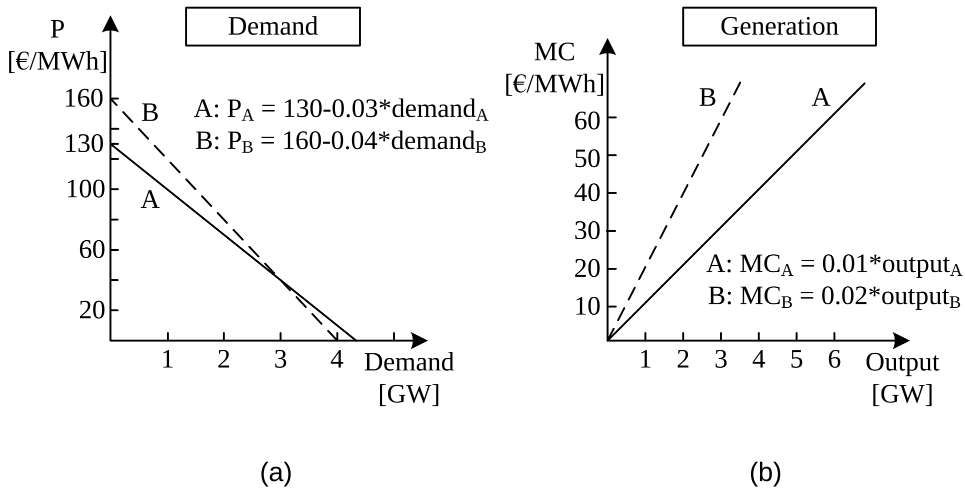

Figure 5.3: Two-zone example: (a) demand functions and (b) generation cost functions

Results and welfare analysis

In Table 5.1 the results for the two-zone example are given. The results (excluding transmission investment costs) are shown on an hourly basis. The situation without a transmission link is compared to the supranational planning solution.

Obviously, in the situation without transmission link, demand and generation are matched at the zonal level. As there is no link, there are also neither congestion revenues, nor investment cost. Due to the higher generation costs in zone B, demand is lower and the price is higher. CS in zone B is lower than in zone A. The opposite is true for PS.

In the supranational planning solution a transmission link with a capacity of 945.2 MW is installed. This link causes the prices in both zones to almost converge. Whereas the price in zone A increases, zone B faces a lower price. Zone A is now exporting to zone B. Both zones enjoy a higher welfare (measured by CS+PS+CR). However, the breakdown into CS, PS and CR has altered. In zone A the higher price results in a lower value for CS, but a higher value for PS (and vice versa for zone B). The amount of CR collected on T_{AB} is split on a 50-50 basis between zones A and B.

The welfare effects can be further clarified using Fig. 5.4. For each zone demand and supply (i.e. generation cost) functions are given. In the middle of the figure

	No link		Supranational optimum	
	Zone A	Zone B	Zone A	Zone B
Generation [MW]	3250	2666.7	3958.9	2036.5
Demand [MW]	3250	2666.7	3013.7	2981.7
Price [€/MWh]	32.5	53.3	39.6	40.7
CS [€]	158437.5	142222.2	136235.7	177814.9
PS [€]	52812.5	71111.1	78364.6	41474.5
CR [€]	0	0	539.5	539.5
CS+PS+CR [€]	211250	213333.3	215139.8	219828.9
Transmission capacity [MW]	0		945.2	
Investment cost [€]	0		1079	
Total welfare [€]	424583.3		433889.7	

Table 5.1: Two zone example: overview of results on an hourly basis

	No link		Supranational optimum	
	Zone A	Zone B	Zone A	Zone B
Net CS	(IJL)	(VWX)	(IJL)-(FIJK)	(VWX)+(RUVW)
Net PS	(IJM)	(NVW)	(IJM)+(EIJK)	(NVW)-(TUVW)
CR	-	-	0.5×CRev	0.5×CRev
ΔWelfare	-		(IEF)+0.5×CRev	(RTV)+0.5×CRev

Table 5.2: Two zone example: welfare effects

the Net Export Curves (NEC) are shown for each zone. It shows for each zone the relationship of the market price and the net export (or import) volume.[23]

When the transmission capacity between both zones is zero, the market outcome is given by the intersection of supply and demand in each zone separately, represented by I and V for respectively zone A and B. Zone A is clearly the low-price region and has a higher demand. The transmission investment done by the supranational planner is shown in the middle pane of Fig. 5.4 and indicated by Cap. The new prices are determined by the intersection of the vertical line Cap with both NECs. Zone A becomes an exporter and zone B importer. Note that prices would converge completely when a capacity of 1000 MW is available. The shaded area (further referred to as $CRev$) in the middle pane is the amount of CR and equals the remaining price difference times the amount of electricity exported from A to B. The welfare effects are summarised in Table 5.2 by referring to areas in Fig. 5.4. Both zones enjoy a positive welfare effect. Note, however, that within a zone there can be a significant transfer between CS and PS.

[23] See [110, 111] for more information on Net Export Curves.

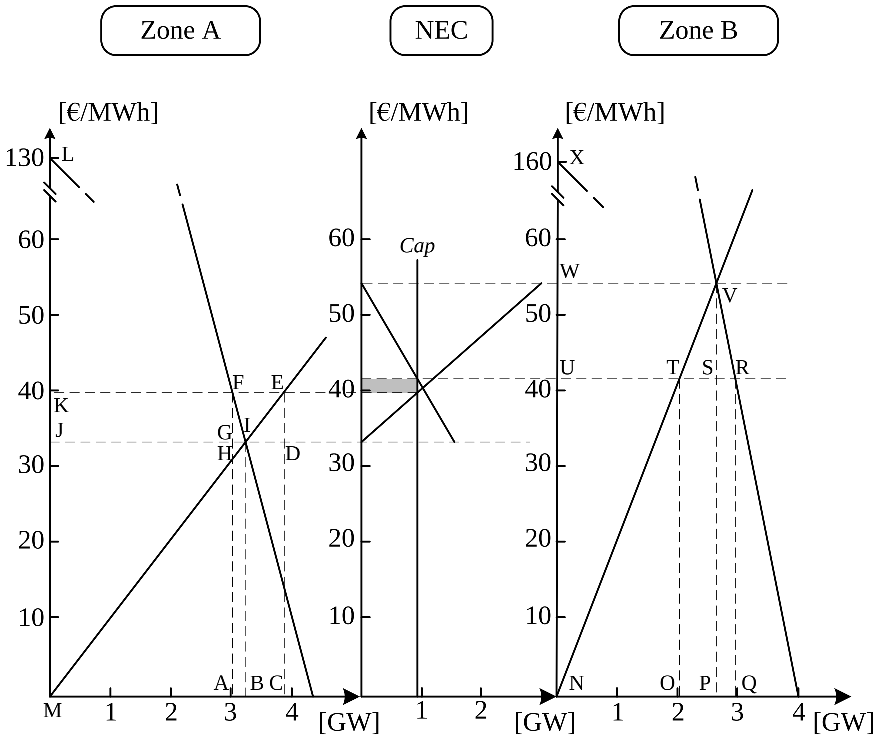

Figure 5.4: Two-zone example: welfare effects

5.4.2 Sensitivity analysis

Before discussing more complicated examples, a better understanding of the supranational planning model's behavior is provided by illustrating the model's sensitivity to changes in the input data. The simple and tractable two-zone example is used for this analysis.

It is not the purpose of this section to perform an extensive sensitivity analysis, but rather to illustrate sensitivities by using examples. The aim is to get better grips on how the model functions. Firstly, the difference or degree of asymmetry between both zones is explored. Secondly, the trade-off made in the objective function is further investigated.

Parameter	Zone A	Zone B
Intercept demand	130	130
Slope demand	-0.03	-0.03
Intercept generation	0	0
Slope generation	0.015	[0.005;0.025]

Table 5.3: Degree of symmetry: data for two-zone example

Degree of asymmetry

As already mentioned, there is no economic reason to develop a transmission link between two perfectly symmetric zones because there is no reason to trade between them. Asymmetry can originate from a different cost structure of the generation park or a different load profile. As indicated in Fig. 5.2, in the two-zone example discussed in the previous section both asymmetries are present. The impact of asymmetry is further illustrated by focusing on generation cost differences.

In Fig. 5.5 the impact of asymmetry on the optimal transmission capacity is illustrated using a two-zone example. As indicated by Table 5.3 the demand functions of zones A and B are identical. The generation cost function of zone A is fixed. The slope of the generation cost function of zone B varies within the interval [0.005;0.025]. Demand and generation levels in both zones and the optimal transmission capacity are shown in Fig. 5.5 for different values of generation costs in zone B. It can be seen from this graph that in the symmetric case, i.e. for the slope in B equal to 0.015, the optimal transmission capacity is zero and demand and generation levels are equal in both zones. Smaller values for the slope in B imply cheaper generation costs. Consequently, demand is higher and there is a strong incentive to trade, thereby justifying a higher transmission capacity. For higher values of the slope in B, generation is more costly, thereby lowering demand and the need for transmission capacity. Note that left from the symmetric case, zone B is cheaper than zone A and vice versa at the right side of the symmetric case. The flow on the transmission link has a different direction at both sides.

In the European context, several asymmetries can be observed, both at generation and demand side:

- Generation mix: The portfolio of installed generation facilities largely varies over different countries. It is the result of available (primary energy) resources, political choice, geography,...For instance, whether or not nuclear energy is installed significantly impacts a countries portfolio as it mostly are large facilities with cheap variable costs. Several countries have historically been dominated by nuclear power and hosted a large number of plants, e.g. France,

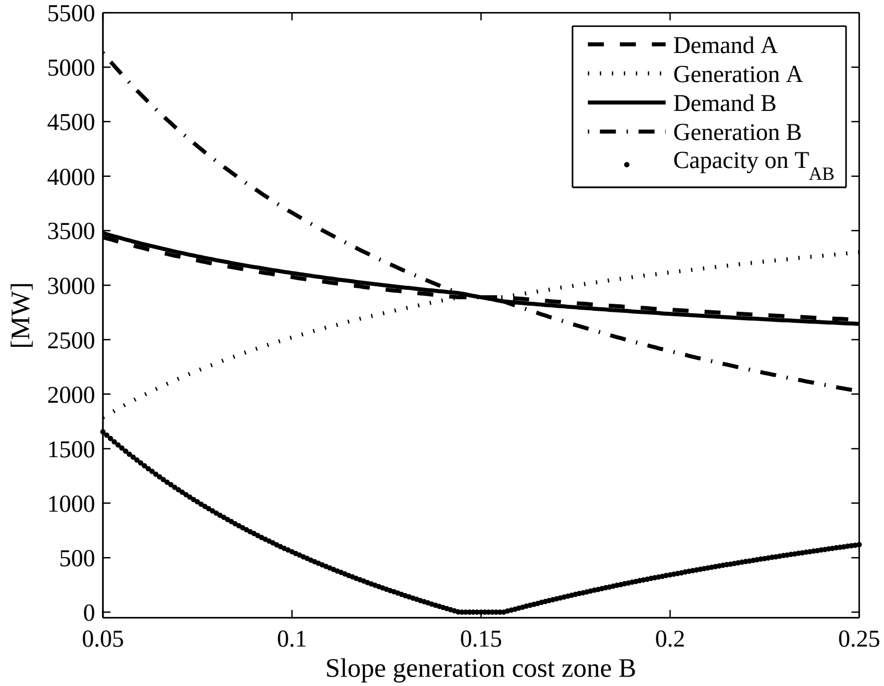

Figure 5.5: Two-zone example: impact of generation cost difference on demand, generation and investment levels

Germany, UK and Belgium. Today, nuclear phase-outs are observed in several countries, but not in all countries. Even stronger, some countries are investing in new nuclear facilities. These choices obviously impact the portfolio and creates asymmetry.

Another source of asymmetry at the generation side can be found in renewable energy sources. Many hydropower plants can be found in mountaineous countries such as Switzerland and Austria. Also in the Nordic countries the generation portfolio is dominated by hydropower, e.g. Norway. Southern countries have a larger potential for solar energy and coastal countries can profit from better wind conditions.

Those differences in generation portfolio are also reflected in the generation cost functions and give a natural incentive to trade. Hydro and thermal systems are considered as complementary. The same is true for hydro systems and systems with a substantial amount of intermittent resources.

- Demand side: Also at the demand side differences between countries occur.

A seemingly trivial issue is created by time zones. For instance, the U.K. and the continent operate with a time difference, which results in the demand peak to be shifted as well. This create opportunities to exchange peak power.

Another difference is observed at the consumption side. When consumers rely more on electricity for heating than on other energy sources (e.g. natural gas), this has an effect on the demand curve. Similarly, different industries have a different demand profile. For some sectors electricity is vital, for others demand is more elastic. As the industry mix is not the same in all countries, this again creates trade opportunities due to asymmetry.

Objective function trade-off

The objective function of the supranational planner consists of two important parts: welfare and transmission investment costs. It is the task of the supranational planner to properly balance both parts. Of course, this trade-off is driven by cost figures. To make an optimal trade-off, the relative difference between welfare and transmission investment costs should be carefully addressed. Therefore, in this section it is analysed how the decision of the supranational planner alters when this relative difference changes. For this purpose transmission investment costs are varied, ceteris paribus.

Transmission investment costs can vary because of a longer distance of the connection, but also due to a more expensive technology used. For instance, it is often stated that underground cables cost a multiple of overhead lines. This obviously changes the trade-off made by the planner and the optimal outcome. The two-zone example from section 5.4.1 is used to illustrate this effect. A fixed distance of 200 km is assumed. Varying the investment cost has the same impact as changing the distance. Transmission investment costs are varied from 0 to 1000 €/(MW.km.year). The latter is of course an extreme value, but it allows assessing when the investment costs becomes prohibitively high to justify any investment. A similar cost sensitivity analysis has been undertaken in [50] where it is investigated how a planner makes a trade-off between connecting wind farms and transmission investments.

In Fig. 5.6 it can be seen that the size of the transmission investment in T_{AB} decreases with its cost and falls back to zero when the costs exceed a value of about 920 €/(MW.km.year). Again, this is a very high value and is more than 18 times higher than the estimated cost of 50 €/(MW.km.year) for a double circuit 380 kV overhead line, which can be regarded as the most economical solution.[24]

[24]Of course, a 380 kV overhead line is not always the preferred solution from a technical or societal point of view. Here, it is just used as a reference. In general, the true cost of a particular technology can be higher than the pure investment cost, even when assessed from a life-cycle

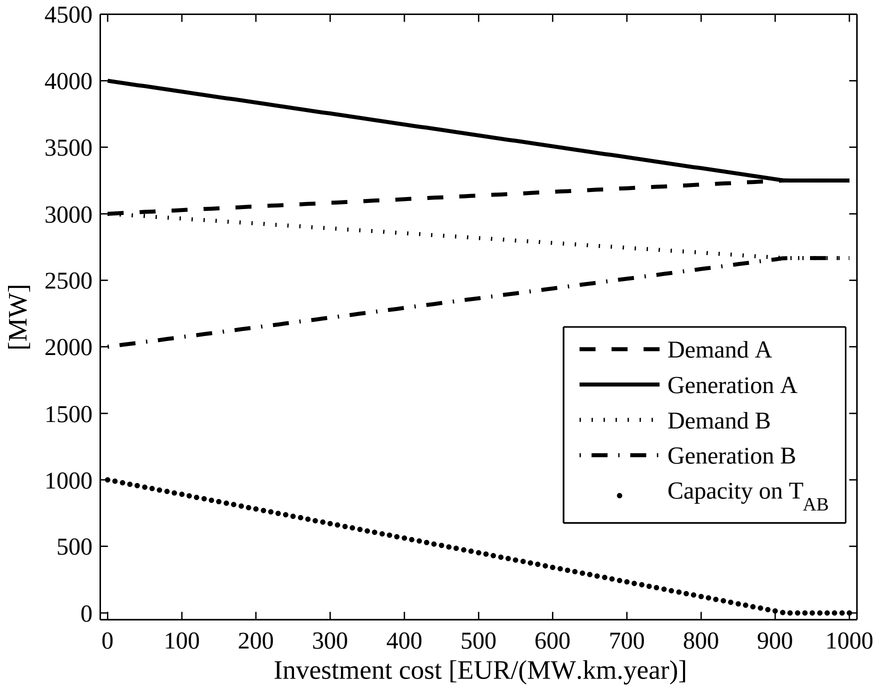

Figure 5.6: Two-zone example: impact of transmission investment costs on demand, generation and investment levels

More interestingly, it can be seen that when costs are only 5 times higher, which can correspond to relying on underground technology instead of AC overhead technology, the amount of transmission capacity decided by the supranational planner drops to approximately 736 MW or about 75% of the case with a cost of 50 €/(MW.km.year).

Another reason for using higher transmission investment costs is take into account external costs related to for instance visual impact, degraded value of property along the corridor, potential health hazards, nature reserve crossing... For several reasons public opposition is often fierce causing many delays for infrastructure projects [112]. Assigning a higher cost to transmission investments can also be a way to cover such 'acceptability' concerns. As this renders the trade-off between welfare and transmission investment cost less favourable for the latter, only those

point of view. Several problems as public acceptance, electromagnetic fields, urban planning requirements, etc. influence the true cost in one or another direction. See, for instance, [112] for a more elaborate discussion.

investments still being worthwhile even after external costs are then retained by the model.

From Fig. 5.6 it was already clear that for a higher investment cost a lower optimal investment capacity is found resulting in a different load and generation dispatch. The upper graph in Fig. 5.7 illustrates the impact on overall welfare. Overall welfare is scaled in such way that the overall welfare level of the situation where investments are free of charge equals 1. Compared to the reference case with a cost of 50 €/(MW.km.year) a loss of 1% of the overall economic welfare is incurred when the investment cost increases to about 200 €/(MW.km.year). Hence, in this example switching from overhead lines to undergound cables costs more than 1% of overall welfare. It is not the aim of the author to argue whether this is a high or low cost as this result is also sensitive to the input data, such as assumed elasticity of demand. The sole purpose of this section it to provide a sensitivity analysis allowing to better capture to subtleties of the model rather than to give an indication of realistic cost increases or savings by using different technologies.

In Fig. 5.7 the impact on overall welfare is illustrated. In the lower graph the relation between overall welfare and the installed capacity on T_{AB} is shown. Overall welfare is scaled in such way that the overall welfare level of the situation without a transmission link equals 1. An investment cost of 50 €/(MW.km.year) is assumed. Two observations can be made for this example. Firstly, investing in transmission capacity can create a welfare increase of more than 2% compared to the case without a transmission link. Secondly, for the given cost, there is an optimum of 945.2 MW. Installing more transmission capacity is detrimental to the overall welfare level. For other cost values the optimum is found at different levels, as indicated by Fig. 5.6.

5.4.3 Three-zone example: radial configuration

In this section a radial three-zone example is used to illustrate the supranational planning model in a context with a possible transit zone. Each zone consists of a single node. Additionally, in this example transmission investments are modelled in a discrete manner, i.e. transmission capacity expansions are lumpy and come per circuit.

Data

As displayed in Fig. 5.8 each zone has 7.5 GW of available generation capacity. Low, medium and high cost generators are located in respectively zone A, B and C. Their respective variable generation costs are 30, 43 and 70 €/MWh. In each zone the same inverse demand function is assumed, namely price $= 130 - 0.04 \times$ demand.

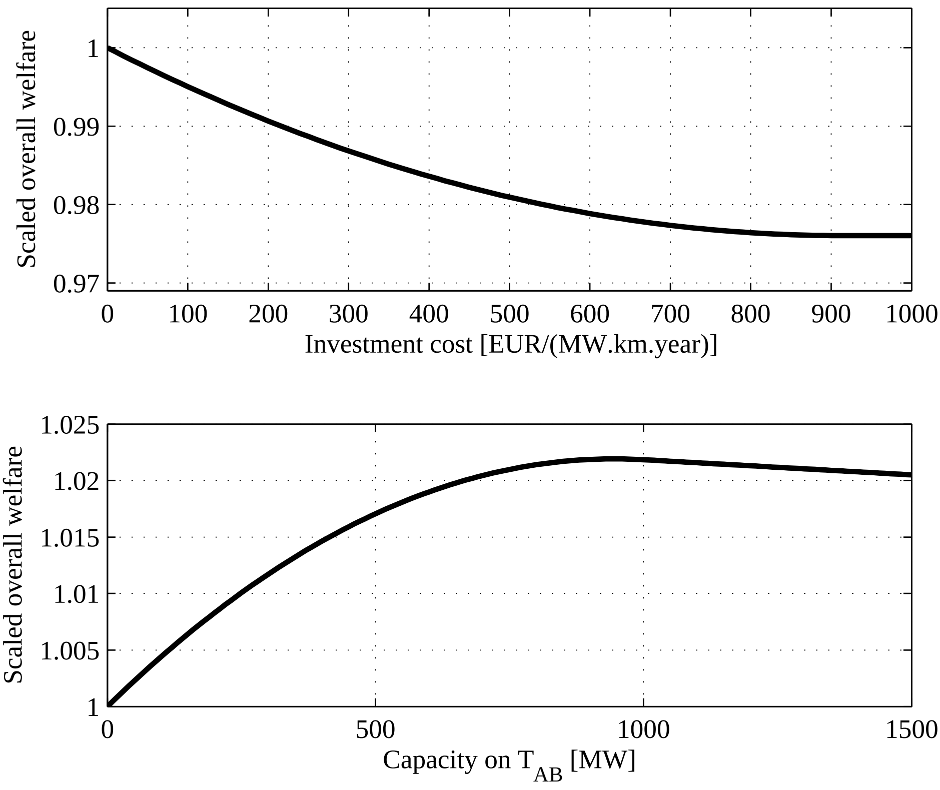

Figure 5.7: Two-zone example: (below) impact of installed transmission capacity (at a cost of for a cost of 50 €/(MW.km.year)) on overall welfare and (above) impact of transmission investment costs on overall welfare

Zones A and B are fairly well interconnected by three lines with a rating of 1 GW. Zone C is poorly connected to zone B by a single line with a rating of 450 MW. F_1 and F_2 indicate the frontiers between respectively zones A and B and zones B and C.[25]

All transmission lines, including new ones, are assumed to have equal impedance and a length of 100 km. Like the existing lines, new lines connecting zones A and B have a rating of 1 GW. They have a yearly cost of 30000 €/km. For new connections

[25] F_1 and F_2 are given here for completeness, but are only used in the following chapters. In the single-zone viewpoint adopted in this chapter borders between zones are neglected.

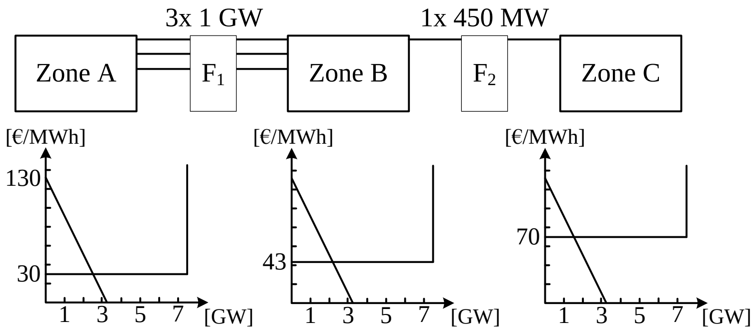

Figure 5.8: Three-zone radial example: data

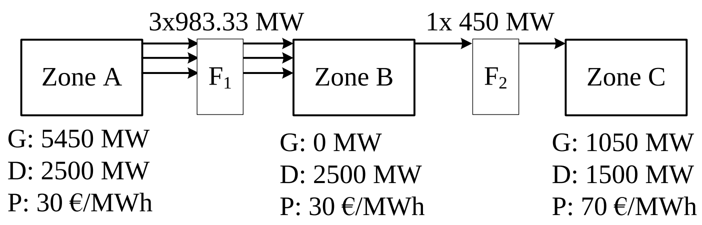

Figure 5.9: Three-zone radial example: initial dispatch

between zones B and C, a rating of 450 MW and a yearly cost of 20000 €/km are assumed, i.e. the same type of lines as in the initial situation. Transmission cost data are again based on [104]. No direct lines between zones A and C can be built.

Results and welfare analysis

The initial situation, i.e. before any transmission investments, is shown in Fig. 5.9. The low cost generator covers demand in zones A and B and partly in zone C. Due to the limited interconnection capacity between zones B and C, the high cost generator in zone C is dispatched to meet demand. The nodal price in zones A and B is 30 €/MWh, whereas in zone C the nodal price runs up to 70 €/MWh. This higher price causes a lower demand in zone C compared to the other zones. 18000 € of congestion revenues are collected on the line between zones B and C. They are split between those zones.

The supranational planner (Fig. 5.10) expands the corridor between zones A and B

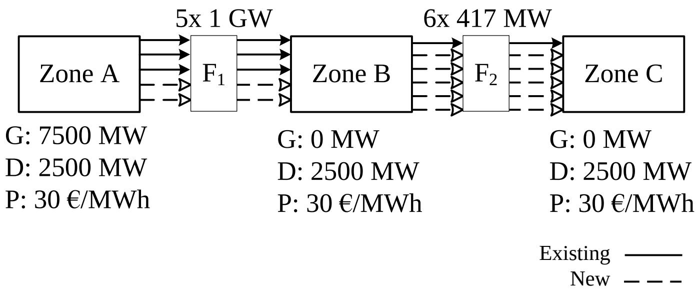

Figure 5.10: Three-zone radial example: supranational planner's solution

with 2 lines and adds 5 connections between zones B and C and thereby increases total welfare to a value of 375000 €. The 62000 € welfare gain by far offsets the required hourly investment cost of 1826 €(= $(100 \times 2 \times 30000 + 100 \times 5 \times 20000)/8760$). This causes an altered market outcome and changed nodal prices. The price in all zones becomes 30 €/MWh. Due to this lower price for zone C demand has risen. The generator in zone A now produces at full capacity. Due to the increased transmission capacity between zones B and C the high cost generator in zone C is not dispatched anymore to cover demand.

The welfare effects are summarised in Table 5.4. Although overall welfare increases, not all zones benefit. Zone A remains status quo. Whereas CS in zone C increased significantly compensating decreased CR, zone B only looses the CR it earned in the initial situation. Furthermore, note that in this three-zone example PS is always zero as the price never exceeds the marginal costs of the generators. This is due to the fact that in each zone there is sufficient generation capacity available.

This example serves very well in illustrating the assumption of possible welfare transfers or compensation mechanisms underlying the supranational planning collaboration concept. Firstly, with respect to the proposed transmission investments, it should be noted that investments take place in the entire network and not only in the zones benefiting from those investments. Therefore it is not unreasonable to expect that zone C finances the investments. The cost of 1826 € is largely compensated by zone C's welfare gain of 71000 €. Otherwise, why would zones A and B care about facilitating investments on their border? Secondly, as zone B in its role of transit country is suffering a loss in the supranational planning solution, zone C should also compensate zone B.

The discrete nature of the transmission investment variables is also visible in the results. For instance, between zones B and C investments are available in

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	125	125	45	125	125	125
PS	0	0	0	0	0	0
CR	0	9	9	0	0	0
ΔWelfare	-	-	-	0	-9	+71

Table 5.4: Three-zone radial example: hourly welfare effects (in k€)

lumps of 450 MW. A total of six parallel lines each with a rating of 450 MW, is installed between those zones resulting in a total transfer capacity of 2700 MW. When investments are represented in a continuous way, the result would be that a capacity of exactly 2500 MW (i.e. 6×416.67 MW) is installed.

5.4.4 Three-zone example: meshed configuration

The two previous examples used a radial network structure. In this example a meshed configuration is introduced. Again three zones are modelled. Hence, transit flows can occur.

Data

A triangular grid with three zones A, B and C is depicted in figure 5.11(a). Each zone consists of a single node. Each link has a length of 100 km and an equal impedance. The cost for investment is 50 €/(MW.km.year). An initial transmission capacity of 200 MW is already installed on each line. A continuous representation of transmission investments is used.

For the next chapters it is important to note that it is assumed that each zone hosts one link entirely. Links T_{AB}, T_{BC} and T_{AC} are located in respectively zones A, B and C.

In figures 5.11(b) and (c) linear demand and generation cost functions are given. Zone A hosts the most elastic demand function, but also the most expensive generators. The generator cost functions differ in the amount of power which can be delivered at zero variable cost, ranging from 0 MW in zone A up to 1000 MW in zone C. The slope of the generation cost function is equal for all zones.

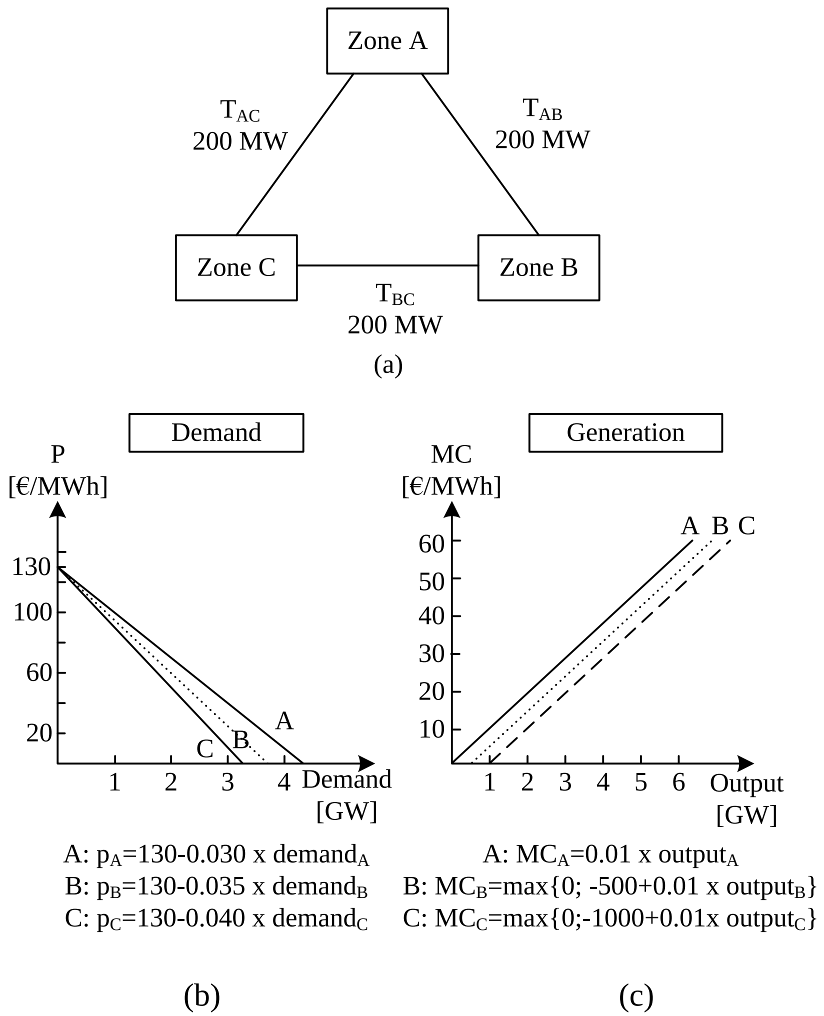

Figure 5.11: Three-zone meshed example: (a) network, (b) demand functions and (c) generation cost functions

Results and welfare analysis

The investments done by the supranational planner are shown in Table 5.5. The capacity increases on each link, but to a different extent. The newly available transmission capacity causes the generation and demand dispatch to change (Table 5.6). As the zones with the cheaper generation costs are now better connected

	T_{AB}	T_{BC}	T_{AC}
ΔCapacity [MW]	+115.9	+75.4	+391.4

Table 5.5: Three-zone meshed example: transmission investments

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
Generation [MW]	3014.5	3021.7	3028.8	2569.5	3031.5	3493.4
Demand [MW]	3328.5	2993.8	2742.8	3476.8	2991.0	2626.6
Price [€/MWh]	30.15	25.22	20.29	25.70	25.32	24.93

Table 5.6: Three-zone meshed example: dispatch and prices in the initial and supranational planning case

to the other zones, they are able to increase their generation output. This is in particular true for zone C, the cheapest zone. In zone A the generation level drops. Globally, demand has risen slightly with 29.5 MW. The nodal prices also changed significantly, especially in zones A and C. Due to the increased transmission capacity, nodal prices almost converge to the initial price of zone B. Note that zone B is the moderate zone with respect to demand elasticity and generation cost levels.

The welfare effects are summarised in Table 5.7. Although considerable increases of the available transmission capacity have taken place, welfare changes at the zonal level appear to be modest. Unlike in the previous example, significant welfare transfers between consumers and generators take place within a zone. The changed nodal prices are at the root of this effect. Although small in absolute numbers, the change in CR is noteworthy as its level is of the same order of magnitude as the zonal welfare changes.

As in the previous example, there is a negatively affected zone. Zone B's welfare slightly decreases. The other zones profit from the supranational investment decisions. Again, the assumption of zonal welfare transfers or a compensation mechanism is to be relied on. Also the observation concerning the parties bearing the transmission cost remains valid. Zone B is not likely to contribute voluntarily in the costs. This should be part of the compensation mechanism.

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	166.1	156.8	150.5	181.3	156.6	138.0
PS	45.4	44.4	40.9	33.0	44.7	56.0
CR	1.266	0.493	1.198	0.285	0.113	0.277
ΔWelfare	-	-	-	+1.735	-0.374	+1.758

Table 5.7: Three-zone meshed example: hourly welfare effects (in k€)

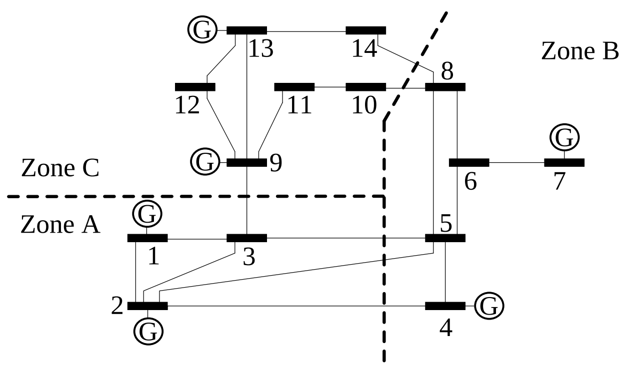

Figure 5.12: 14 node example: transmission corridors, location of generators and zone borders

5.4.5 14-node, three-zone example

Although in this example again a three-zone network is used, each zone now consists of multiple nodes.[26] On the one hand there are transmission links entirely located within a single zone and on the other hand there are cross-border links with both ends located in different zones. The zones themselves are positioned in a meshed way, i.e. each zone has at least one link with the other two zones. A discrete investment representation is used.

Data

Fig. 5.12 shows the network structure of the 14 node, three-zone example. Three zones A, B and C are defined. All transmission corridors are indicated as well as the

[26]The network topology resembles the topology of the IEEE 14 bus network. However, only the location of nodes and lines is maintained. Electrical properties, ratings, generation costs, etc. are changed.

Node	Zone	Variable cost	Initial generation	Supra generation
1	A	35	8849	10000
2	A	40	9200	10000
4	B	60	0	0
7	B	70	300	0
9	C	45	8755	9814
13	C	55	0	0

Table 5.8: 14 node example: Generation cost data (in €/MWh) and generation output for the different planners' solutions (in MW)

Corridor			# circuits		Corridor			# circuits	
From	To	Zone	Initial	Supra	From	To	Zone	Initial	Supra
1	2	A	6	0	6	7	B	7	0
1	3	A	10	3	6	8	B	6	0
2	3	A	6	0	8	10	BC	3	0
2	4	AB	8	0	8	14	BC	3	0
2	5	AB	12	4	9	11	C	6	2
3	5	AB	6	0	9	12	C	6	0
3	9	AC	3	0	9	13	C	6	1
4	5	B	6	0	10	11	C	6	0
5	6	B	6	4	12	13	C	6	0
5	8	B	7	1	13	14	C	6	0

Table 5.9: 14 node example: initial situation and different planners' investments

location of the generators. Each zone has two generators with an available capacity of 10 GW. The variable generation costs are given in the third column of Table 5.8. In each node the same linear demand function holds: price $= 130 - 0.04 * \text{demand}$. The initial number of circuits, i.e. before any investment, on each corridor is given by the fourth and nineth column of Table 5.9. New lines have a yearly cost of 20000 €/km. They have equal impedance, a length of 100 km and a rating of 450 MW. Additional lines with the same specifications can be added to each corridor shown in Fig. 5.12 with a maximum of six extra circuits per corridor.

Results and welfare analysis

In Table 5.9 the initial number of circuits on each corridor and the extra circuits decided by the supranational planner are given. In each zone transmission

Node	Zone	Initial		Supra	
		LMP	D	LMP	D
1	A	35.00	2375	44.37	2141
2	A	40.00	2250	44.31	2143
3	A	44.99	2125	44.40	2140
4	A	42.13	2197	44.29	2143
5	B	44.97	2126	44.26	2144
6	B	70.00	1500	44.74	2131
7	B	70.00	1500	44.74	2131
8	B	58.85	1779	45.55	2111
9	C	45.00	2125	45.00	2125
10	C	62.02	1699	45.26	2119
11	C	63.61	1660	45.11	2122
12	C	49.54	2012	45.05	2124
13	C	54.08	1898	45.10	2123
14	C	55.67	1858	45.25	2119

Table 5.10: 14 node example: Nodal prices (LMP, in €/MWh) and demand (D, in MW)

investments are proposed. Most circuits are added in zone A in order to allow the generation units in nodes 1 and 2 to increase their output. Also the generator in node 9 is better connected. Not surprisingly, the generators in nodes 1, 2 and 9 have the cheapest generation costs (Table 5.8).

For both the initial situation and the supranational planner's outcome Table 5.10 provides the nodal price (LMP) and local demand (D) in each node. Generators' output for both situations is given in Table 5.8. Due to the investments done by the supranational planner overall demand has risen. In particular in zones B and C demand increases. In zone A a slight reduction of demand is noticed. These changes in demand are caused by altered nodal prices. Due to the investments, the network is less congested and prices almost converge. The high prices initially observed in several nodes of zones B and C drop significantly. Zone A undergoes a slight price increase. These price drops are possible because the cheap generation units in nodes 1, 2 and 9 are now dispatched as much as possible.

All zonal welfare effects are summarised in Table 5.11. Per zone an aggregation is made by summing the effects for all nodes part of that zone. CR collected on a link within a zone are entirely allocated to that zone, for cross-border lines a 50-50 split is applied between the two zones linked by the line.

Compared to the initial situation overall welfare increases. A total investment of

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	304.4	340.2	425.2	275.0	454.6	540.3
PS	0	0	0	136.8	0	0
CR	78.8	129.3	87.1	0	6.2	1.4
ΔWelfare	-	-	-	+32.7	-8.7	+29.3

Table 5.11: 14-node example: hourly welfare effects (in k€)

3.42 k€ creates a welfare increase of 53.3 k€ (excl. investment cost). However, the benefits only accrue to zones A and C. Zone B is negatively affected. Although zone B enjoys lower nodal prices, increased demand and therefore also a higher level of CS, the significant drop in CR is not sufficiently compensated to render the supranational planner's result positive for zone B. The drop in CR also affects the other zones, but they are sufficiently compensated. In zone A a significant portion of PS is created as the generation units are inframarginal and therefore able to make profit. This largely compensates the drop in CR and the slight reduction in CS. The story is different for zone C where the drop in nodal prices and the according increase in demand and CS by large compensates the loss of CR. As in the previous example, a welfare transfer from zones A and C to B is required to compensate zone B for its loss. As the values in Table 5.11 do not yet take into account the investment costs, it is not sufficient to only finance the investments in zone B (i.e. an amount of 1.14 k€[27]).

5.4.6 From simple examples to reality

The four presented examples are obviously very simple and it can be doubted to what extent the results, i.e. the decided investments and the resulting welfare distribution, are not purely a result of the data. When making the link to the research questions and the policy debate of chapter 2, it is important to verify whether or not similar results would occur in real life. In particular, it is important to get an idea whether it is likely or not to have both winners and losers.

Real transmission grids of course count thousands of nodes and cannot always be simplified to a network of two or three nodes. Nevertheless, the presented examples should not be neglected. With some imagination, a two-zone network as used in section 5.4.1 can represent situations like the connection of the Iberian peninsula to France and the main continent or of the British Isles to the continent. Of course, this assumes that internally those countries are considered as copper plates.

[27]This value only takes into account the five circuits built within zone B and not the cost of the four new cross-border circuits between zones A and B. Including the latter does not change the conclusion.

Similar geographic matches can be made for the other examples and especially when, like in the 14-node, three-zone example, the national network is modelled as well. A similar topology is of course not sufficient to suggest that the observations with respect to welfare also hold in real situations. Calibration of cost functions and demand elasticities is also required. As already indicated in section 5.4.2 asymmetry between countries exists, but asymmetry alone is not always sufficient to have winners and losers (as illustrated by the two-zone example). It is difficult to check for real situations the observations made in the simple examples, but two recent contributions provide convincing indications.

Firstly, it is stated by [94] that for concrete investment projects in the Nordic countries costs and benefits are not equally distributed. This observation is based on a study of the Danish TSO. For instance, for the Great Belt project in Denmark it is stated that the overall gain is positive. However, Norway and Finland would loose welfare, whereas Sweden, Denmark and UCTE would win.

Secondly, the work presented in [113] discusses the welfare effects of an offshore grid in the North and Baltic Seas. Although the examples used in this thesis do not specifically address offshore networks, they could be applied in this context as well. It is concluded by [113] that overall welfare effects of several projects are positive, but that on a national level winners and losers can be identified. Also within a country, winners and losers exist.

These two studies suggest that the results obtained in the simple examples can be considered as realistic in terms of policy impact and they can be relied upon for a policy-oriented analysis.

5.5 Assessment of design choices

The purpose of this section is to discuss the impact of the design choices made in section 4.2. The underlying philosophy for the current choice is to keep the models as simple as possible but as complex as required to address the research questions.

Although often requiring more complex modelling and solution methods, the supranational planning model can be altered to accomodate other design choices. As the supranational planning model is closely linked to existing models described in the literature, the literature review of chapter 4 underlying the identification of transmission planning model aspects already provides an overview on how different aspects can be dealt with. Here, a limited number of specific elements are highlighted:

- Treatment of the planning horizon: The presented supranational planning model assumes a static treatment of the planning horizon. Adopting a dynamic planning model is possible, but would not alter the results with respect to the research questions. As it does not alter the single-zone viewpoint, the welfare distribution can sill be unequal and winners and losers still exist. As a dynamic approach would introduce a time dimension, the welfare distribution can change at each moment a decision is taken by the model. The identification of winners and loosers becomes more complex. However, it does not change the impact of the assumption of a perfect cost/benefit allocation mechanism. Mathematically, the model would become more complex and the time dimension requires more variables and often requires a mixed integer approach.

- Uncertainty incorporation: Introducing uncertainty in the supranational model would not alter the intuition of the model and how it contributes to answering the research question. Nevertheless, the impact on the model itself highly depends on the kind of uncertainty that is introduced. The current model allows a rather easy incorporation of different scenarios, for instance with respect to the installed generation portfolio. In fact, the provided model already inherently has such a feature. The possibility to use different time periods can be considered as scenarios. These scenarios are then weighted by the number of hours they occur, but any other kind of weight could be applied.

- Transmission planning objectives: The current model only considers economic welfare. Expanding the model towards other objectives is possible. As long as other objectives can be expressed in the same units (i.e. euros) the incorporation is straightforward and objectives can be easily compared and traded off. For instance, reliability can be expressed via a cost of non-supplied energy. Of course, not only the objective function matters, other objectives can also require extra constraints. Another apporach is to set up a multi-objective framework. Although such approach does not require the same measurement unit for each objective, the trade-off between different objectives is not straightforward. Weighting factors per objective become a necessity. Again the intuition of the supranational model does not alter by applying mutliple objectives. Only the interpretation of the welfare distribution has to be enlarged in order to capture all objectives. The same holds for the assumption of a perfect cost-benefit allocation mechanism.

- Market incorporation: The supranational planner assumes a perfectly competitive market modelled via a DCOPF. Assuming other market models, e.g. an oligopolistic setup, would not change the intuition of the supranational planner, but it would seriously affect the mathematical modelling. As explained in section 5.2, by assuming a welfare maximizing DCOPF as underlying market, the entire supranational planning model can be simplified to a QP. Other market models would result in more complicated models and require other solution methods. Additionally, the assumptions of the DCOPF hide to a certain extent the technical reality. A strong assumption is the flat voltage profile, which elimates some stress in the system. Although an AC network representation is possible, this overly complicates the model without contributing to the research questions.

- Link with generation investment planning: A reactive approach is assumed for the supranational planner. Adopting a proactive approach under the same assumption is possible (see section 4.1.5), without changing the intuition. It, however, adds another mathematical level to the problem, rendering the QP simplification impossible.

Multi-area awareness is not discussed in the above list, as this design aspect is varied throughout this thesis and direclty relates to the research question.

As can be observed from the above analysis, the supranational planning model can be altered in various ways without truly changing the intuition of the model with respect to the research question. Applying other or multiple objectives is the most interesting way to expand the existing model while still contributing to the research question. Taking into account different objectives results in a different welfare distribution as welfare then comprises different aspects.

5.6 Conclusions

In this chapter the supranational planning concept introduced in section 3.1.2 is further refined. A bilevel structure is proposed to model the investment problem faced by a supranational planner. At the upper level the planner takes the investment decision while taking into account its impact on the market outcome which takes place at the lower level. The market outcome is dealt with as a separate problem out of the planner's control. In this work a perfectly competitive market is opted for.

Translated to a mathematical model the bilevel structure can be represented by a Stackelberg game where the supranational planner is the leader and the market is the follower. Given the choice for a perfectly competitive market modelled as a DCOPF, the bilevel mathematical formulation has been reformulated as a single-level problem. This allows the use of less complex solution methods. Two alternatives are discussed for modelling the transmission investments themselves: a continuous and a discrete representation. Whereas the former results in models which are easier to solve, the latter makes the model more realistic. Both approaches are used throughout the examples.

By using a simple two-zone example, this chapter also provides an insight in the sensitivities underlying the supranational planning concept. Although in monetary terms transmission investments can be small compared to the overall welfare level, they can create a significant welfare effect. Of course, the size of the actual effects depends on the specific case considered. As illustrated, the degree of asymmetry between the different zones in the network and the cost of transmission itself are important factors influencing the ultimate welfare gains.

The different examples illustrate how the supranational planning concept truly works. By considering the entire network as a single zone abstraction is made of the underlying multi-area context. As a consequence, the proposed investments maximized overall welfare, but not all zones in the network necessarily benefit. Apart from the two-node example, the examples have been chosen in such way that they clearly show this effect.

Additionally, by referring to other studies it is indicated that this is not only an academic curiosity, but it is very likely to run in situations with winners and losers in real international transmission networks. Moreover, although the simplicity of two-zone and three-zone networks masks the complexity of the real world to some extent, at an international scale these simple topologies are relevant. Together, both observations imply that the chosen examples can be used for further policy-oriented analysis.

The important assumption of possible welfare transfers between zones plays a vital role when negatively affected zones occur. It is also observed in the examples that an allocation mechanism based on investment costs alone is insufficient to make the supranational planner's solution beneficial (or at least status quo) for all zones. The welfare loss or benefit can be significantly larger than the transmission investment costs. Hence, only reshuffling the costs does not always alters the incentives. In the next chapter extra constraints are added to the planning problem allowing to relax the assumption of the existence of mechanism arranging zonal welfare transfers.

6

Pareto-planner

In this chapter the second planning collaboration concept is profoundly analysed. Firstly, in section 6.1 the intuition and structure behind the Pareto-planning concept is discussed. Two variants of the Pareto-planner differing in the treatment of investment costs are distinguished. Next, for each variant two different mathematical formulations are given in section 6.2. A bilevel formulation and a single-level mathematical program with equilibrium constraints (MPEC) are described. For each formulation, a solution method is described in section 6.3. Genetic algorithms and mathematical optimisation methods are implemented. Finally, both formulations are required to analyse the examples in section 6.4. The examples clearly indicate the subtleties of the Pareto-planning collaboration concept and the differences with the supranational planner. The four examples of chapter 5 are also used here.

6.1 Model intuition and structure

The Pareto-planning collaboration concept is intuitively analysed. Two variants are distinguished. Next, the structure of the model is given. The differences with the supranational planning concept are emphasised.

6.1.1 Intuition

As defined in chapter 3 the second planning collaboration concept describes a Pareto-planner as a planner deciding on transmission investments with the objective of maximizing overall welfare, but constrained by the initial zonal welfare distribution. Whereas the supranational planner was built on the assumption of the existence of an adequate mechanism arranging welfare transfers between different zones, the Pareto-planner assumes that there is no such complete mechanism available. However, in one variant of the Pareto-planner a partial mechanism limited to cost allocation only is introduced. Hence, the Pareto-planner assumes less collaboration between different zones.

As already indicated in section 3.1.4 two slightly different variants of the Pareto-planner are possible:

- Pareto-planner *without* cost allocation (Pareto w/o CA),
- Pareto-planner *with* cost allocation (Pareto CA).

They differ in the definition of the welfare constraints with respect to the incorporation of transmission investment costs. Whereas in the Pareto-planner without cost allocation it is assumed that all zones have to bear the cost of transmission investments done on their territory, the Pareto-planner with cost allocation assumes that those costs can be allocated among the different zones in the network. The latter interpretation is obviously less stringent, but assumes more collaboration. Note that this collaboration is less intense than a full welfare distribution mechanism. Here, only investment costs can be redistributed over the different zones, other components determining welfare (i.e. CS, PS or CR) are not transferred. The overview in Fig. 3.6 is further refined in Fig. 6.1. In section 6.2 the difference between both variants is further clarified by means of a mathematical formulation.

Crucial for the welfare constraints is of course the definition of what constitutes zonal welfare. In line with the definition provided in chapter 5, here the sum of zonal PS, CS and CR is used. However, an alternative definition excluding PS is possible when it is assumed that PS is not considered as being zonal. Capital markets and the international scale of generation companies render that PS is not zonal anymore and local decision makers could therefore be more focussed on CS and CR. In general, by eliminating the possibility of internal welfare transfers (e.g. changing zonal CS for zonal PS) the welfare constraints become more restricted. Such an alternative definition is not used in this chapter, but appendix B provides a brief illustration of the possible effects. Note that also other definitions are possible. For instance, it could be argued to also exclude large industrial customers for the same reason as excluding PS.

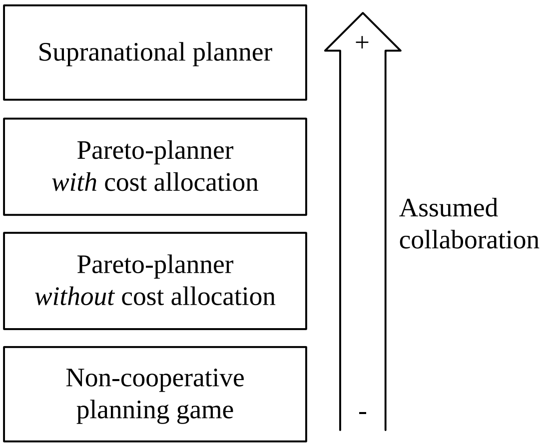

Fig. 6.1: Assumed collaboration in different models

It is important to realize that the Pareto-planning concept has two important drawbacks. Firstly, apart from checking whether no zone is worse off, there are no further constraints on the welfare distribution. As a consequence, the newly created welfare can be unequally spread across all zones and can appear unfair. Even stronger, it is possible that the burden of hosting new investments does not match the welfare distribution. Zones barely remaining status quo can be required to host significant new investments for the welfare gain in other zones. Also the internal split in CS, PS and CR can be different before and after investments. Secondly, it is perfectly possible that no Pareto-improvements are feasible. In such case, the presented solution equals the initial situation, i.e. no investments are done.

Despite the drawbacks, it is correct to state that in terms of multi-area awareness the Pareto-planner scores better than the supranational planner as it explicitly incorporates the welfare effects on different zones into its constraints. The objective function, however, remains unchanged and adopts the same single-zone viewpoint. It covers welfare and investments over the entire network and all zones at once.

6.1.2 Structure

The structure of the Pareto-planner is similar to the supranational planner. A bilevel structure or Stackelberg setup again captures the problem. The structure is presented in Fig. 6.2. The leader is the investment planner. Overall economic

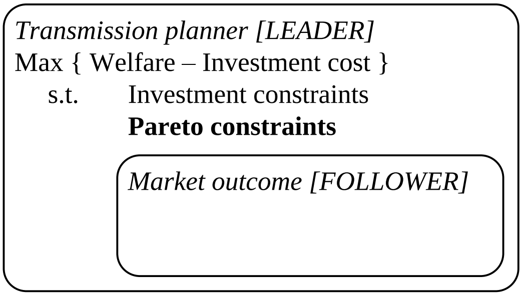

Fig. 6.2: Bilevel structure of the Pareto-planning concept

welfare minus total transmission investment cost is maximised. Also the investment constraints of the supranational planner remain unchanged. Different from the supranational planner are the newly added Pareto-constraints acting at the leader's level. The following problem is again the underlying market problem, which is the same as in the case of the supranational planner.

The extra Pareto-constraints are clearly the only difference from the supranational planner. Due to these extra constraints, the Pareto-planner is never able to outperform the supranational planner. When they are not binding, the Pareto-planner's outcome coincides with the supranational planner's solution.

6.2 Mathematical formulation

In this section the structure presented in Fig. 6.2 is transformed into a mathematical formulation. The Pareto-planner with cost allocation is first presented as it is more closely linked to the supranational planner than the Pareto-planner without cost allocation. The required changes to obtain the latter variant are presented in section 6.2.3.

Two mathematical formulations are given. Firstly, a bilevel formulation is provided. It clearly demonstrates the model structure and the link of the Pareto-constraints with the following market problem. Next, this bilevel formulation is rewritten as a single-level MPEC. In section 6.3 two solution methods are presented, each using one of the two formulations presented here.

6.2.1 Bilevel formulation of the Pareto-planner with cost allocation

The bilevel model of the Pareto-planner with cost allocation is given below. A continuous representation of transmission investments is used.[1]

Maximize

$$\sum_p \sum_n T_p \left(A_{n,p}\, d_{n,p} - \frac{1}{2} B_{n,p}\, d_{n,p}^2 \right) \tag{6.1a}$$

$$- \sum_p \sum_n \sum_t T_p \left(C_{n,t,p}\, g_{n,t,p} + \frac{1}{2}\, D_{n,t,p}\, g_{n,t,p}^2 \right) \tag{6.1b}$$

$$- \sum_l \left(CL_l\, LN_l\, x_l \right) \tag{6.1c}$$

subject to:

$$\forall l \qquad x_l \geq 0 \qquad [\alpha_l] \tag{6.2}$$

$$\forall z \qquad \sum_p T_p \Bigg(\sum_{n \in \Omega^{N(z)}} \left(A_{n,p} d_{n,p} - \frac{1}{2} B_{n,p} d_{n,p}^2 - \lambda_{n,p} d_{n,p} \right) \tag{6.3a}$$

$$+ \sum_{n \in \Omega^{N(z)}} \sum_t \left(\lambda_{n,p} g_{n,t,p} - C_{n,t,p} g_{n,t,p} - \frac{1}{2} D_{n,t,p} g_{n,t,p}^2 \right) \tag{6.3b}$$

$$+ \sum_{n \in \Omega^{N(z)}} \sum_l \left[\frac{1}{2} \left| INC_{l,n} \right| f_{l,p} \sum_b \left(-INC_{l,b} \lambda_{b,p} \right) \right] \Bigg) \tag{6.3c}$$

$$\geq WF_z^{init} \qquad [\beta_z] \tag{6.3d}$$

[1]Note, however, that the bilevel formulation is used to deal with discrete investments as explained in section 6.3.1. Only minor changes are required when a genetic algorithm is used to solve the problem (cfr. infra).

$$\text{where} \quad \forall p: \qquad d_{n,p}, \theta_{n,p}, \theta_{n_s,p}, g_{n,t,p} \in arg: \quad Maximize$$

$$\sum_{n} \left(A_{n,p}\, d_{n,p} - \frac{1}{2} B_{n,p}\, d_{n,p}^2 \right) \tag{6.4a}$$

$$- \sum_{n} \sum_{t \in \Omega^T} \left(C_{n,t,p}\, g_{n,t,p} + \frac{1}{2}\, D_{n,t,p}\, g_{n,t,p}^2 \right) \tag{6.4b}$$

subject to:

$$\forall n,p \qquad \sum_{t} g_{n,t,p} - d_{n,p} - \sum_{l} (INC_{l,n} f_{l,p}) = 0 \qquad [\lambda_{n,p}] \tag{6.5a}$$

$$\forall l,p \qquad -F_l^{max} - x_l \leq f_{l,p} \qquad \left[\mu_{l,p}^a\right] \tag{6.5b}$$

$$\forall l,p \qquad f_{l,p} \leq F_l^{max} + x_l \qquad \left[\mu_{l,p}^b\right] \tag{6.5c}$$

$$\theta_{n_s,p} = 0 \qquad [\xi_p] \tag{6.5d}$$

$$\forall l,p \qquad f_{l,p} = H_l \sum_{n} (INC_{l,n}\, \theta_{n,p}) \qquad [\psi_{l,p}] \tag{6.5e}$$

$$\forall n,t,p \qquad g_{n,t,p} \leq G_{n,t,p}^{max} \qquad [\nu_{n,t,p}] \tag{6.5f}$$

$$\forall n,t,p \qquad g_{n,t,p} \geq 0 \qquad [\rho_{n,t,p}] \tag{6.5g}$$

$$\forall n,p \qquad d_{n,p} \geq 0 \qquad [\kappa_{n,p}] \tag{6.5h}$$

The bilevel structure is clear. The leader's objective function is (6.1) and consists of three terms. They respectively represent gross CS, total generation costs and transmission investment costs. Note that all terms are calculated for the entire network, i.e. a single-zone perspective is used. The constraints directly applying at the leader's level are the investment constraints in (6.2) denoting that the invested capacity on each line has to be positive and the Pareto-constraints in (6.3).

For each zone a Pareto-constraint is added to the problem. It states that the obtained welfare level after investments has to be equal to or larger than WF_z^{init}, the initial welfare level. Zonal welfare is a weighted average of welfare created in each period p weighted by T_p, the number of hours in period p. Whereas in the leader's objective function overall welfare is calculated on an aggregated basis, here zonal welfare is calculated on a net basis and summed for each node in the zone.[2] Such a net welfare calculation for a single node consists of three terms:[3]

- Net CS in (6.3a) is given by the area below the demand function minus the payments made by the loads in that node. These payments equal the level of demand $d_{n,p}$ multiplied by the nodal price $\lambda_{n,p}$.
- Net PS in (6.3b) equals the revenue received by generators in that node minus the generation costs in that node. The former equals the generation output multiplied by the nodal price $\lambda_{n,p}$.
- CR accrueing to the considered node in (6.3c) are calculated as 50% of the CR collected on all lines starting or leaving the particular node. When a line is located entirely in a zone, all CR originating from that line are added to this zone's welfare. For cross-border lines, only 50% accrues to the zone. CR on a line is a function of the flow $f_{l,p}$ through the line and the nodal price difference between both terminals of the line.

Clearly, the zonal welfare calculation is not only a function of demand and generation levels (as is the case for the overall welfare calculation), but also of the nodal prices and the flows. Note that the nodal prices are the dual variables of the nodal balance constraints in the following market problem. This is a significant difference with the supranational planner, where at the leader's level only primal variables are required.

Similar to the supranational planner the follower's problem again represents the market and is modelled using a DCOPF. The objective function is given by (6.4) and the constraints are modelled by (6.5). Their interpretation is the same as in section 5.2.2.

It is important to fully understand the changed leader's planning problem and how investment costs are dealt with by the Pareto-planner with cost allocation. Investment costs only appear in the leader's objective function and are treated in line with a single-zone viewpoint. It does not matter in which zone the costs are made, because the Pareto-constraints in (6.3) do not address transmission investment costs. Hence, implicitly this formulation assumes an investment cost allocation mechanism. Such a mechanism assures that transmission investment costs are shared in such way that all zones are willing to accept the Pareto-planner's solution. For instance, when for one zone the Pareto-constraint is binding, i.e. the

[2] Note that in constraints 6.3 the sum is made for all $n \in \Omega^{N^{(z)}}$, i.e. only the nodes located in zone z.

[3] It can be shown that when summed over all nodes in the network, the sum of welfare calculated on a net basis for each node separately equals the level of welfare calculated on aggregated basis for the entire network at once. However, it is not possible to use such an aggregation at the zonal level, because it is not able to differentiate between the zones when CR have to be distributed.

level of welfare remains status quo, and transmission investments are required in that zone in order to obtain an overall higher level of welfare, the cost burden is shared by the other zones. Otherwise, the considered zone would still be worse off.

It is important to realize that the Pareto-planner as modelled in this thesis does not provide an answer on how such a cost allocation mechanism should look like. It only assumes its existence and ability to allocate costs to zones.

6.2.2 Single-level MPEC formulation of the Pareto-planner with cost allocation

In section 5.2.3 the bilevel supranational planning problem was recast as a single-level problem. This was possible because the objective functions of both levels were aligned. Although for the Pareto-planner the objectives remain aligned, another difficulty arises when a single-level formulation is sought for. The leader's constraints are now not only a function of the primal variables of the following problem, but also of the dual. As a consequence, it is no longer possible to drop the follower's objective function and add the follower's constraints to the leader's problem and then solve the problem as a single-level one.

Another approach to reformulate the bilevel problem as a single-level one is relying on an MPEC formulation. As already briefly mentioned in section 5.1 an MPEC is a Mathematical Program with Equilibrium Constraints. Before entering into a reformulation of the Pareto-planner, a brief introduction to MPECs is provided.

Introduction to MPECs

As described in [114], transportation planning problems are typical examples to be modelled using MPECs. On the one hand the total system with its design costs has to be optimised, on the other hand the behaviour of the users should be taken into account. The leader-follower structure is clear.

MPECs are optimisation problems with special constraints, i.e. so-called equilibrium constraints resulting from an underlying problem. The term *equilibrium* refers to the underlying problem which has to be solved optimally. As explained in [114], these constraints can be represented by Karush-Kuhn-Tucker (KKT) conditions.

In (6.6) a general formulation of a (potentially non-linear) optimisation problem is given. The DCOPF of the follower's problem, a QP, is an instance of this more general formulation. Equations (6.6b) and (6.6c) represent the equality and inequality constraints. λ and μ are their respective dual variables or Lagrange multipliers [115].

$$\text{Maximize} \qquad F(x) \tag{6.6a}$$

subject to:

$$H(x) = 0 \qquad [\lambda] \tag{6.6b}$$

$$G(x) \geq 0 \qquad [\mu] \tag{6.6c}$$

For the above optimisation problem, it can be proven that x is an optimal solution when x satifies the constraints in (6.6) and when there exist Lagrange multipliers such that the following statements hold [115, 116]:

$$\nabla_x F(x) - \nabla_x G(x)^T \mu + \nabla_x H(x)^T \lambda = 0 \tag{6.7a}$$

$$H(x) = 0 \tag{6.7b}$$

$$0 \leq G(x) \quad \perp \quad \mu \geq 0 \tag{6.7c}$$

In (6.7c) the $\perp$-operator is used to indicate complimentarity of the expressions at both sides of the operator. It means that at least one of the expressions has to be binding. Hence, $G(x)$ and μ cannot be non-zero at the same time.

The above derivation of equilibrium conditions is valid when $F(x)$ is a concave function and when the constraints are convex functions [115]. For the DCOPF modelled as a QP, this is guaranteed.

Given the above definition of equilibrium constraints resulting from an underlying problem, an MPEC can be written as follows:

$$\text{Maximize} \qquad W(x, y) \tag{6.8a}$$

subject to:

$$g(x, y) \geq 0 \tag{6.8b}$$

$$h(x, y) = 0 \tag{6.8c}$$

$$\nabla_x F(x, y) - \nabla_x G(x, y)^T \mu + \nabla_x H(x, y)^T \lambda = 0 \tag{6.8d}$$

$$H(x, y) = 0 \tag{6.8e}$$

$$0 \leq G(x, y) \quad \perp \quad \mu \geq 0 \tag{6.8f}$$

The single-level objective function (6.8a) is now a function of x and y. Whereas x denotes the decision variables of the following problem, y is the leader's set of decision variables. The constraints directly applying to the leader's level are (6.8b) and (6.8c). The equilibrium conditions are given by (6.8d)-(6.8f).

The introduction of complementarity constraints significantly increases the complexity of the problem as they act in a discrete way. The two constraints linked in a complementarity constraint can be interpreted as disjunctive constraints because either $G(x, y) = 0$ *or* $\mu = 0$. Although the underlying problem is convex and easy to solve, its reformulation renders the MPEC non-linear and non-convex.

Pareto-planner with cost allocation as MPEC

The MPEC structure of (6.8) is applicable to the Pareto-planning concept. The Pareto-planner can be formulated according to (6.9)-(6.11). A continuous representation of transmission investments is used.

Maximize

$$\sum_{p} \sum_{n} T_p \left(A_{n,p}\, d_{n,p} - \frac{1}{2} B_{n,p}\, d_{n,p}^2 \right) \tag{6.9a}$$

$$- \sum_{p} \sum_{n} \sum_{t} T_p \left(C_{n,t,p}\, g_{n,t,p} + \frac{1}{2}\, D_{n,t,p}\, g_{n,t,p}^2 \right) \tag{6.9b}$$

$$- \sum_{l} (CL_l\, LN_l\, x_l) \tag{6.9c}$$

subject to:

$$\forall l \in \Omega^{L(z)} \qquad x_l \geq 0 \tag{6.10a}$$

$$\forall z \quad \sum_p T_p \left(\sum_{n \in \Omega^{N(z)}} \left(A_{n,p} d_{n,p} - \frac{1}{2} B_{n,p} d_{n,p}^2 - \lambda_{n,p} d_{n,p} \right) \right. \tag{6.10b}$$

$$+ \sum_{n \in \Omega^{N(z)}} \sum_t \left(\lambda_{n,p} g_{n,t,p} - C_{n,t,p} g_{n,t,p} - \frac{1}{2} D_{n,t,p} g_{n,t,p}^2 \right) \tag{6.10c}$$

$$\left. + \sum_{n \in \Omega^{N(z)}} \sum_l \left[\frac{1}{2} \left| INC_{l,n} \right| f_{l,p} \sum_b \left(-INC_{l,b} \lambda_{b,p} \right) \right] \right) \tag{6.10d}$$

$$\geq WF_z^{init} \tag{6.10e}$$

$$\forall n,p \quad A_{n,p} - B_{n,p} d_{n,p} + \lambda_{n,p} + \kappa_{n,p} = 0 \tag{6.11a}$$

$$\forall n,t,p \quad -C_{n,t,p} - D_{n,t,p} g_{n,t,p} - \lambda_{n,p} - \nu_{n,t,p} + \rho_{n,t,p} = 0 \tag{6.11b}$$

$$\forall n \neq n_s, p \quad \sum_l INC_{l,n} H_l \psi_{l,p} = 0 \tag{6.11c}$$

$$\forall p \quad \sum_l INC_{l,n} H_l \psi_{l,p} + \xi_p = 0 \tag{6.11d}$$

$$\forall l,p \quad -\sum_n INC_{l,n} \lambda_{n,p} + \mu_l^a - \mu_l^b + \psi_{l,p} = 0 \tag{6.11e}$$

$$\forall p \quad \theta_{n_s,p} = 0 \tag{6.11f}$$

$$\forall n,p \quad \sum_t g_{n,t,p} - d_{n,p} - \sum_l \left(INC_{l,n} f_{l,p} \right) = 0 \tag{6.11g}$$

$$\forall l,p \quad f_{l,p} - H_l \sum_n \left(INC_{l,n} \theta_{n,p} \right) = 0 \tag{6.11h}$$

$$\forall l,p \quad 0 \leq F_l^{max} + x_l + f_{l,p} \quad \perp \quad \mu_{l,p}^a \geq 0 \tag{6.11i}$$

$$\forall l,p \quad 0 \leq F_l^{max} + x_l - f_{l,p} \quad \perp \quad \mu_{l,p}^b \geq 0 \tag{6.11j}$$

$$\forall n,t,p \quad 0 \leq G_{n,t,p}^{max} - g_{n,t,p} \quad \perp \quad \nu_{n,t,p} \geq 0 \tag{6.11k}$$

$$\forall n,p \quad 0 \leq d_{n,p} \quad \perp \quad \kappa_{n,p} \geq 0 \tag{6.11l}$$

$$\forall n,t,p \quad 0 \leq g_{n,t,p} \quad \perp \quad \rho_{n,t,p} \geq 0 \tag{6.11m}$$

The objective function is given by (6.9). The investment and Pareto-constraints are enforced via (6.10). Equations (6.11) are the KKT conditions of the DCOPF. They are the equivalent of the DCOPF formulation given by (6.4)-(6.5). The bilevel structure is now replaced by a single-level notation, albeit by the use of complementarity constraints.

6.2.3 Pareto-planner without cost allocation

The previous section discussed in detail the formulation of the Pareto-planner with cost allocation. In this section the necessary changes for the Pareto-planner without cost allocation are provided. As only the Pareto-constraints are altered, no full model formulation is given. Both the bilevel and MPEC formulation remain valid.

Under the assumption that no transmission investment cost allocation mechanism is available, the investment costs have to be borne by the zone hosting the new investment on its territory. In order to remain Pareto-improving under this new assumption, the investment costs have to be included into each zone's Pareto-constraints. The Pareto-constraints in (6.3) and (6.10b)-(6.10e) have to be reformulated:

$$\forall z \qquad \sum_p T_p \Bigg(\sum_{n \in \Omega^{N(z)}} \left(A_{n,p} d_{n,p} - \frac{1}{2} B_{n,p} d_{n,p}^2 - \lambda_{n,p} d_{n,p} \right) \tag{6.12a}$$

$$+ \sum_{n \in \Omega^{N(z)}} \sum_t \left(\lambda_{n,p} g_{n,t,p} - C_{n,t,p} g_{n,t,p} - \frac{1}{2} D_{n,t,p} g_{n,t,p}^2 \right) \tag{6.12b}$$

$$+ \sum_{n \in \Omega^{N(z)}} \sum_l \left[\frac{1}{2} \left| INC_{l,n} \right| f_{l,p} \sum_b \left(-INC_{l,b} \lambda_{b,p} \right) \right] \Bigg) \tag{6.12c}$$

$$+ \sum_{l \in \Omega^{L(z)}} \left(CL_l \; LN_l \; x_l \right) \tag{6.12d}$$

$$\geq WF_z^{init} \qquad [\beta_z] \tag{6.12e}$$

The zonal transmission investment costs are addressed by (6.12d). Note that only lines within the zone are considered as indicated by $l \in \Omega^{L(z)}$.[4]

[4]Cross-border lines are not specifically adressed in this notation. In the examples two situations occur. Firstly, a cross-border line can be fully assigned to a zone, as if the cross-border line is located entirely within that zone. Secondly, it is possible to introduce an extra artificial node

Obviously, by adding an extra cost term to the Pareto-constraints in the case without cost allocation, they are more stringent than in the case with cost allocation. As a consequence, the solution found by the Pareto-planner with cost allocation always outperforms the solution obtained by the Pareto-planner without.

6.3 Solution methods

In general two groups of solution methods exist for solving optimisation problems: mathematical optimisation models and heuristics. This distinction can also be observed in transmission planning literature [34, 117]. Whereas the former solution methods try to find the optimum by directly solving the mathematical formulation of the problem, the latter adopts techniques based on adaptation of a solution environment driven by specific operators that change solutions with the purpose of attaining a better performance [118]. The flexibility of heuristics regarding problem formulation and mathematical properties (e.g. convexity) is a great advantage.

Examples of mathematical optimisation models are linear, non-linear, dynamic and mixed-inter programming. Benders decomposition and branch-and-bound techniques are often used. They can sometimes guarantee a global optimum. Genetic algorithms (GA), tabu search, simulated annealing, etc. are commonly used heuristics. If properly implemented, they guarantee a near-optimal solution. A literature overview on the different solution methods in transmission planning is given in [34].

As outlined in the previous section, the Pareto-planner can be formulated as a bilevel problem which can also be recasted as a single-level MPEC. Both formulations are used for the examples in this thesis. The bilevel formulation easily deals with discrete transmission investments. The MPEC approach is applied for the examples with a continuous representation. For both approaches, the solution methods are presented in this section. The bilevel approach relies on GAs and the MPEC is solved using mathematical optimisation methods.

6.3.1 Solving the bilevel problem using a genetic algorithm

In general, genetic algorithms (GA) provide a flexible methodology for solving optimisation problems without limitations on the problem with respect to convexity, continuity, linearity, etc. It can be easily tailored to the problem considered. It is also a useful way to tackle the bilevel problem and to find near-optimal solutions.

indicating the frontier between the zones. The cross-border line is then split into two equal parts and each zone pays 50% of the costs.

A GA consists of an algorithm based on the natural principle of evolution. In general, an initial population of individuals evolves towards a next generation by undergoing selection, cross-over and mutation. The fittest solutions have the highest probability to survive and generate offspring [118, 119]. GAs are widely used for solving combinatorial problems in different fields of research, including power systems [120]. A clear discussion on how GAs can be implemented and fine-tuned in the context of transmission planning models is given by [77, 121]. There are several examples of (modified) GAs used for transmission planning available in literature, e.g. [117, 122, 123].

GAs are particularly interesting for solving the bilevel structure when a discrete investment representation is used. Although adaptations for continuous variables exist, discrete variables are particularly suited to be handled by a GA. In the bilevel structure of the Pareto-planning problem, all decisions concerning the discrete investment variables are taken at the leader's level. Those variables act as parameters for the underlying market problem. Letting the GA decide on the investment variables leaves the underlying market problem and the Pareto-constraints to determine the fitness of a particular investment set, which serves as a measure for the welfare level. Checking the investment and Pareto-constraints and solving the market problem are very easy tasks. Although it is further explained in the remaining part of this section, it should already be clear that the bilevel structure is very well captured by a GA.

Firstly, the general GA structure and its implementation in this thesis are described. Next, the calibration of several key parameters is discussed.

GA structure

The different steps of the GA's setup are shown in Fig. 6.3 and illustrated by an example. The main characteristics are:

- Representation: An individual represents a possible set of investments and consists of alleles. Each allele corresponds to the number of circuits added to a specific corridor. A decimal representation of the number of circuits is opted for. Decimal representation is preferred above binary representation in GA's for transmission planning. This avoids Hamming cliffs[5] when cross-over and mutation are applied to this problem [77, 124]. Moreover the implicit cardinality[6] of the problem is lower when using decimal representation [77].

[5]Hamming cliffs occur when more than one bit has to be flipped in order to reach the nearest neighbour. This can happen with a binary representation, but not with a decimal one.

[6]The cardinality refers to the number of elements in a set. For instance, when 20 elements are required a binary code requires 5 digits. However, with five digits it is possible to represent 32 elements. Hence, the cardinality is higher than required.

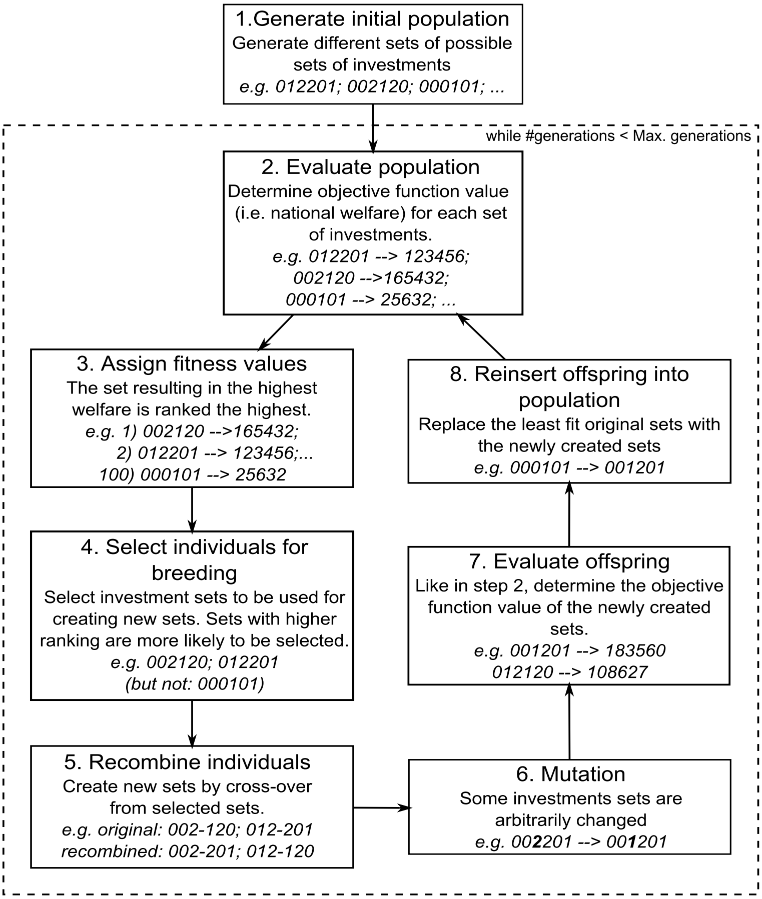

Figure 6.3: Genetic algorithm: schematic overview

A box constraint can be used in the population generation and mutation stages to limit the number of new circuits in a corridor. By doing so, the investment constraints at the leader's level can be covered.

- Initial population: A good initial set of individuals can enhance the GA's performance. Sometimes solutions found for a relaxed problem or an easy to solve approximation are used (e.g. [54, 124]). In this thesis, the initial population is randomly generated. Additionally, both the initial situation (i.e. no investments) and - when available - the supranational solution (found using a MIQP formulation) are added to the initial population.
- Fitness function: There are different ways to assign a fitness value to individuals, e.g. linear scaling, proportional scaling, ranking, etc. [125].

In this thesis, a ranking method is applied. This is illustrated in step 3 of Fig. 6.3. Individuals are ranked according to their objective function value. For instance, individuals resulting in a higher overal economic welfare are ranked higher. The performance of an individual is determined by how it performs compared to the other individuals in the population and is decoupled from the welfare value itself.

For the Pareto-planner a fitness function including a penalty function capturing the Pareto-constraints is used (cfr. infra).

- Selection: The selection mechanism selects individuals for creating offspring. Fitter individuals are more likely to be selected. Different routines are available, e.g. stochastic universal sampling or roulette wheel selection. In this thesis, the former technique is applied.[7]

  Apart from the selection mechanism it is also important to define how many new individuals are created in each new generation and how many already existing individuals survive to the next generation. In this thesis a generation gap of 50% is applied implying a fifty-fifty split between already existing and new individuals.

- Cross-over: The cross-over mechanism is used to create offspring from recombining two parents. It provides for diversification in the search for the optimum [127]. Crossing-over parts of individuals creates new individuals which can be located in other parts of the solution space than the parents were. Single and double point cross-over are often used techniques. Also more complex techniques exist, e.g. based on matroid theory [128]. Whereas in the former one allele is chosen at which cross-over takes place (see also the example in step 5 of Fig. 6.3), the latter determines two alleles of the individuals at which cross-over takes place. The algorithm decides on which individuals cross-over is applied according to a pre-defined probability, i.e. the cross-over rate. In this thesis a cross-over rate of 70% is used.

- Mutation: By mutation single alleles of an individual can be changed (see also the example in step 6 in Fig. 6.3). By doing so, individuals can contain values for alleles different from the initial population, something not possible by only applying cross-over. In general, mutation introduces so-called intensification in the algorithm [127]. It allows exploring a neighborhood of a particular individual. Higher mutation rates change the GA towards a more random search algorithm benefiting to a smaller extent from the information included in the individuals at hand [120]. However, sometimes superior results with high mutation rates are reported for transmission planning applications [124].

[7] Stochastic universal sampling is a technique developed by [126] and relies on the generation of a single random number for selecting individuals. The probability of being selected is equal to the individual's fitness value divided by the sum of fitness values of all individuals.

In this thesis mutation is applied on a random basis with a mutation rate of 15%, meaning that each allele has a probability of 15% for being mutated.

Alternatives based on simulated annealing (e.g. [77, 121]) or specific algorithms improving local solutions (e.g. [54]) can also be used.

- Stopping criterion: A GA has no information on whether the optimal solution is found or not. As a consequence, a stopping criterion has to be defined. In this thesis a maximum number of generations of 1500 is used. This number should be high enough in order to guarantee a near-optimal solution. An alternative used in [124] is to stop the GA after a number of generations without improvement and thereby indicating convergence.

The GAs have been implemented in MATLAB using the GATBX toolbox.[8]

GAs perform very well for unconstrained optimisation problems, but also constrained problems can be dealt with, e.g. by using a penalty function. This is an important feature when considering the Pareto-planner which is bound at the leader's level by the Pareto-constraints. It is important to emphasize the difference with the follower's problem.

The fitness value is obviously a function of the overall welfare obtained by a set of investments. It is found by running a simple DCOPF given the investments done in the individual considered. This is done using CPLEX 12.1.0 in TOMLAB[9] and poses no problems. The Pareto-planner, however, also has to cope with the Pareto-constraints guaranteeing initial zonal welfare levels. They play a crucial role in the fitness of a particular individual. An individual is only feasible when none of these constraints are violated. One possibility is to rule out all individuals not meeting such a constraint. This strategy, however, throws out the baby with the bathwater as such an individual can contain valuable information possibly leading to a better and feasible offspring. A feasible solution can sometimes lay further away from the optimum than an infeasible. Therefore, it is opted for to utilize a penalty function [120, 124]. For each violated constraint the zonal welfare loss is used as penalty in the objective function. This allows the GA to move to infeasible, but strong individuals and at a later stage return to feasible solutions. The results in this thesis are obtained using a linear penalty function.

The penalty is defined as the sum of the Pareto-constraint violations. The violation is zero when the constraint is met and positive when the welfare in a particular zone is lower than the initial welfare level. In such a case the violation equals the lefthand minus the righthand side of (6.3) (or (6.12)). The penalty then equals the

[8] GATBX is a matlab toolbox for genetic algorithms developed at the University of Sheffield (UK) available from `http://www.shef.ac.uk/acse/research/ecrg/gat.html` [129].

[9] Tomlab is an optimisation platform and modelling language for solving applied optimisation problems in Matlab. It integrates commercial solvers in the Matlab environment. `http://tomopt.com/tomlab/`

total sum of all violations and is multiplied by a constant. The constant determines the weight of the penalty in the objective function.[10]

GA calibration

GA calibration is useful as each problem behaves differently and no single set of parameters performs well for all problems considered. However, some attempts for finding generally applicable parameters are undertaken [130].

According to [130] there are two forms of calibrating an evolutionary algorithm like a GA: parameter tuning and parameter control. Parameter tuning determines a static set of parameters ex ante, i.e. the set of parameters remains fixed once the GA is started. The opposite is true for parameter control where the set of parameters evolves in a dynamic way. Parameters can change during the GA execution, e.g. the mutation rate can change with the number of generations.

Parameter tuning can rely on analogy with similar problems, theoretical analysis and experimentation. Analogy with similar problems looks attractive, but it is unclear what defines 'similar' in the context of such complicated systems. Using a theoretical analysis for determining parameters is difficult as often several assumptions are required. Experimentation seems a feasible technique, but also struggles with several drawbacks.

- The effect of parameters cannot always be isolated, they can interact.
- The tuning exercise can be very time consuming.
- There is no guarantee that the parameters found are optimal.

Parameter controlling techniques change the parameters during the run. In [130] three categories on how they are altered are defined: deterministic, adaptive and self-adaptive control. In deterministic parameter control an ex ante rule on how the parameters change during the run is defined. For instance, the mutation rate increases with the number of generations. There is no feedback during the run. Adaptive and self-adaptive control base the parameter values on information obtained during the run, e.g., the quality of the best solution found so far. The latter technique even encodes the parameters into the chromosomes. The fittest parameter set has a higher probability to survive.

In this work parameter calibration is limited to a parameter tuning approach only. Tuning based on analogy with similar problems is possible to a limited

[10] In this thesis the constant is set equal to 10 as this resulted in the best solutions. This value is obtained by intuitive trial-and-error on a test case. No guidance has been found in the literature on this particular calibration issue.

extent as literature concerning transmission planning using GA provides some hints. Additionally, experimentation on the supranational planning problem is done in order to have a higher degree of similarity. To calibrate the GA used for the Pareto-planners, it is used to solve the supranational planning problem. As the supranational planner can be solved with a guaranteed optimum using the MIQP formulation, that optimum can be used as a benchmark for the GA's solution. In fact, it is assumed that the GA parameters obtained for the supranational planner also perform well for the Pareto-planners. Unfortunately, similarity is not perfect as the Pareto-planner also has the Pareto-constraints and the penalty function to deal with. The three-zone, 14-node example of section 5.4.5 is used for this purpose. The calibration results are discussed in Appendix A. Here, only a brief overview of the outcome is given.

The calibration results revealed that the mutation rate is the most important parameter impacting both the quality of the result and the required number of generations before convergence. A mutation rate of 15% is selected. A further analysis of different runs using only this mutation rate learned that the cross-over rate is the second most important parameter. A cross-over rate of 70% is selected. The other parameters do not render large differences in the quality of the result nor in the convergence speed. Based on the average results the generation gap is set at 50%, the selection mechanism is stochastic universal sampling and the cross-over mechanism is single point cross-over. Population size is set at 40 individuals and the maximum number of generations at 1500.

6.3.2 Solving the MPEC using a mathematical optimisation method

Solving MPECs is not straightforward due to the non-convex nature of the complementarity constraints. The research on methods for solving MPECs is still ongoing and so far no generally accepted superior methods are available.

Methods for solving an MPEC rely on reformulating the MPEC as another problem and then solving it. One possibility is to further exploit the discrete nature of the complimentarity constraints and rewrite the model as a Mixed Integer Program (MIP). This technique is investigated in [131] and introduces an explicit set of disjunctive constraints and an integer variable for each complimentary constraint. Although global optima can sometimes be guaranteed, the integer approach can significantly affect the calculation time. Another group of methods reformulates an MPEC as a Non-Linear Program (NLP) [114, 132]. This second approach is chosen in this thesis.

However, no own implementation of this method is performed. The GAMS software package provides an interface for solving MPECs using NLP reformulations. The NLPEC module only requires a model formulation as in section 6.2.2 which defines all necessary equations and the complimentarity conditions. The reformulation as an NLP is done by the NLPEC module and is then solved using a typical NLP-solver. For this thesis the Knitro-solver[11] is used for this purpose. Although NLPEC provides for a variety in NLP-reformulations [133], the default setting based on an inner-product reformulation is used.[12] A drawback of this technique is that it is not possible to guarantee a globally optimal outcome. The NLP-solver only guarantees local optimality.

This approach is tested using the supranational planning problem with continuous investment representation where the DCOPF is modelled using its KKT conditions. This is the same as the model in section 6.2.2 without the Pareto-constraints. The example of sections 5.4.1 and 5.4.4 are used and the same (optimal) solution was found.

6.4 Examples

The examples introduced in chapter 5 are now used to illustrate the Pareto-planning concept. The data description is not repeated in this chapter. Both variants concerning cost allocation are implemented. summarised results of the initial situation and the supranational planning concept are shown for comparison.

6.4.1 Two-zone example

In Table 6.1 the results for the two-zone network are shown. As the supranational planning solution does not violate the Pareto-constraints for both variants, this solution is also the one of the Pareto-planners. Hence, this simple example illustrates that the Pareto-constraints are not always binding.

This is also illustrated by means of Fig. 6.4, which should be interpreted like the conceptual idea explained in section 3.1.3 and Fig. 3.3. For different values of T_{AB}, the welfare for zones A and B are indicated. It can be seen that for all values of T_{AB} the welfare distribution lies in zone IV indicating a Pareto-improvement for both zones. Hence, the supranational solution is also the solution of the Pareto-planners.

[11] Knitro is a non-linear optimisation solver developed by Ziena optimisation LCC which can interface with the GAMS modelling framework. http://www.ziena.com/knitro.html

[12] The inner product consists of the non-negative terms in the complementarity constraints: a slack variable and the difference between a variable and its bound. Either the slack variable or its complement must be zero in order to have a solution. Hence, complementarity is forced by the multiplication of both terms.

	No link		Supranational = Pareto CA = Pareto w/o CA	
	Zone A	Zone B	Zone A	Zone B
Generation [MW]	3250	2666.7	3958.9	2036.5
Demand [MW]	3250	2666.7	3013.7	2981.7
Price [€/MWh]	32.5	53.3	39.6	40.7
CS [€]	158437.5	142222.2	136235.7	177814.9
PS [€]	52812.5	71111.1	78364.6	41474.5
CR [€]	0	0	539.5	539.5
CS+PS+CR [€]	211250	213333.3	215139.8	219828.9
Transmission capacity [MW]	0		945.2	
Investment cost [€]	0		1079	
Total welfare [€]	424583.3		433889.7	

Table 6.1: Two zone example: overview of results on an hourly basis

Although seemingly trivial, this result can have a significant implication for policy-makers. It shows that in some cases it is possible to achieve the best outcome without a very strong framework arranging the collaboration between different zones as assumed by the supranational planner. No welfare distribution mechanism is required, even not for distributing investment costs. Of course, this result is case-dependent. The following examples illustrate that this strong result is not always valid. As a consequence, policy-makers cannot use this result to claim that the optimal solution is found without a strong framework without checking whether the result holds for the network considered.

6.4.2 Three-zone example: radial configuration

The three-zone radial example illustrates very well the difference between both Pareto-variants, i.e. the impact of assuming on the one hand no welfare transfer mechanism at all and on the other a mechanism limited to investment cost allocation only. As can be seen from Fig. 6.5, both variants have a different outcome. Moreover, both Pareto-planning outcomes are different from the supranational solution. Table 6.2 explains why differences occur.

In the supranational solution zone B clearly looses welfare, even when it does not have to contribute in the investment cost. Hence, this solution violates the Pareto-constraints and is not acceptable for the Pareto-planner. The solution found by the Pareto-planner with cost allocation (indicated by Pareto CA) is acceptable

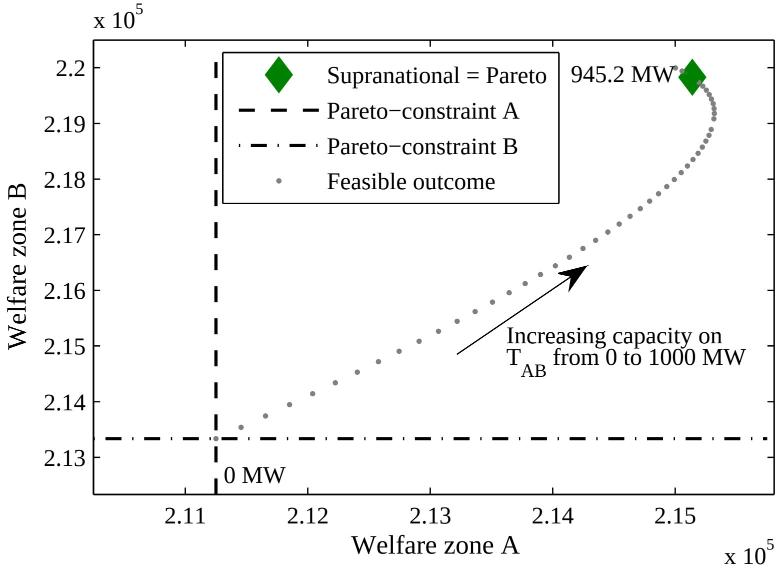

Figure 6.4: Two-zone example: Evolution of zonal welfare for different values of T_{AB} (using steps of 50 MW)

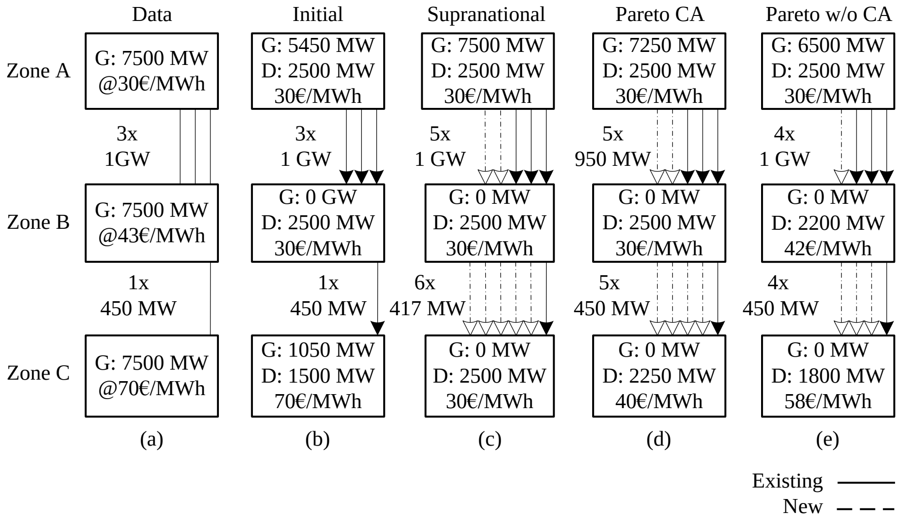

Figure 6.5: Three-node radial example: Pareto-planners' solutions

to all zones. Note, however, that zone A is not gaining any welfare compared to the initial situation and is therefore not willing to bear any investment cost. This clearly indicates the importance of the cost allocation assumption. This solution is only feasible when zones B and C bear all investment costs, even the costs made in zone A. These findings are also supported by Fig. 6.6.

The outcome changes when no such mechanism is available. In case of the Pareto-planner without cost allocation (denoted by Pareto w/o CA) the investments are different. Zone A now benefits from a welfare increase enabling this zone to cover the investment cost of infrastructure on its territory, i.e. 50% of the cost of an extra connection between zones A and B. The extra welfare going to zone B is limited to 1.2 k€, but this amount is sufficient to cover its investment cost of 0.51 k€.

From the different results, it can also be learned that the Pareto-constraints do not ensure an equal distribution of the acquired benefits. When cost allocation is possible, zone C is the big winner, whereas zone A remains status quo and zone B only wins a small amount of welfare. Without cost allocation, zones A and C both win about the same amount of welfare, but zone B only benefits marginally. The above findings are also supported by Fig. 6.6.

The differences between the solutions can also be observed via the price levels in the different zones. Zone A always has a price of 30 €/MWh and except for the Pareto w/o CA never receives CR. In zone C the welfare benefits mostly originate from a decreased price level compared to the initial situation. The size of this price drop, however, differs depending on the investments done. The situation is more complicated in zone B. The price in zone B can increase, but in order to remain Pareto-improving, the loss in CS due to the increased price has to be compensated by extra CR.

Finally, the Pareto-constraints and the assumption concerning cost allocation impact the total welfare gained in the entire network. Obviously, with an amount of 373.17 k€, welfare is highest for the supranational planner. The Pareto-planners with and without cost allocation obtain a welfare level of respectively 372.15 and 364.08 k€. As already mentioned in the previous example, the lack of a full welfare transfer mechanism can in some cases cause a welfare loss. The cost can be smaller when a limited mechanism dealing with investment costs only is available.

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	125	125	45	125	125	125
PS	0	0	0	0	0	0
CR	0	9	9	0	0	0
CS+PS+CR	125	134	54	125	125	125
ΔWelfare	-	-	-	0	-9	+71
Investment cost	-	-	-	-1.83		
	Pareto CA			Pareto w/o CA		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	125	125	101.25	125	96.8	64.8
PS	0	0	0	0	0	0
CR	0	11.25	11.25	24	38.4	14.4
CS+PS+CR	125	136.25	112.5	149	136.9	79.2
ΔWelfare	0	+2.25	+58.5	+24	+1.2	+25.2
Investment cost	-1.60			-0.17	-0.51	-0.34

Table 6.2: Three-zone radial example: hourly welfare effects [k€]

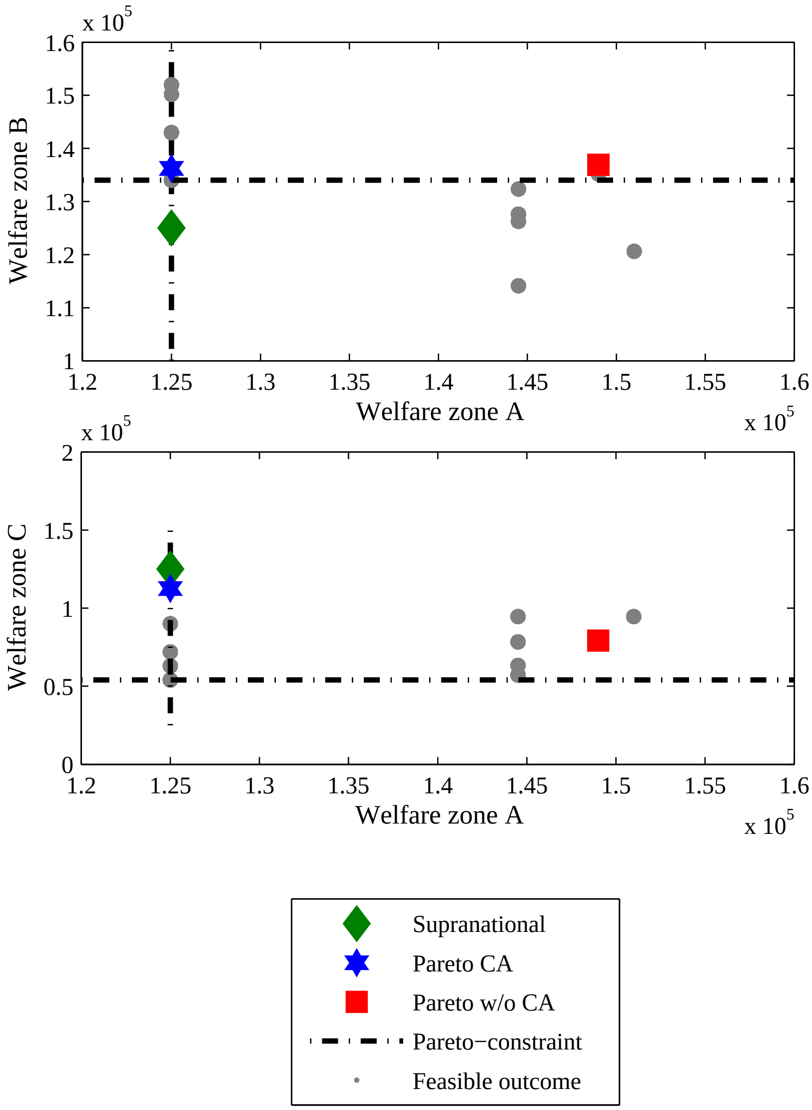

Figure 6.6: Three-zone radial example: Evolution of zonal welfare for different feasible investments (up to 6 circuits per corridor)

	T_{AB}	T_{BC}	T_{AC}
Supranational	+115.9	+75.4	+391.4
Pareto CA	+24.5	+0	+224.5
Pareto w/o CA	+24.5	+0	+224.5

Table 6.3: Three-zone meshed example: invested capacity compared to the initial situation [MW]

6.4.3 Three-zone example: meshed configuration

In the three-zone meshed example the Pareto-planners' solutions differ from the supranational result. However, unlike in the previous example, there is no difference between both variants. It makes no difference whether there is a cost allocation mechanism or not. This is possible because the welfare gains are sufficiently high for each zone. They exceed the investment cost for each zone. Consider in particular the situation of zone B. Zone B remains status quo and no costs are incurred on the link T_{BC}.[13] This is sufficient to meet the Pareto-constraints.

In Table 6.3 the invested capacities are shown for each link. Table 6.4 provides the welfare calculation and the investment costs. It can be observed that in the Pareto-solutions zonal prices diverge more than in the supranational case. The resulting overall economic welfare is also lower due to the lower investment levels. This is required to keep the welfare balance for zone B non-negative. Generation dispatch, demand and prices are given in Table 6.5.

In Fig. 6.7 both the supranational and the Pareto-solutions are indicated in a cloud of technically feasible outcomes. The Pareto-constraints visually confirm that the supranational planning solution is not acceptable and that the Pareto-constraint is binding for zone B.

[13] Note that in section 5.4.4 it is assumed that links T_{AB}, T_{BC} and T_{AC} are located in respectively zones A, B and C. Hence, investment costs on a single line do not have to be split among the two adjacent lines.

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	166.1	156.8	150.5	181.3	156.6	138.0
PS	45.4	44.4	40.9	33.0	44.7	56.0
CR	1.266	0.493	1.198	0.285	0.113	0.277
CS+PS+CR	212.9	201.7	192.5	214.6	201.4	194.3
ΔWelfare	-	-	-	+1.735	-0.374	+1.758
Investment cost	0	0	0	-0.333		
	Pareto CA			Pareto w/o CA		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	174.7	156.9	143.1	174.7	156.9	143.1
PS	38.2	44.3	49.4	38.2	44.3	49.4
CR	1.258	0.494	1.203	1.258	0.494	1.203
CS+PS+CR	214.1	201.7	193.8	214.1	201.7	193.8
ΔWelfare	+1.201	0	+1.239	+1.201	0	+1.239
Investment cost	-0.142			-0.014	0	-0.128

Table 6.4: Three-zone meshed example: hourly welfare effects [k€]

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
Generation [MW]	3014.5	3021.7	3028.8	2569.5	3031.5	3493.4
Demand [MW]	3328.5	2993.8	2742.8	3476.8	2991.0	2626.6
Price [€/MWh]	30.15	25.22	20.29	25.70	25.32	24.93
	Pareto CA			Pareto w/o CA		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
Generation [MW]	2763.2	3019.1	3299.6	2763.2	3019.1	3299.6
Demand [MW]	3412.3	2994.6	2675.1	3412.3	2994.6	2675.1
Price [€/MWh]	27.63	25.19	23.00	27.63	25.19	23.00

Table 6.5: Three-zone meshed example: dispatch and prices for different solutions

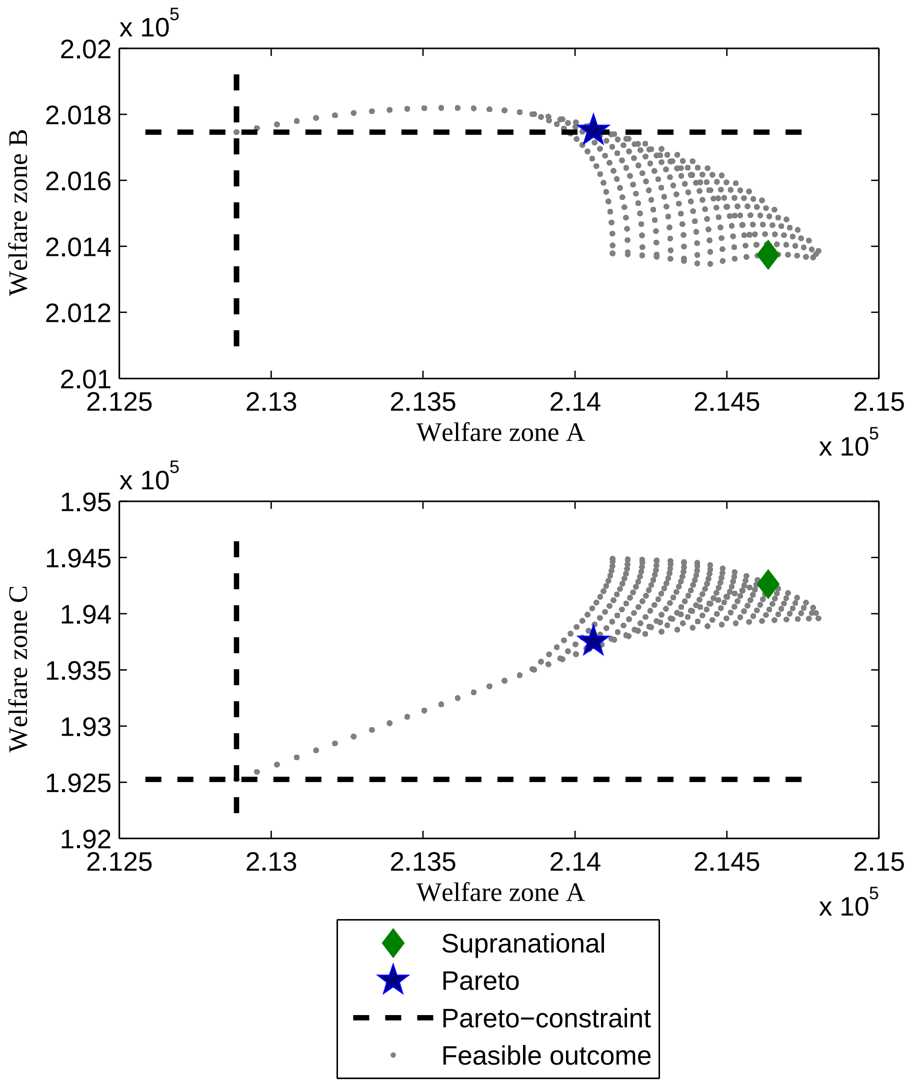

Figure 6.7: Three-zone meshed example: Evolution of zonal welfare for different feasible investments (using steps of 10 MW for each line starting from 200 MW up to 600 MW)

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	304.4	340.2	425.2	275.0	454.6	540.3
PS	0	0	0	136.8	0	0
CR	78.8	129.3	87.1	0	6.2	1.4
CS+PS+CR	383.2	469.5	512.3	411.8	460.8	541.7
ΔWelfare	-	-	-	+32.7	-8.7	+29.3
Investment cost	0	0	0	-3.42		
	Pareto CA			Pareto w/o CA		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	279.7	457.8	538.5	281.9	459.3	537.6
PS	122.1	0	0	115.1	0	0
CR	0.198	13.1	2.82	0.254	16.4	3.50
CS+PS+CR	401.9	471.0	541.3	397.3	475.8	541.1
ΔWelfare	+18.75	+1.47	+29.00	+14.05	+6.27	+28.80
Investment cost	*-1.26*	*-1.71*	*-0.685*	-1.71	-1.94	-0.685

Table 6.6: 14-node example: hourly welfare effects [k€]

6.4.4 14-node, three-zone example

The 14-node, three-zone example provides a second illustration for the difference between the two Pareto-variants. All welfare effects are summarised in Table 6.6. The supranational solution is also in this case violating the Pareto-constraints because zone B is worse off compared to the initial situation. For the Pareto-planner with cost allocation, Table 6.6 shows the breakdown of the investment costs over the different zones.[14] Clearly a cost allocation mechanism is required as otherwise zone B is unable to cover the investment costs (i.e. 1.71 k€) with the increased welfare gains accrueing to its zone (i.e. 1.47 k€). In the solution without cost allocation mechanism, this is no longer so. However, the overall welfare level is lower.

Tables 6.7 and 6.8 give respectively the generation dispatch and the investments in transmission circuits per corridor. Unlike in the previous examples, both variants of the Pareto-planner invest more in transmission than the supranational planner. Also the total generation output is higher than in the supranational case.[15] This suggests that in order to meet the Pareto-constraints and ensure an acceptable

[14]The investment costs for the Pareto-planner with cost allocation is printed in italic because for this planner the costs are not split per zone and only considered for the entire network at once (like for the supranational planner). Here, the breakdown is only shown in order to prove the violation of the Pareto-constraint of zone B.

[15]Note that demand is flexible and determined by a linear demand function.

welfare distribution, overinvestments are done. However, this result should be dealt with with great caution. It is not proven that the presented Pareto-solutions are optimal and that the optimum cannot have less investments than the supranational case. The GA used is a heuristic only guaranteeing a near-optimal outcome.

Node	Zone	Variable cost	Initial output	Supra. output	Par. CA output	Par. w/o CA output
1	A	35	8849	10000	10000	10000
2	A	40	9200	10000	10000	10000
4	B	60	0	0	0	0
7	B	70	300	0	0	0
9	C	45	8755	9814	9885	9917
13	C	55	0	0	0	0

Table 6.7: 14-node example: Generation cost data [€/MWh] and generation output for the different solutions [MW]

Corridor			# circuits			
From	To	Zone	Initial	Supra.	Par. CA	Par. w/o CA
1	2	A	6	0	0	0
1	3	A	10	3	3	4
2	3	A	6	0	0	0
2	4	AB	8	0	0	1
2	5	AB	12	4	3	3
3	5	AB	6	0	2	3
3	9	AC	3	0	0	0
4	5	B	6	0	0	0
5	6	B	6	4	4	4
5	8	B	7	1	1	1
6	7	B	7	0	0	0
6	8	B	6	0	0	0
8	10	BC	3	0	0	0
8	14	BC	3	0	0	0
9	11	C	6	2	2	2
9	12	C	6	0	0	0
9	13	C	6	1	1	1
10	11	C	6	0	0	0
12	13	C	6	0	0	0
13	14	C	6	0	0	0

Table 6.8: 14-node example: initial situation and different planners' investments

6.5 Assessment of design choices

Whereas the assessment of design choices for the supranational planner (section 5.5) revealed that the supranational planner can be rather flexibly adapted for different choices, in principle the same holds for the Pareto-planner. However, the already complicated structure of the Pareto-planner should not be underestimated as a complicating factor. This is relevant when considering a dynamic treatment of the planning horizon and a proactive link with generation investments.

For incorporating uncertainty and altering the market modelling, the impact on the Pareto-planner is the same as for the supranational planner and can be rather limited. In particular with respect to the Pareto-planner, another market model would not further complicate the model, as here no simplification towards a single-level model is made in the first place. As long as the market model can be written as a set of constraints, the structure remains unchanged.

The impact of changing the objective function or using multiple objectives is stronger on the Pareto-planning than on the supranational planning model. The interpretation of the initial welfare constraints is crucial. Two possibilities arise:

- When all different objectives are included within a single constraint, the initial welfare constraint allows for an internal, i.e. within a zone, trade-off of the different objectives. For instance, lower reliability can be compensated with higher economic welfare. This approach allows for more flexibility. Of course, whether or not the solution space increases, depends on the performance of different countries for each objective in the initial situation (e.g. is one country outporming the others on all objectives or is the initial situation more differentiated?).
- When for each objective a separate constraint reflecting the initial situation is used, the Pareto-planner becomes more constrained. A Pareto-improving solution would now require that for each objective each country should improve or at least remain status-quo. For instance, it is not possible to accept a lower level of reliability, even if the economic welfare increases. The solution space reduces in size and chances for finding a Pareto-improvement decrease.

6.6 Conclusions

In this chapter the Pareto planning collaboration concept introduced in section 3.1.2 is further refined. This concept assumes less collaboration than the supranational planning concept presented in chapter 5. Whereas the supranational planner assumes a full welfare transfer mechanism able to compensate negatively affected zones, the Pareto-planning concept does not go that far. Firstly, the Pareto-planner avoids any outcome that negatively affects a zone by adding Pareto-constraints to the planning problem. Hence, this concept and the planning models score better with respect to multi-area awareness. Although there still is a single objective function maximizing overall economic welfare, the single-zone treatment is left behind and makes place for explicit zonal welfare constraints, i.e. the Pareto-constraints. Two drawbacks are inherent to this concept. It is not always possible to find a Pareto-improving solution and the solution does not guarantee an equal welfare distribution.

Secondly, two variants of the Pareto-planner varying in the treatment of the transmission investment cost are identified. One assumes that investment cost allocation between different zones is possible. The other does not allow this and assumes that each zone bears the cost of new infrastructure hosted on its territory. Clearly, the Pareto-planner with cost allocation assumes more collaboration than the one without, but still less than the supranational planner. As a consequence, the variant without cost allocation never outperforms the other case (or at best they have the same solution). The Pareto-planning variants can also never outperform the welfare level reached by the supranational planner. This is illustrated by both the mathematical formulation of the planning models and the examples in this chapter.

Modelling the Pareto-planning concept and solving those models prove to be more complicated than the supranational planning concept. Again a bilevel structure is considered to model the problem. However, no simple reformulation is possible. On the one hand GAs are required to tackle the bilevel problem directly when a discrete investment representation is used. On the other hand, for a continuous investment representation the bilevel model is reformulated as a single-level MPEC using the KKT conditions of the underlying DCOPF. Unfortunately, both solution mechanisms provide no proven optimal solution.

Despite the drawbacks, the implementation of the Pareto-planning concept is considered useful because it can provide a way-out when the supranational solution is not acceptable for one or more zones or when the required level for collaboration in the supranational concept is considered too high.

The examples reveal that various situations are possible. Firstly, it is possible that the supranational solution is Pareto-improving for all zones (e.g. the two-zone example). In such case it is not necessary to adopt a framework for a high level of collaboration as assumed in the supranational concept. The lighter conditions of the Pareto-concept are then sufficient to attain the maximal welfare level. Secondly, the three-zone examples illustrated the possible impact of a cost allocation mechanism. Whereas in the meshed example it does not matter, the radial example shows that a higher welfare is possible when such a mechanism is available. Finally, the 14-node, three-zone example carefully suggests that the Pareto-planning solutions do not necessarily result in a lower level of investments than in the supranational solution as is the case in the other examples.

7

Non-cooperative planning game

In this chapter the third and final planning collaboration concept is dealt with: the non-cooperative planning game. It is clearly different from the previous concepts discussed with respect to the assumed level of collaboration and mathematical complexity. Firstly, the non-cooperative planning game is described by intuitively discussing several of its properties and by outlining its structure (section 7.1). Next, a mathematical formulation is provided (section 7.2). After briefly highlighting several issues related to solution methods (section 7.3), three examples are analysed (section 7.4).

7.1 Model intuition and structure

Firstly, the intuition of the non-cooperative planning game is explained by emphasizing three crucial differences with the supranational and Pareto-planning concepts. Next, from this intuition a model structure is derived.

7.1.1 Intuition and limitations

Compared to the supranational and Pareto-planning collaboration concepts, the non-cooperative planning game is different in various ways. Intuitively, three major differences can be identified. Next, several limitations of this concept are discussed.

Intuition

Firstly, it assumes no collaboration at all in developping transmission links. Despite (possible) interconnections and a jointly operated market, this concept assumes that all planning and investment decisions take place at the zonal level. This differs substantially from the previous concepts where a single objective function maximizing overall economic welfare throughout the entire network is assumed and investments are thought to be decided at a higher level than zonal.[1] Indeed, in the non-cooperative planning game only zonal welfare is evaluated. The overall level is never taken into account. Interestingly, as it is never accounted for, it is also not possible to make ex ante statements on how the non-cooperative planning game scores in terms of overall welfare compared to the other concepts. As illustrated by the examples, it is not true to claim that concepts with a certain incorporation of the supranational viewpoint always outperform the non-cooperative planning game.

A second difference concerns the very high multi-area awareness of the non-cooperative planning game. Whereas the supranational planner adopts a pure single-zone viewpoint and the Pareto-planner incorporated a light form of awareness via zonal welfare constraints, this concept goes one step further. By trading the single-zone objective function for maximizing welfare at the zonal level, no single-zone element remains at the investment level. The resulting network is a patchwork of interconnected zonal networks. It is the result of zonal decision-making without any involvement of a higher decision level. Note, however, that despite the strong multi-area awareness and zonal focus on transmission investments, other aspects remain unchanged. The network is assumed to remain interconnected[2] and the market still covers the entire network.

As already high-lighted in the literature study on design options for planning models, existing models or concepts with a high multi-area awareness in investment planning are scarce (section 4.1.6). The most valuable source for this thesis' research question is provided by [90] where also non-cooperative behaviour in transmission

[1] Another interpretation of investments being decided at a higher than zonal levels assumes that investments are decided zonally but that a welfare transferring framework is in place giving correct incentives to the zonal level such that they decide in line with the higher level.

[2] At least when zones are interconnected at the start. When initially energy islands are considered, there is no guarantee that they will be connected in the result of the non-cooperative planning game.

investments is addressed. However, the analysis is limited to the intuition behind competing merchant investors. This chapter goes beyond an intuitive analysis by setting up and solving a mathematical model. Moreover, the presented approach deals with regulated investments and does not consider merchant investors.[3]

A third change concerns the consequence of this increased multi-area awareness on the planning process. Whereas in the previous concepts there always is a single planner deciding upon investments for the entire network (with or without Pareto-constraints), there are now many decision-makers. Investments are evaluated by the zonal planners with zonal economic welfare levels in mind. Of course, these planners all interact as the zonal networks are interconnected and interact via a single market covering all zones. Each zonal planner is affected by the investment decisions taken by other zones and vice versa. In fact, they play a game. As now each player has its own decision variables, i.e. transmission investments, it is important to clearly define property rights and indicate which player can invest in which connections.

As the zonal planners now play a game, the result is no longer defined as an optimum. It is better characterised as an *equilibrium*. By simultaneously solving the different zonal optimisation problems and for each problem taking into account the behaviour of other decision-makers, an outcome is sought for in which no single zonal planner has an incentive to deviate from the result. In other words, in an equilibrium no player can improve his own objective function given the decisions of the other players. Translated to the non-cooperative planning game, this means that in the equilibrium no zonal planner is able to improve zonal welfare by changing its investment decisions given the decisions of the other zonal planners.

This equilibrium is of course the main result of the non-cooperative planning game and can be compared with the results found for the other planning concepts. However, zonal planners' *reaction curves* are an interesting by-product of the non-cooperative planning game. A reaction curve provides an insight in a zonal planner's best response given the decisions of the other players. It can also be used to check whether the solutions found by the other concepts are stable, i.e. whether they represent an equilibrium or not. When this is not the case, one or more zonal planners have an incentive to alter their investment decisions.

Section 7.1.2 formalises several of the above findings by relating them to the structure of the non-cooperative planning game. Firstly, several limitations of this concept are discussed.

[3]Note that in a recent contribution, the analysis presented in this chapter is already broadened by the incorporation of zonal cooperation on renewable objectives [134].

Limitations

The non-cooperative planning game as intuitively described above and further developed in the remainder of this chapter represents an extreme concept for collaboration. In different ways it is very restricting. Nevertheless, the choice for this concept can be justified by the research question. Additionally, solving the limitations would require more complicated models. As explained in section 7.3, the current concept represents already a harsh mathematical challenge.

The literature on game theory provides a broad variety of games that can be played. With respect to the non-cooperative planning, repeated and sequential games, games with imperfect information, bargaining theory and the relevance of the threatpoint herein all present interesting routes to follow to render the game among zonal planners more realistic. Textbooks on game theory provide useful insights on how such games are organised [135, 136]. Nevertheless, for the purpose of this thesis, the presented non-cooperative game already provides for sufficient complexity.

One-stage game The non-cooperative planning game is conceived as a one-stage game. This means that all decisions are taken in a single round, i.e. once and forever. All zonal planners decide on their investments simultaneously. There is no possibility to change the decision afterwards or to observe the actions of the other players. Planners cannot react upon decisions of the other planners. In reality, all planners do not have to decide on the same moment. They can observe actions of others and then take their decision. This of course alters the rules of the game. Repeated games or games with sequential moves can be used to relax this assumption.

Similarly, the one-stage nature of this concept automatically rules out any form of negotiation between different planners. This is an extreme assumption which allows exploring the other end of the spectrum of collaboration (i.e. compared to the supranational planner where full collaboration is assumed). In reality, however, it is possible (and common practice) for countries to negotiate, for instance, cost-sharing keys. Despite that in reality negotiations are possible for all investments, it is likely that only for interconnector projects such negotiations take place and often only in bilateral way. This implies that not always all affected parties have been around the negotiation table. These subtleties can be captured by models based on bargaining theory.

Perfect information In section 4.1 the incorporation of uncertainty into the different concepts is discussed. A deterministic world without uncertainties is opted for as this allows models to to be simpler, but at the same time to be sufficiently complex to answer the research questions.

For the non-cooperative planning game another kind of uncertainty emerges and extra assumptions are required. How much information does one zonal planner has about the other zones? Does he know the demand and generation cost functions? Does he have knowledge on the existing network and the transmission investment costs? For the non-cooperative planning game, it is assumed that all zonal planners have perfect information. Although in reality this would obviously not be the case, this simplification is acceptable keeping in mind the research questions. It is not the purpose to model reality as perfectly as possible, rather the aim is to sketch the impact of different forms of collaboration.

Threatpoint The non-cooperative planning game always starts from an initial situation, in game theory sometimes called the threatpoint. This initial situation of course determines the possible actions for each planner. In this thesis, this situation is given and not further discussed. Nevertheless, slight changes to this initial situation can result in a different equilibrium. It can also change the impact one player can have on the others. Consequently, planners can have an incentive to alter the initial situation, e.g. by investing in the own internal network and thereby changing initial flow patterns, resulting in a stronger (bargaining) position in the game itself. An example can be found in negotiations for natural gas contracts [137].

7.1.2 Structure

Fig. 7.1 gives a clear overview of the structure of the non-cooperative planning game. The zonal emphasis is found in the existence of multiple zonal planners each maximizing the zonal welfare minus zonal investment costs. Each planner is also bound by some investment constraints. As for the previous concepts, they can include limits on new circuits added, corridors used, budget, etc. The zonal planners are deciding on the investments and all act as leaders. Hence, the problem at hand is a multi-leader problem.

A zonal planner can be described by a bilevel problem structure because also in the non-cooperative planning game each zonal planner is subject to the underlying market outcome. The mutual influence between planner and market remains unchanged. Investments are still impacted by their market effects and the market is bound by the transmission network, including the newly decided investments. This is true for each zonal planner. Of course, as all planners act on the same interconnected network, it is important to ensure that they all take into account the same market conditions and outcome. For instance, the investment decisions of planner 1 are reflected in all prices and the dispatch in the entire network. Planner 2 has to take this into account for his decisions. Hence, a single common

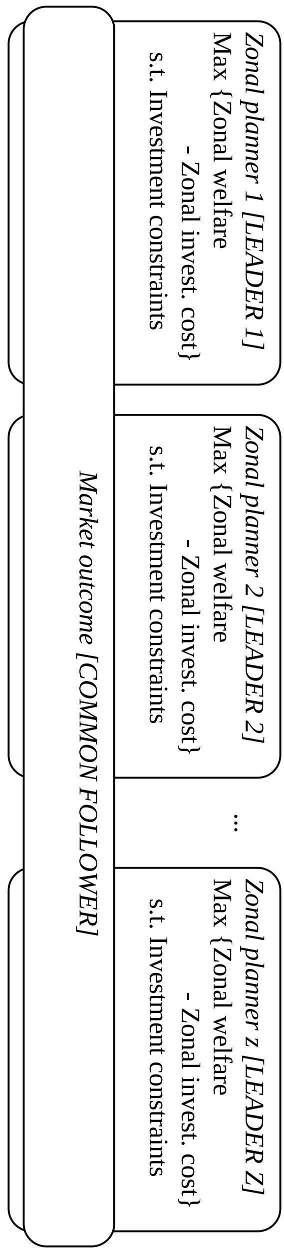

Fig. 7.1: Structure of the non-cooperative planning game: multi-leader common follower

market has to be ensured. This is called a common follower. In Fig. 7.1 this is indicated by a single box with the market outcome stretching over all leaders' constraints.

The problem boils down to solving simultaneously several MPEC or Stackelberg problems. Such a problem is a game with multiple players (i.e. the zonal planners) and a common underlying problem (i.e. the market) and can be classified as a Generalised Nash Equilibrium Problem (GNEP) as defined in [138]. A GNEP is characterised by the dependence of each player's feasible set on the decisions of the other players.

More specifically, the game played by the zonal planners is in fact a Nash game played by multiple Stackelberg leaders with a common follower. References [139] and [140] provide a thorough discussion of this type of games. In [140] the common nature of the following market problem determining a single market outcome with dispatch and prices is defined as ensuring price consistency. The non-cooperative solution is then found by simultaneously solving the zonal planners' MPECs while ensuring price-consistency, i.e. while solving a single underlying DCOPF.

Mathematically, GNEPs or multi-leader common follower problems are often formulated as Equilibrium Problems with Equilibrium Constraints (EPEC). An EPEC is an equilibrium found by simultaneously solving multiple MPECs. In fact the equilibrium conditions of each MPEC have to be determined keeping in mind that the MPEC itself partly consists of equilibrium conditions. Solving EPECs is hard and subject of ongoing research. This is further discussed in section 7.3. First, a mathematical formulation of the non-cooperative planning game is described in the next section.

7.2 Mathematical formulation

This section explains how the non-cooperative planning game is mathematically modelled as an EPEC. This is done in two steps. The first step describes the problem faced by a single zonal planner. This problem is an MPEC. The second step brings together several MPECs and shows how they are welded into a single EPEC.

7.2.1 Single-level MPEC formulation of a zonal planner

The bilevel problem representing the zonal planner is directly formulated as a single-level MPEC for two reasons. Firstly, the same reasoning as for the Pareto-planner applies. The leader uses both primal and dual variables (in particular nodal prices) in its objective function. Secondly, the objective functions of the leader and the follower are not aligned as the former maximizes only zonal welfare and the latter considers overall welfare. Hence, it is not possible to drop the lower level objective function and add the constraints of the DCOPF directly to the leader's problem. MPECs and their ability to model bilevel problems are already described in section 6.2.2. An analogous reasoning is applied on the non-cooperative planning game. It is again the DCOPF which is rewritten by using its KKT conditions. The zonal planner can be described by the following optimisation problem.

Maximize

$$\sum_p T_p \Bigg(\sum_{n\in\Omega^{N(z)}} \left(A_{n,p} d_{n,p} - \frac{1}{2} B_{n,p} d_{n,p}^2 - \lambda_{n,p} d_{n,p} \right) \tag{7.1a}$$

$$+ \sum_{n\in\Omega^{N(z)}} \sum_t \left(\lambda_{n,p} g_{n,t,p} - C_{n,t,p} g_{n,t,p} - \frac{1}{2} D_{n,t,p} g_{n,t,p}^2 \right) \tag{7.1b}$$

$$+ \sum_{n\in\Omega^{N(z)}} \sum_l \left[\frac{1}{2} \left| INC_{l,n} \right| f_{l,p} \sum_b \left(-INC_{l,b} \lambda_{b,p} \right) \right] \Bigg) \tag{7.1c}$$

$$+ \sum_{l\in\Omega^{L(z)}} \left(CL_l \; LN_l \; x_l \right) \tag{7.1d}$$

subject to:

$$\forall l \qquad x_l \geq 0 \tag{7.2a}$$

$$\forall n,p \qquad A_{n,p} - B_{n,p} d_{n,p} + \lambda_{n,p} + \kappa_{n,p} = 0 \tag{7.2b}$$

$$\forall n,t,p \qquad -C_{n,t,p} - D_{n,t,p} g_{n,t,p} - \lambda_{n,p} - \nu_{n,t,p} + \rho_{n,t,p} = 0 \tag{7.2c}$$

$$\forall n \neq n_s, p \qquad \sum_l INC_{l,n} H_l \psi_{l,p} = 0 \tag{7.2d}$$

$$\forall p \qquad \sum_l INC_{l,n} H_l \psi_{l,p} + \xi_p = 0 \tag{7.2e}$$

$$\forall l,p \qquad -\sum_n INC_{l,n} \lambda_{n,p} + \mu_l^a - \mu_l^b + \psi_{l,p} = 0 \tag{7.2f}$$

$$\forall p \qquad \theta_{n_s,p} = 0 \tag{7.2g}$$

$$\forall n,p \qquad \sum_t g_{n,t,p} - d_{n,p} - \sum_l (INC_{l,n} f_{l,p}) = 0 \tag{7.2h}$$

$$\forall l,p \qquad f_{l,p} - H_l \sum_n (INC_{l,n} \theta_{n,p}) = 0 \tag{7.2i}$$

$$\forall l,p \qquad 0 \leq F_l^{max} + x_l + f_{l,p} \quad \perp \quad \mu_{l,p}^a \geq 0 \tag{7.2j}$$

$$\forall l,p \qquad 0 \leq F_l^{max} + x_l - f_{l,p} \quad \perp \quad \mu_{l,p}^b \geq 0 \tag{7.2k}$$

$$\forall n,t,p \qquad 0 \leq G_{n,t,p}^{max} - g_{n,t,p} \quad \perp \quad \nu_{n,t,p} \geq 0 \tag{7.2l}$$

$$\forall n,p \qquad 0 \leq d_{n,p} \quad \perp \quad \kappa_{n,p} \geq 0 \tag{7.2m}$$

$$\forall n,t,p \qquad 0 \leq g_{n,t,p} \quad \perp \quad \rho_{n,t,p} \geq 0 \tag{7.2n}$$

The zonal planner's MPEC is composed as follows. The objective function is given by (7.1) and consists of all terms determining zonal welfare: zonal CS and PS, CR accrueing to the zone and the cost for transmission investments within the zone. This is identical to the zonal welfare defined in the Pareto-constraints for the variant without cost allocation (6.12). The constraints of the zonal planner are the same as for the supranational planner (and the Pareto-planner except for the Pareto-constraints). The investment constraint is given by (7.2a) and the underlying DCOPF by its KKT conditions in (7.2b)-(7.2n). Their interpretation remains unchanged.

7.2.2 EPEC formulation of the non-cooperative planning game

The solution of an EPEC is an equilibrium for all players, i.e. the zonal planners. Hence, in order to ensure this property the equilibrium conditions of all players have to be met. As already explained (see section 6.2.2), KKT conditions can be used as equilibrium conditions.

Whereas in case of the Pareto-planner and the zonal planner only the underlying DCOPF is reformulated using its KKT conditions, now the equilibrium conditions of the entire MPEC have to be determined. In order to achieve this, the MPEC is first reformulated as an NLP. In particular the complementarity constraints need an alternative formulation. Equation (6.8f) of section 6.2.2 can be rewritten as in (7.3) [140, 141]. Equation (7.3c) now ensures that both elements cannot be non-zero at the same time.

$$G(x,y) \geq 0 \tag{7.3a}$$

$$\mu \geq 0 \tag{7.3b}$$

$$G(x,y) * \mu = 0 \tag{7.3c}$$

Next, the KKT conditions of this NLP can be determined. In order to do so, first the Lagrangian L of the NLP is defined:

$$\begin{aligned} &L(x, y, \lambda, \mu, \gamma^g, \chi^h, \eta, \gamma^G, \chi^H, \omega, \zeta) \\ &= W + g^T \gamma^g + h^T \chi^g + \left(\nabla_x F - \nabla_x G^T \mu + \nabla_x H^T \lambda\right)^T \eta \\ &\quad + \mu^T \omega + H^T \chi^H + G^T \gamma^G + \left(G(x,y) * \mu\right)^T \zeta \end{aligned} \tag{7.4}$$

The Greek symbols γ^g, χ^h, η, χ^H are the dual variables corresponding to constraints (6.8b)-(6.8f). γ^G, ω, ζ are the duals of constraints (7.3a)-(7.3c). The KKT conditions of the reformulated MPEC then become:

$$\nabla_x L = 0 \tag{7.5a}$$

$$\nabla_y L = 0 \tag{7.5b}$$

$$\nabla_\lambda L = 0 \tag{7.5c}$$

$$\nabla_\mu L = 0 \tag{7.5d}$$

$$0 \leq g(x,y) \quad \perp \quad \gamma^g \geq 0 \tag{7.5e}$$

$$0 = h(x,y) \tag{7.5f}$$

$$0 \leq G(x,y) \quad \perp \quad \gamma^G \geq 0 \tag{7.5g}$$

$$0 \leq \mu \quad \perp \quad \omega \geq 0 \tag{7.5h}$$

$$\nabla_x F(x,y) - \nabla_x G(x,y)^T \mu + \nabla_x H(x,y)^T \lambda = 0 \tag{7.5i}$$

$$H(x,y) = 0 \tag{7.5j}$$

$$G(x,y) * \mu = 0. \tag{7.5k}$$

A zonal planner's MPEC can be modelled with the above set of equilibrium conditions. For the full EPEC representing the non-cooperative planning game for each planner, such a set of equilibrium conditions is required. However, in order to ensure price consistency and a common follower, i.e. a single underlying DCOPF, the constraints related to the DCOPF should only be added once to the EPEC problem. Moreover, each zonal planner should use the same set of dual and primal variables relating to the market problem.

7.3 Solution methods

Like MPECs the mathematical properties of EPECs make them a hard challenge to solve. The complementarity constraints, even when reformulated as non-linear constraints, render them very difficult to solve. Moreover, it is not guaranteed that a solution always exists, and if it exists whether it is unique or multiple equilibria exist. The properties with respect to the existence of (multiple) solutions and convergence of solution methods strongly vary with the specific problem adressed. The difficulties with solving and interpreting EPEC results are outlined in [141].

In [132, 139] the concept of a Nash equilibrium is extended towards a local Nash equilibrium in case of an EPEC.

Based on [142] two categories of solution algorithms are identified in [132]. Like for MPECs one group first reformulates each player's MPEC to an NLP and then solves for the KKT conditions of each NLP as set up in section 7.2. An alternative is applied by [139, 143]. A diagonalisation method is used in which MPECs are solved sequentially using the intermediate results of previous players until convergence for all players is reached. This methodology does not require the full EPEC model as discussed in the previous section. In [144] another method is proposed which sequentially solves relaxed MPEC problems. The latter problems are written as non-linear problems.

When solving an EPEC it may happen that multiple equilibria are found. Choosing a single equilibrium is not straightforward and without extra assumptions often not even possible. This problem is also discussed in [141].

As there are no clear-cut methods available (yet) to solve EPECs, in this thesis the problem of solving the EPEC is circumvented by enumerating all possible solutions and then ex post looking for equilibria. Obviously, enumeration is very time consuming and therefore, only feasible for small problems. Nevertheless, this approach has at least three advantages. Firstly, it is very easy to check whether there are multiple equilibria or just one (if any at all). Secondly, convergence problems are avoided. Finally, the reaction curves are also easily constructed. Hence, for providing an insight in the non-cooperative planning game this is sufficient and no more sophicaticated methods are required.

7.4 Examples

In this chapter the examples introduced in section 5.4 serve again to illustrate the non-cooperative planning game and compare its result with the other concepts. However, only the two-zone and both three-zone examples are used. The non-cooperative planning game is not analysed for the 14-node, three-zone example. Enumeration is no longer a workable solution method for an example of that size.

7.4.1 Two-zone example

In contrast to the two previous concepts with a single decision-maker, for the non-cooperative planning game it is important to clearly identify who decides on which transmission link. As already outlined in section 5.4.1 and indicated in Fig. 5.2, the connection between zones A and B can be split in two equal segments T_{AF} and T_{BF} where F denotes the frontier between both zones.

	No link		Supra = Pareto CA = Pareto w/o CA		Non-coop	
	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
Gen. [MW]	3250	2667	3959	2037	3805	2173
Dem. [MW]	3250	2667	3014	2982	3065	2913
Price [€/MWh]	32.5	53.3	39.6	40.7	38.1	43.5
CS [€]	158438	142222	136236	177815	140913	16750
PS [€]	52813	71111	78365	41475	72390	47234
CR [€]	0	0	540	540	2004	2004
CS+PS+CR [€]	211250	213333	215140	219829	215308	218988
Inv. cost [€]	0		1079		422	422
Capacity [MW]	0		945.2		740	
Overall welf. [€]	424583		433890		433451	

Table 7.1: Two-zone example: overview of results on an hourly basis for all concepts

An important consequence of this split in two segments is that when the transmission capacity on these segments is not equal, it is the segment with the lowest capacity which determines the maximum flow between A and B. For instance, if on T_{AF} the capacity is 500 MW and on T_{BF} only 300 MW, the flow between A and B can never exceed 300 MW. Hence, 200 MW on T_{AF} remains unused.

In the last column of Table 7.1 the results for the non-cooperative planning game are displayed. A transmission capacity of 740 MW is installed on both segments.[4] This is clearly less than in the cases of the supranational and Pareto-planners where 945.2 MW[5] is installed. A larger price difference remains between both zones in the non-cooperative outcome. From the welfare results it can be analysed that zone A has most interest in keeping the capacity limited to 740 MW. Its welfare (CS+PS+CR) is slightly higher than when 945.2 MW is installed. The overall welfare level is obviously smaller than in the supranational case.

This result and zone A's incentive to limit the capacity to 740 MW can also be seen from Fig. 7.2 where zonal and overall welfare are depicted for a transmission capacity varying from 0 to 1000 MW. The overall welfare function peaks at

[4]Note that this value is found using enumeration with a step size of 10 MW. This means that all transmission capacities between 0 and 1000 MW are tested with a 10 MW interval. The upper bound of 1000 MW is sufficient because price convergence is reached by then rendering higher investments useless.

[5]This result is found using the QP and MPEC from chapters 5 and 6. When using enumeration with a 10 MW step size, the result would be 950 MW.

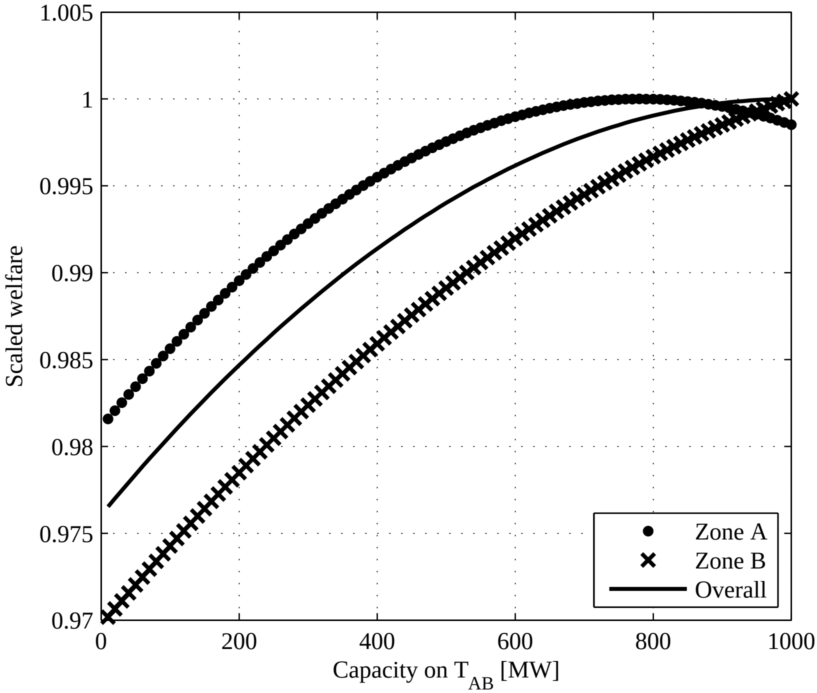

Fig. 7.2: Two-zone example: zonal and overall welfare for different levels of transmission capacity

950 MW.[6] For zone B a monotonically increasing curve is observed. It benefits from higher transmission capacity until price convergence is reached. However, a clear maximum for zone A is found at 740 MW after which zonal welfare drops.

The reaction curves shown in Fig. 7.3 provide a similar insight. In the upperright corner of the figure a discrepancy between zone A's and B's reaction curves is noted. Even if zone B decides upon a capacity higher than 740 MW, zone A would still install a capacity of only 740 MW. Zone B, however, always follows zone A's decision by installing the same amount of capacity.

Additionally, from the same figure it can be observed that a multitude of equilibria exists and that the 740 MW is just one (but extreme) outcome. All solutions on the section from 0 to 740 MW where both reaction curves coincide, are equilibria of the non-cooperative planning game. In general, it is very difficult to pick a single

[6] Cfr. previous footnote.

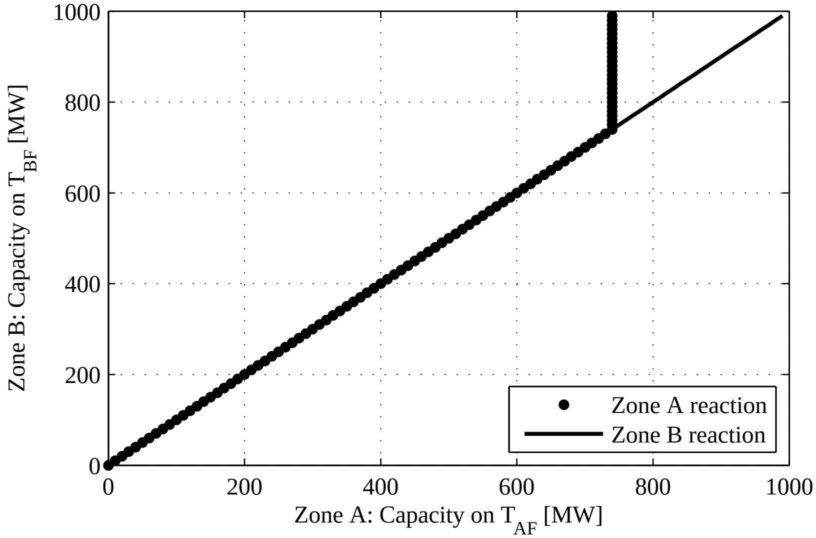

Fig. 7.3: Two-zone example: reaction curves

outcome as there is no reason why under the given circumstances one equilibrium should be favoured above the others. However, here the solution of 740 MW is put forward as this is the equilibrium with the highest overall welfare and the highest welfare for both zones separately.

The difference in total welfare for zone A between both outcomes is small enough to be compensated by zone B's welfare gains when going from 740 to 945.2 MW. This illustrates that a welfare compensation mechanism can facilitate an overall welfare maximizing solution whilst taking into account different zonal intrests. Note that this observation is based on welfare figures before taking into account investment cost, i.e. CS+PS+CR in Table 7.1. Even if zone B would bear the full cost of moving from 740 to 950 MW, namely 239.7 €/h[7], and not only the cost for its own segment an extra compensation for zone A is still required to convince zone A to host the infrastructure on its territory. This suggests that a mechanism based on cost allocation alone is not sufficient to reach the supranational solution.

[7]239.7 €/h = (950 MW − 740 MW) × 200 km × 50 €/(km.MW.year) × (1/8760 h)

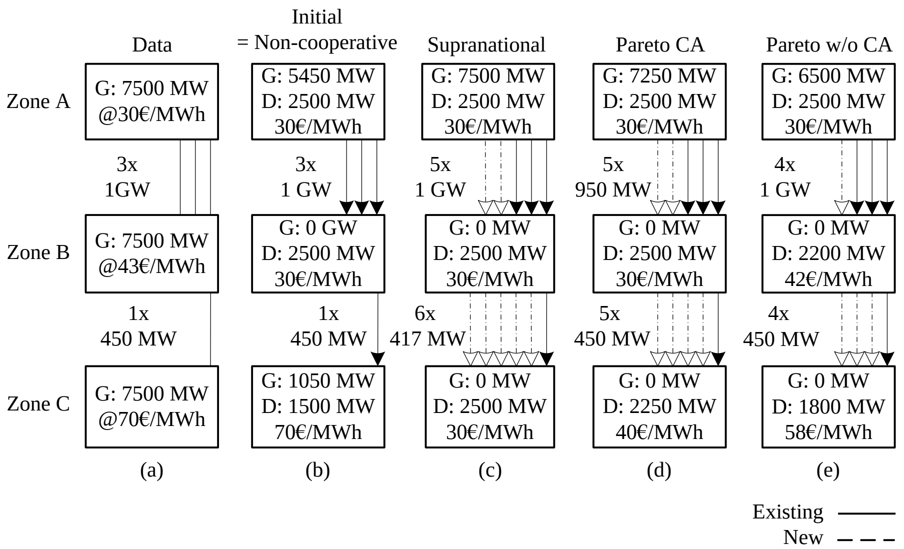

Fig. 7.4: Three-zone radial example: overview of solutions

7.4.2 Three-zone example: radial configuration

As for the two-zone example, it is also for this case important to highlight which zone can invest in which lines. In Fig. 5.8 four line segments have already been defined. Zones A and C respectively decide on line segments T_{AF_1} and T_{CF_2}.[8] Zone B can invest in the remaining two segments adjacent to its zone, i.e. T_{BF_1} and T_{BF_2}.

The investments in the non-cooperative planning game are given in Fig. 7.4(b). It turns out that the initial situation is the only equilibrium. Hence, no zone has an incentive to deviate from the initial outcome. The welfare effects are given in Table 7.2. Although large welfare gains are possible in the supranational case and both Pareto-outcomes, this cannot be reached without any form of cooperation or welfare compensation.

In particalur zone B, located centrally in the network, is crucial for this equilibrium. As in the initial situation zone B already enjoys the lowest possible price, i.e. 30 €/MWh, it uses its decision power on the two links in its territory to keep the

[8] F_1 and F_2 respectively denote the frontier between zones A and B and zones B and C. They are artificial nodes without generation nor demand.

	Initial = Non-cooperative			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	125	125	45	125	125	125
PS	0	0	0	0	0	0
CR	0	9	9	0	0	0
CS+PS+CR	125	134	54	125	125	125
ΔWelfare	-	-	-	0	-9	+71
Investment cost	-	-	-	-1.83		
	Pareto CA			Pareto w/o CA		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	125	125	101.25	125	96.8	64.8
PS	0	0	0	0	0	0
CR	0	11.25	11.25	24	38.4	14.4
CS+PS+CR	125	136.25	112.5	149	136.9	79.2
ΔWelfare	0	+2.25	+58.5	+24	+1.2	+25.2
Investment cost	-1.60			-0.17	-0.51	-0.34

Table 7.2: Three-zone radial example: hourly welfare effects [k€]

price at this level and avoid any price increase. Whatever the decisions of the other zones are, zone B can always take appropriate action to ensure its welfare level. In Fig. 7.5 zone B's reaction curve is given. Zone C is clearly the victim of zone B's decision power. Its best response is to copy zone B's reaction on segment T_{BF_2}. For zone A the situation is better because the cheapest generator is located in its zone. Nevertheless, also for zone A better outcomes exist, like the Pareto-planner without cost allocation.

Note that any case with price convergence (30 €/MWh in all three zones), like the supranational result, is not an equilibrium. Although zone B profits from a price of 30 €/MWh in this case, zone B has no incentive at all to pay for the necessary investments on link T_{BF_2} enabling zone C to also benefit from zone A's cheaper generation. Both Pareto-outcomes are also no equilibria. The Pareto-planner with CA is not an equilibrium because zone A has an incentive to limit the number of circuits on T_{AF_1} to 4 instead of 5 because it is then able to retrieve a higher amount of CR. Similarly, zone B has an incentive to keep the number of circuits on T_{BF_2} on 3 instead of 4 in the Pareto-case without cost allocation. By doing so, it prevents a higher price of 42 €/MWh resulting in a lower zonal CS.

As in the two-zone example, moving away from the non-cooperative outcome to the supranational case is possible when the benefitting party compensates the negatively affected one. Hence, zone C should compensate zone B for the welfare

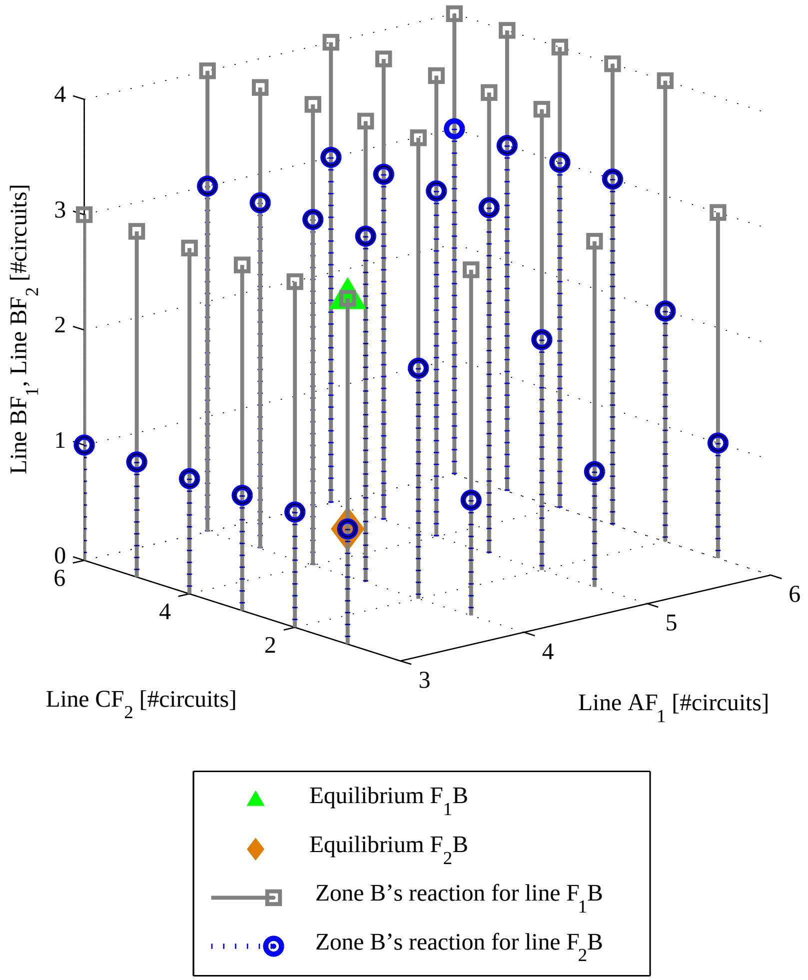

Fig. 7.5: Three-zone radial example: reaction curve for zone B

loss. Note, again, that it is insufficient to only finance the transmission investment costs. Zone B's welfare loss exceeds the transmission costs. Additionally, zone C should also finance the investments on zone A's territory.

	T_{AB}	T_{BC}	T_{AC}
Supranational	+115.9	+75.4	+391.4
Pareto CA	+24.5	+0	+224.5
Pareto w/o CA	+24.5	+0	+224.5
Non-cooperative	+150	+0	+350

Table 7.3: Three-zone meshed example: invested capacity compared to the initial situation [MW]

7.4.3 Three-zone example: meshed configuration

In this example zones A, B and C respectively decide on links T_{AB}, T_{BC} and T_{AC} as outlined in section 5.4.4. There are no artificial nodes indicating frontiers.

The results for the non-cooperative planning game are again different from the other concepts. Like in the Pareto-outcomes, no investments take place on link T_{BC} as indicated in Table 7.3. In contrast, a higher level of investments is noted on the other links. However, it is important to acknowledge that a multitude of equilibria exists and that the solution given by Tables 7.3 and 7.4 is the outcome resulting in the highest overall welfare and the highest welfare for zones A and C. Whereas for T_{BC} the invested capacity is zero in all equilibria and the initial capacity of 200 MW is maintained, for zones A and C, the invested capacity varies between +40 and +150 MW on T_{AB} and between +240 and +350 MW on T_{AC}. In Fig. 7.6 the zonal welfare evolution is shown for all equilibria.

In Table 7.4 the welfare effects are given and compared to the other concepts. The non-cooperative equilibrium is not Pareto-improving because zone B is worse off. Note, however, that this is not so severe for all equilibria as can be seen in Fig. 7.6. The first equilibrium at the left-hand side of the graph with invested capacities +40, +0 and + 240 MW on respectively T_{AB}, T_{BC} and T_{AC} is nearly Pareto-improving. It is also interesting to note that overall welfare is higher in the non-cooperative planning equilibrium than in the Pareto-outcomes. Less collaboration creates more welfare, albeit with a negative effect on zone B.

In Fig. 7.7 the reaction curves of each zone are given. Whereas in the horizontal plane the decisions of the two other zones are given, the vertical axis is used to indicate the reaction of the concerned zone. All axes depart from 200 MW, which is the initially present transmission capacity on each link. For instance, Fig. 7.7(a) shows the investment of zone A in T_{AB} given the amount invested by zones B and C in respectively T_{BC} and T_{AC}. The black dots represent the different non-cooperative solutions.[9]

	Initial			Supranational		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	166.2	156.8	150.5	181.1	156.6	138.0
PS	45.4	44.4	40.9	33.0	44.7	56.0
CR	1.266	0.493	1.198	0.285	0.113	0.277
CS+PS+CR	212.9	201.7	192.5	214.6	201.4	194.3
ΔWelfare	-	-	-	+1.735	-0.374	+1.758
Investment cost	0	0	0		-0.333	
	Pareto w/o CA =Pareto CA			Non-coop		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
CS	174.7	156.9	143.1	181.1	154.0	140.5
PS	38.2	44.3	49.4	33.2	47.3	52.8
CR	1.258	0.494	1.203	0.408	0.144	0.698
CS+PS+CR	214.1	201.7	193.8	214.7	201.5	194.0
ΔWelfare	+1.201	0	+1.239	+1.810	-0.265	+1.423
Investment cost		-0.142		-0.086	0	-0.200

Table 7.4: Three-zone meshed example: hourly welfare effects [k€]

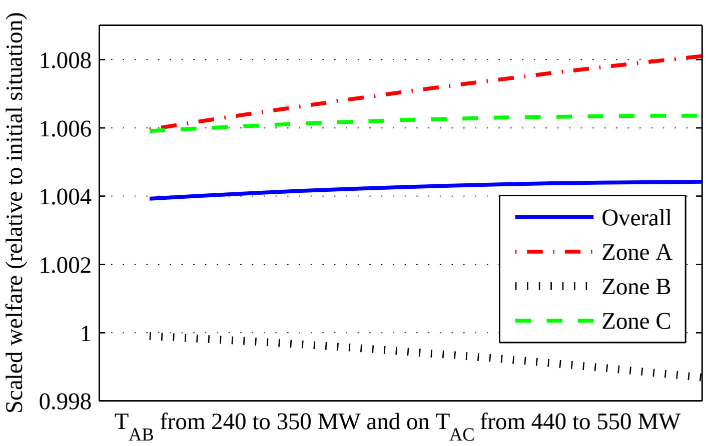

Fig. 7.6: Three-zone meshed example: welfare evolution for different non-cooperative equilibria

[9] Again a step size of 10 MW is used for enumeration of all solutions.

From Fig. 7.7 it can also be seen that the supranational solution is not an equilibrium. In particular zone B is the spoilsport. When zones A and C invest according to the cooperative solution, zone B has an incentive to keep the capacity on T_{BC} limited to the initial 200 MW. An opposite behaviour can be observed for zone C. Given that zones A and B decide upon the supranational solution for their transmission line, zone C invests up to a capacity of 590 MW, i.e. the supranational solution. An almost similar situation occurs for zone A, assuming the supranational output for zones B and C, zone A increases the capacity of T_{AB} to 320 MW, only 10 MW more than in the supranational solution.[10]

The observations in the previous examples concerning a compensation mechanism remain valid for this case. Again the welfare loss for zone B in the cooperative solution compared to the non-cooperative solution is smaller than the gains accrueing to zones A and C together. A compensation mechanism incenting zone B to act in line with the supranational solution is possible. Again it is, however, insufficient to cover only the investment cost that zone B has to make for attaining the supranational solution. Even without taking this hourly cost of 347 €/h into account, zone B would suffer a loss of 265 €/h. Therefore, a welfare compensation mechanism should ensure compensating zone B with an extra amount of 82 €/h.

[10]Note, however, that the step size for enumarating all solutions is 10 MW and it can be assumed that it coincides with the supranational solution.

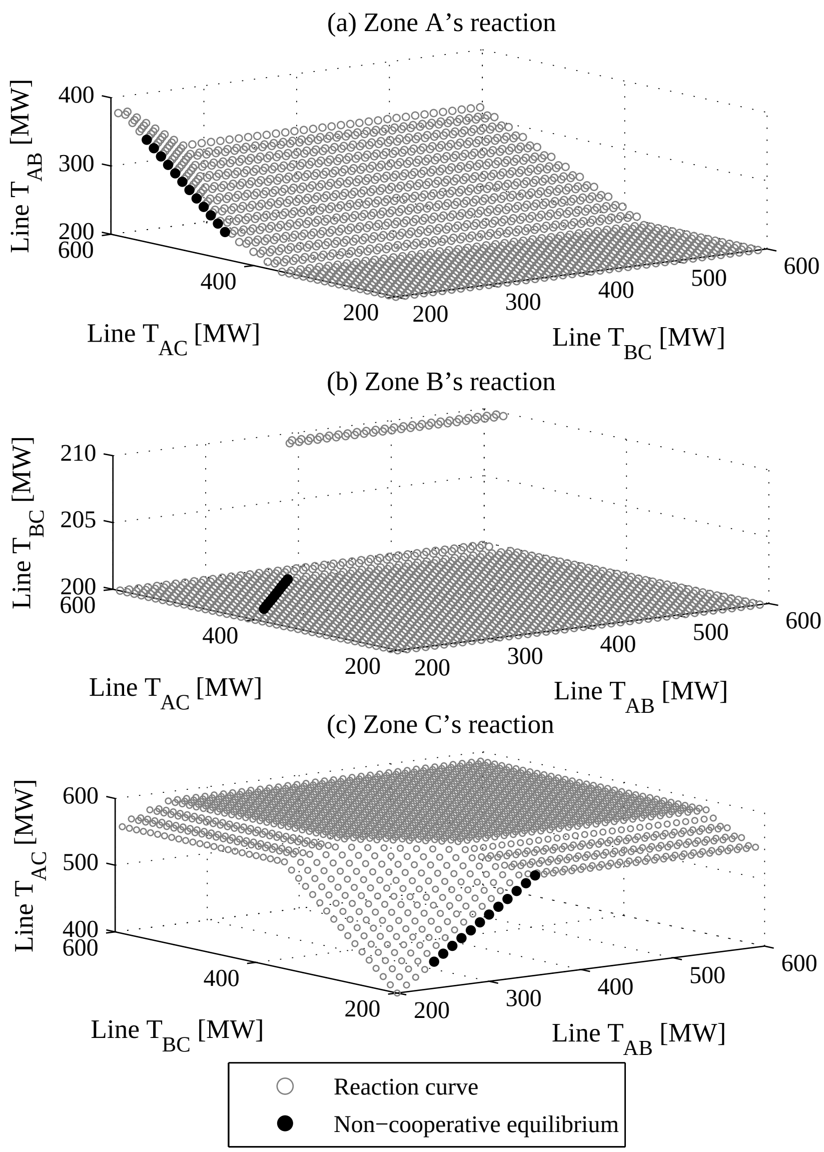

Fig. 7.7: Three-zone meshed example: reaction curves

7.5 Assessment of design choices

The assessment of design choices for the non-cooperative planning game closely follows the analysis made for the Pareto-planner (section 6.5). The mathematical complexity limits the options to structurally extend the model. A dynamic treatment of the planning horizon and a proactive link with generation investments become very hard challenges. In particular, solving even more complicated EPEC systems requires extensive research, especially if enumeration is not considered an adequate solution method.

With respect to uncertainty and market incorporation, the non-cooperative planning game can be adapted for other choices. As for the Pareto-planner, another market does not create new modelling challenges. For uncertainty, it depends on the kind of uncertainty introduced, but scenario-analysis should not significantly increase the complexity.

Keeping in mind the research question, extending the objective function with other objectives is the most interesting route to follow. As described in the supranational planner's design choice assessement, it is possible to have a single objective function in which all objectives are measured in the same units. This should not introduce too many difficulties. Also a multi-objective framework is possible, but is inherently more complicated. The issue of interpretation of multiple objectives raised for the Pareto-planner does not hold for the non-cooperative planning game, as no initial welfare constraints are applied. It is difficult to assess how the results would change when extra objectives are introduced, but is likely that more equilibria emerge because zones have the possibility to internally trade-off different objectives.

7.6 Conclusions

In this chapter the third and last planning collaboration concept is described, mathematically formulated and illustrated by means of simple examples. The analysis reveals that this concept is extreme with respect to its multi-area awareness. Zones and their individual welfare are explicitly modelled. This is the strength of this concept and makes it unique compared to the other concepts and the available academic literature on multilateral investments.

Structurally and consequently also mathematically this concept is different from the previous ones. A multi-leader common follower problem with multiple zones modelled as Stackelberg leaders with a common (price-consistent) underlying market is required to capture its complexity. In terms of operations research, the model is an EPEC. Theory on EPECs is still under development and solution methods are not readily available. Hence, enumeration of the solution space is used to solve the examples.

From the structure and its underlying intuition, it is clear that the overall welfare is never taken into account and it is not possible to generally rank this concept in terms of overall welfare compared to the previous planning collaboration concepts. This is confirmed by the provided examples. For instance, in the three-zone meshed example it is noted that the non-cooperative outcome scores better than the Pareto-outcomes in terms of overall welfare. Hence, having an intermediate level of collaboration like in the Pareto-planning concept is not always better than having no collaboration at all. This is a rather strong conclusion and is obviously subject to the assumptions made. It can definitely not be generalised to all situations as shown by the other examples where the non-cooperative planning game results in a lower level of overall economic welfare.

The reaction curves for different zones prove to be a useful tool to analyze zonal investment behaviour and incentives. Depending on the topology and assumed cost figures, it is possible that one zone is more dominant in determining the non-cooperative outcome than others. This is illustrated by all three examples.

Finally, a similar conclusion as in chapter 5 can be made. In order to move from the non-cooperative outcome to the supranational outcome it is in several cases insufficient to limit compensation mechanisms between zones to investment costs only. A broader welfare transfer is required to alter investment incentives.

8

Conclusions and recommendations for further research

This thesis started with an analysis of the challenges for European electricity transmission investments and the surrounding framework for collaboration between different countries. Two questions have been raised. These questions are answered in this chapter by recapitulating the main results and conclusions from the previous chapters. In addition, this chapter makes recommendations for further research.

8.1 Conclusions

From the analysis of European energy policy, it can be learned that there is huge transmission investment challenge driven by the aim for a secure, sustainable and competitive energy supply. Ensuring reliability on the short and long term (including solidarity between different countries), creating a level playing field for a single European electricity market and supporting climate change goals by accomodating substantial connection of renewable energy sources, are three policy goals put forward by Europe. Each of them heavily relies on the transmission grid as enabler. This challenge is widely recognized. However, the framework for delivering on these investments is not (yet) adapted to the challenge. Correct incentives should be given to all parties. Especially the finding that today the national level is still the most important one and in the end drives investment decisions, should not be neglected as its consequence can be that the European goals are not adequately incorporated in the decision-making process and the objective function of national decision-makers.

Given this call for an adequate framework and incentives, a more detailed analysis of the current framework was done. It revealed that the Third Package clearly introduced a European flavour in transmission investments. The creation of ENTSO-E and ACER are important milestones. The TYNDPs have the potential to become powerful tools for meeting the challenges. However, it should also be clear that the Third Package does not go far enough to ensure that European goals will be met. An area of tension between the national and the European level remains. The national level of decision-making remains very strong and lacks incentives to truly incorporate the European goals in its decisions. Planning, regulatory oversight and financing are not fully adapted to the European investment challenge.

The upcoming EIP again takes some steps forward, but it is unlikely to fix all remaining loopholes. Although extra Euopean money is made available, the core of existing financing mechanims is not altered with respect to incentives. The national level remains the most powerful and no true incentives to think in line with Europe are created. An important element in the EIP is the creation of an investment cost allocation mechanism. It is thought to align the European and national interests. However, as argued throughout this thesis, the way the tool is created, i.e. by limiting it to investment cost allocation only, it is not an adequate solution. These findings are further discussed by answering the two research questions.

What outcome can be expected when the national level of decision-making remains strong without incentives to really take into account the European goals?

Three collaboration concepts A new formal framework based on basic welfare economics is developed to clearly address this question. Three different collaboration concepts are identified. In each concept a different assumption is made on the level of collaboration between different countries. Stated otherwise, the collaboration concepts differ in the assumed severity of the wedge driven between the European and national levels.

A first concept is the supranational planner. Full collaboration is assumed and the European objectives are put forward as the single objective function. In fact, national borders are neglected in this concept. It can be understood as a single European planner taking all decisions without considering the welfare distribution caused by these decisions. Obviously, this is an extreme situation compared to reality. Nevertheless, it serves as an interesting benchmark as it determines an upper bound for overall welfare. Moreover, it illustrates that a European solution can result in winners and losers.

A second concept relaxes the level of collaboration and increases the importance of the different countries in the decision-making process. A Pareto-planner is proposed. Like in the supranational planning concept a single planner with a European objective function is still in place. However, this Pareto-planner is constrained by national welfare: there may be no losers compared to the initial situation. Obviously, this situation is closer to today's reality. With a national flavour in investment decision-making, it is unlikely that countries can agree on investments which result in lower welfare for their grid users. However, already from the formal welfare economics' framework, it could be derived that this can result in a suboptimal situation. This is also clear from the mathematical formulation and is confirmed by the examples presented.

A third concept presents another extreme, namely a situation without collaboration on investment planning. A non-cooperative planning game with national planners as players is developed. The European objectives are not pursued and only national welfare is maximized by the different players. This situation represents a failing framework in which adequate incentives are lacking to incorporate the European goals in national investment decisions.

An important role in the different concepts is given to the underlying assumption concerning the (non-)existence of a welfare compensation mechanism. This is discussed in the next subsection dealing with this thesis' second question.

Although the three concepts have a different degree of collaboration and European spirit and it could be expected from the formal framework that the resulting investment outcomes reflect this difference, the examples presented in this thesis clearly indicated that conclusions have to be more subtle. In general it is true that in terms of overall welfare the supranational planner always outperforms the other concepts. In the examples, however, it is shown that the other concepts can result in the same supranational outcome. Hence, the strong assumptions made for the supranational planner are not always necessary and good outcomes can sometimes be achieved with lighter forms of collaboration. This result should, however, not be abused. It cannot serve as a reason to rely on a lighter form of collaboration without verification.

A second subltety is found in the comparison of the results of the Pareto-planner and the non-cooperative planning game. Although the latter inherently assumes less collaboration than the Pareto-planner, it is possible that in terms of overall economic welfare, the non-cooperative planning game scores better. This is a consequence of the fact that in that planning concept it is possible that countries loose welfare, whereas this is strictly forbidden in the Pareto logic. Whether or not this can happen in the European case is difficult to judge and depends on the actual topology and, for instance, the ability of one country to block investments.

Positioning in academic literature and major contributions The comparison of the different concepts in order to assess the impact of multiple planners on a single interconnected network is unprecedented. The effects on planning arising from such situation are not addressed in the literature. Hence, this is considered as an important contribution of this thesis.

With respect to the mathematical modelling of the collaboration concepts themselves, it was possible to partly rely on the existing literature. A thorough literature review revealed that transmission planning models can be categorized using a limited set of design building blocks: treatment of the planning horizon, uncertainty incorporation, transmission planning objectives, market incorporation, link with generation investment planning and multi-area awareness. The latter option specifically addresses the research topic. For the other blocks choices are made in order to keep a balance between simplicity and transparency of the models and the required level of detail allowing to answer the research question. The approach followed can be described as explicit market modelling in a static, reactive, deterministic planning context, while maximizing economic welfare. The level of multi-area awareness is different for each concept.

The mathematical model representing the supranational planner is not new and builds on existing models. The Pareto-planner is a new approach created by adding extra constraints to an existing model. The non-cooperative planning game is a novel approach in the transmission planning literature. It introduces game theory in transmission planning.

From an operations research point of view no new concepts or solution methods are developed. Quadratic programs, mathematical programs with equilibrium constraints and equilibrium problems with equilibrium constraints are known problem formulations. Also the solution methods (genetic algorithms, branch-and-bound, enumeration) build on existing and widely known techniques.

Is investment cost allocation a sufficient tool to align European and national goals?

This second question is again inspired by the ongoing debate on how incentives between national and European levels can be aligned. It particularly addresses the issue of new transmission investments causing welfare transfers. This can result in winners and losers which obviously influences the decisions made by the different players. An investment cost allocation tool is sometimes put forward to resolve this issue and bridge the gap between the European and national objectives.

Already from the formal framework and the general description of the three concepts it is clear that a compensation mechanism plays a crucial role. An important question is, however, what is really included in the compensation? Is it only the transmission investment cost or is full economic welfare considered? Investment costs are only a portion of the full welfare.

The different collaboration concepts drive on different assumptions concerning such mechanism. A full welfare mechanism is assumed in the supranational planning concept. Not only investment costs, but also changes in congestion revenues, consumer and producer surplus are taken into account. When such a full compensation mechanism is in place, it is always possible to compensate all losers and align incentives with the European objective function.

For the Pareto-planner two variants are defined. Either no compensation at all is assumed or a light form of compensation limited to investment costs only. Obviously, the latter approach has more potential in achieving a higher overall welfare level. Nevertheless, the limitation to costs only performs worse than a full welfare compensation mechanism.

In the non-cooperative planning game, no compensation at all is assumed. Hence, the outcome can include countries loosing welfare without being compensated. As already highlighted above, from an overall welfare point of view, this is not always worse.

The main lesson learned from this analysis is that a compensation mechanism based on investment costs only is not guaranteeing an adequate alignment of European and national goals. As illustrated by the examples, it can work in some cases, but without any guarantee for the European case.

Lessons for Europe

Earlier studies providing an insight in the welfare distribution for large European projects (e.g. an offshore grid) indicated that overall welfare gains are certainly possible, but that those gains are not evenly distributed among all countries. Hence, ending up with winners and losers is not a fiction. Such a distribution of the gains from traded is of course linked to the initial asymmetry between the different countries. Starting from this finding, this thesis' results can be translated to the European case.

As the supranational planner results in an outcome with winners and losers, the assumption of a full welfare compensation mechanism is prerequisite for the European context with several countries connected to a single network. With winners and losers in the suprantional outcome, the Pareto-planning approach without any form of cost allocation cannot result in a supranational outcome. Also the Pareto-variant with the allocation of investment costs to the winners, is also not resulting in the optimal European outcome. However, better results than without cost allocation are certainly possible, especially for investments where the investments cost occur on the territory of the winners or countries remaining status quo. Whenever countries with an overall welfare loss going beyond investment costs are to be relied upon for certain investment projects, the variant with cost allocation is insufficient to bridge the gap between European and national interests. The outcome of the non-cooperative planning game is not easily predicted for the European situation. From this concept, a relevant lesson for Europe learned from the examples, is the importance of the topology and the potential for one country to become the most influential player (cfr. zone B in the radial 3-zone example).

Consequently, both the Third Package and the EIP are insufficient to fully align European and national interests.

8.2 Recommendations for further research

The presented research calls for further steps on several fronts. Not only recommendations concerning the methodology, but also new questions arising from the results can be formulated.

- Three concepts are modelled in this thesis. These concepts represent, however, different (extreme) points on a spectrum of possible collaboration. As already discussed in chapter 7 more complicated models with more realistic assumptions on negotiation can be defined. Such models have the potential to more closely mimic the existing situation. Similarly, different CR allocation keys can be looked at in the Pareto-planning concept.
- In this thesis all concepts are illustrated using small-scale examples. This was a deliberate choice as it allows for a clear insight in the intuition underlying each concept. Extreme examples have been selected making results more tractable. Nevertheless, testing the concepts on larger networks and networks explicitly representing the European topology could shed a brighter light on how extreme the differences in results can be for real(istic) networks.
- In addition to the previous recommendation, it was highlighted in the examples that a degree of asymmetry between different zones is required in order to have gains from trade. It should be assessed how large this asymmetry is for real cases and how it evolves in time. A more exact calibration of generation cost and demand data is necessary. Also the returns to scale in

transmission investments can be introduced in order to reach a more realistic situation.

- In order to achieve the first suggestion it is required to enhance the solution methods for the different mathematical models. A better fine-tuning of the GA with cross-over and mutation strategies better adapted to the problem addressed, are recommended. Another route to follow is to switch to dynamic programming. Even more crucial is implementing a solution method for solving the EPEC problem. Enumeration was sufficient for this thesis' research goals, but is not acceptable as solution method for larger networks.

- Given the triangular European energy policy challenge, it is useful to investigate what happens when the objective function is extended with measures for sustainability and reliability. In this thesis only competitiveness by means of economic welfare is dealt with. In the chapters discussing the three concepts it is already indicated that the models should be up to this challenge, but that new assumptions will be necessary, e.g. with respect to the welfare constraints in the Pareto-planning concept.

- It is concluded that a full welfare mechanism is beneficial for aligning national and European goals. In this thesis no statement is made on how such mechanism should look like. Remembering the experiences with the ITC mechanism, a careful design is important.

- In European market design and legislation congestion revenues are explicitly present. This is not the case for consumer and producer surplus, the other parts of economic welfare. Given this rather 'tangible' presence of congestion revenues, it could be investigated how they can be used in a compensation logic. One route to follow is to change the assumed 50-50 distribution key.

- Going further than only addressing congestion revenues, a more fundamental approach would entail a complete rethinking of transmission tariffs. Instead of keeping its design national and adding a compensation mechanism on top of it, a harmonization or a complete new European standard tariff design can open opportunities in streamlining European and national incentives. It can even render an explicit compensation mechanism obsolete.

- This thesis assumed that all investments are done by welfare (either national or European) maximizing planners. In reality, TSOs are often profit-maximizing rather than welfare-maximizing players. This can alter the game played by investors. Secondly, in Europe and other parts of the world merchant investors are also investing in transmission assets. They have a different objective function and invest for profit. How can they contribute to the investment challenge?

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A

Calibration GA

This appendix outlines the experimentation used to calibrate several parameters of the genetic algorithm used in chapter 6. The supranational planning problem is used to calibrate the Pareto-planning problem. The three-zone, 14-node example of section 5.4.5 is used. The optimum is calculated using the model and techniques of chapter 5 and is used here as reference for evaluating the performance of different parameter settings. The tested parameters and their ranges are given in Table A.1.

The initial population can impact the quality of the solution found. Therefore, each possible parameter combination is tested twice. Moreover, each parameter is tested numerous times in different settings for the other parameters. A total of 512 runs of the GA is used to calibrate. 256 runs per possible parameter value are run for the selection and cross-over mechanisms. For instance, half of all runs use single-point cross-over and the other half uses double-point cross-over. 128 runs are performed for each possible value for the generation gap, cross-over rate and mutation rate. The number of generations is set at 2000 as convergence is reached by then in most cases. The number of individuals per generation is set at 40.

In Tables A.2, A.3, A.4, A.5 and A.6 the average number of runs required to obtain the best solution found and the average final value of that solution is given for each parameter tested. The former is a measure for speed, the latter for quality. The average final value is expressed relative to the known optimum. When this value equals 1 the optimum is found by the GA. Hence, the higher the value in the third column of these tables, the better the parameter scores. The lower the number in the second column, the lower the number of generations required to obtain that score. From Tables A.2-A.6 it can be learned that in particular the mutation rate has a significant impact on both the convergence speed and the actual solution found. A value of 0.15 is preferred.

For a mutation rate of 0.15, Tables A.7, A.8, A.9 and A.10 show the impact of the remaining parameters. The cross-over rate is the most relevant parameter further impacting the quality and the convergence speed. A cross-over rate of 0.7 is selected. The other parameters exhibit only minor differences. For those parameters, the setting with the highest average final value is selected. A generation gap of 0.5, stochastic universal sampling and single-point cross-over are chosen. In Fig. A.1 it is illustrated that using a mutation rate of 0.15 and a cross-over rate of 0.7 results in good GA performance.

Parameter	Parameter values used for experimentation
Generation gap	0.5, 0.6, 0.7, 0.8
Selection	rws, sus
Cross-over	Single-point (xovsp), Double-point (xovdp)
Cross-over rate	0.5, 0.6, 0.7, 0.8
Mutation rate	0.15, 0.2, 0.25, 0.3

Table A.1: GA calibration: tested parameters and values

Mutation rate	Average #generations	Average final value
0.15	699	0.99996887
0.20	1050	0.99994699
0.25	1542	0.99990521
0.30	1587	0.99965099

Table A.2: Impact of mutation rate

Generation gap	Average #generations	Average final value
0.5	1204	0.99988341
0.6	1207	0.99987051
0.7	1209	0.99987463
0.8	1255	0.99984560

Table A.3: Initial impact of generation gap

Cross-over rate	Average #generations	Average final value
0.5	1208	0.99988184
0.6	1168	0.99987673
0.7	1205	0.99987566
0.8	1194	0.99986137

Table A.4: Initial impact of cross-over rate

Selection mechanism	Average #generations	Average final value
rws	1231	0.99986877
sus	1208	0.99987585

Table A.5: Initial impact of selection mechanism

Cross-over mechanism	Average #generations	Average final value
Single point	1231	0.99986725
Double point	1209	0.99986878

Table A.6: Initial impact of cross-over mechanism

Generation gap	Average #generations	Average final value
0.5	1074	0.99996315
0.6	1006	0.99991949
0.7	1113	0.99993138
0.8	1210	0.99992813

Table A.7: Impact of generation gap with mutation rate=0.15

Cross-over rate	Average #generations	Average final value
0.5	1569	0.99978771
0.6	587	0.99996576
0.7	842	0.99997671
0.8	1487	0.99990306

Table A.8: Impact of cross-over rate with mutation rate=0.15

Selection mechanism	Average #generations	Average final value
rws	1111	0.99993140
sus	1087	0.99994329

Table A.9: Impact of selection mechanism with mutation rate=0.15

Cross-over mechanism	Average #generations	Average final value
Single point	1081	0.99993940
Double point	1117	0.99994329

Table A.10: Impact of cross-over mechanism with mutation rate=0.15

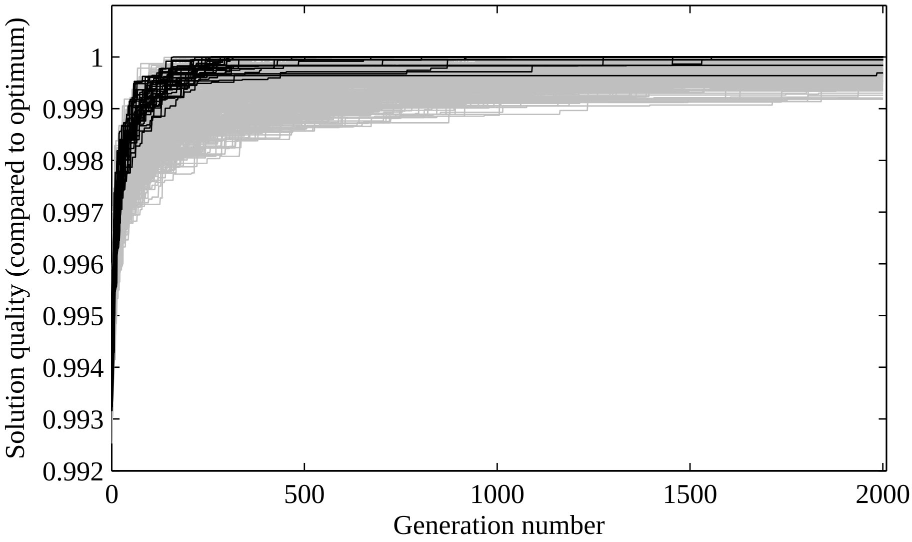

Figure A.1: GA calibration: runs with mutation rate =0.15 and cross-over rate=0.7 (in black) and all other runs (in grey)

B

Alternative welfare definition

In chapter 5 welfare was defined as the sum of PS, CS and CR. Due to the existence of international capital markets it could be argued that PS should not be accounted for in the same way as for CS. In particular, when zonal welfare is addressed, this can turn out to be more realistic. Should, for instance, a country try to maximimise zonal welfare including zonal PS when it knows that the generation companies holding this PS are in fact owned by other another country? This appendix briefly illustrates on the two-zone example what happens when PS is neglected and only the sum of CS and CR is used as definition for welfare.

By not allowing welfare transfers within a zone (e.g. CS is replaced by PS), the problem becomes more restricted. This illustrated in Fig. B.1. For zones A and B now only the sum of CS and CR are shown on the different axes. The Pareto-constraints are positioned at the initial level of CS and PS. It can be seen that no Pareto-improvements are feasible. Zone A looses CS whenever the capacity between zones A and B is different from zero. In this case the loss in CS cannot be compensated by increased CR. Given this situation, the only equilibrium in the non-cooperative game is also the initial situation, i.e. 0 MW installed on T_{AB}.

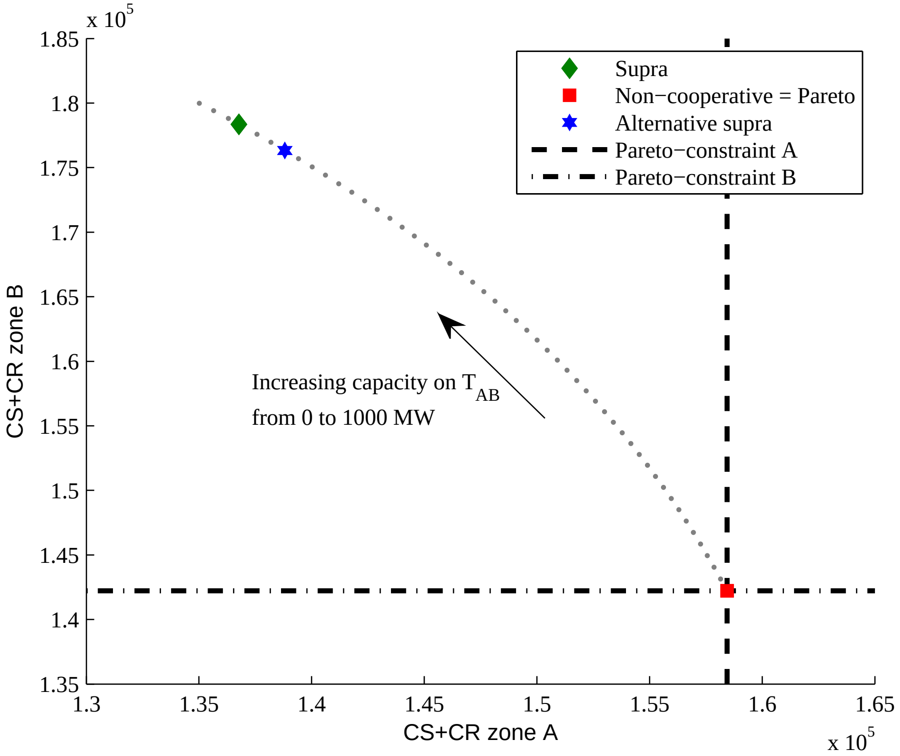

Figure B.1: Two-zone example: outcomes for different concepts and an alternative welfare definition

Note that when for the supranational planner the planner's objective function also excludes PS and only maximizes overall CS+CR minus transmission investment costs, the supranational outcome also differs from the results in chapter 5. Now only 880 MW would be installed and not 945.2 MW. When a higher transmission capacity is installed, the investment costs are not covered by the increase in CS+CR.

List of publications

Most publications are available at: http://www.esat.kuleuven.be/electa

Reviewed Journals

[1] P. Buijs, R. Belmans, "Transmission investments in a multilateral context," *IEEE Transactions on Power Systems*, accepted for publication, 2011.

[2] P. Buijs, D. Bekaert, S. Cole, D. Van Hertem, R. Belmans, "Transmission investments in Europe: Going beyond standard solutions," *Energy Policy*, vol. 39, issue 3, pp. 1794-1801, 2011.

[3] P. Buijs, D. Bekaert, R. Belmans, "Seams Issues in European Transmission Investments," *The Electricity Journal*, vol. 23, issue 10, pp. 18-26, Dec. 2010.

International Conferences

[4] P. Buijs, L. Meeus, R. Belmans, "Modelling bi-level games in transmission investment planning," *34^{th} IAEE International Conference*, Stockholm, Sweden, Jun. 2011, 17 pages.

[5] S. Hadush, P. Buijs, R. Belmans, "Locational Signals in Electricity Market Design: Do they really matter?," *8^{th} International Conference on the European Energy Market*, Zagreb, Croatia, pp. 622-627, May 2011.

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[12] P. Buijs, L. Meeus, R. Belmans, "A SWOT analysis of the Belgian generation adequacy," *4th International Conference on The European Electricity Market*, Krakow, Poland, pp. 17-23, May 2007.

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