Abstract

Despite increased RES penetration, increasing demand and an increased number of international transactions, the level of transmission investments was limited during the last decade. New investments are necessary in order to be able to cope with these challenges in the future. Whereas the investment scene used to be national, the regional and European level are gaining importance. Recent European legislation requires that national, regional and European transmission grid development plans have to be published on a regular basis. Moreover, these plans cannot be drafted independently from each other. National interests have to be aligned with supranational (i.e. regional and/or European) objectives. This is no easy task as all planning levels have different objective functions.

This paper investigates the potential divergence between national and supranational transmission planners. By setting up different mathematical optimization models (LP and MPEC), the impact of the nature of the planner can be determined. Potential divergence between development plans at different levels is assessed. The multi-area nature of the transmission planning problem is explicitly addressed. The models have a static time horizon and assume a perfectly competitive market. The models are applied to a 3-node example and a 15-node representation of the Benelux.

1 Introduction

European energy network infrastructure has a pivotal role in attaining European policy goals. Without adequate network infrastructure it is impossible to foster further market integration and to securely connect massive renewable energy sources. Mostly erected in the first decades after the Second World War, today’s transmission grid was originally not designed for the new context it is now facing, i.e. a European instead of a national context with an emerging European energy infrastructure policy.

Although they can fluctuate over years, price differences between national markets and congestion on major transmission lines persist. Moreover, the deployment of renewable energy sources puts extra pressure on the grid, requiring new transmission investments in the (near) future. There is a clear demand for more transmission capacity, but few major transmission lines have been built during the last decade. Moreover, constructing new lines, especially overhead, is a cumbersome process suffering often taking several years or even more than a decade.
Despite the trend towards “more Europe” in the field of energy and energy infrastructure, the framework supporting investment decisions is inadequate. Network investments are thought to be self-financing without intervention of supportive schemes. The current system, however, stems from an era where it are mostly nationally oriented investments to be decided upon. The new cross-border nature of transmission investments and its financing are not captured by the legislative framework and hampers European-scale grid development.

As will be discussed in section 2, the third legislative package takes already important steps towards a better integration of European viewpoints in network development. Especially network planning is addressed by introducing a 10-year network development plan (TYNDP). Both a bottom-up, based on national plans by transmission system operators (TSO), and a top-down approach, i.e. the incorporation of the European viewpoint, are put forward to come to such a plan. It remains to be seen to what extent the result will be a patchwork of different national plans or a true European development plan. It is the aim of this paper to demonstrate the potential divergence between the bottom-up and the top-down approach and to emphasize the importance of a thorough energy network policy including cross-border financing arrangements.

In section 2, two groups of models are presented: national planners (bottom-up) and supranational planners (top-down). Most presented models are Mathematical Programs with Equilibrium Constraints (MPEC), one model is a Linear Program (LP). They are first applied on a 3-node example (section 4) in order to provide some insights in how the models behave. Next, in section 5 a 15-node example representing the Benelux further illustrates the divergence between different planning approaches. Section 6 concludes the paper.

2 European network planning: between bottom-up and top down

The third legislative package (further called “3rd 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) No714/2009 creates the European Network of Transmission System Operators for Electricity (ENTSO-E) bringing together all TSOs who until now have been cooperating on a voluntarily basis only within for instance in UCTE, ETSO, Nordel… Also, European Regulation (EC) No713/2009 establishes the Agency for the Cooperation of Energy Regulators (ACER) and bundles all energy regulators.

With respect to transmission planning Art. 8(3) of Regulation (EC) No714/2009 gives ENTSO-E the task to publish each two year a non-binding Community-wide 10-year network development plan.

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1Note, however, that on a recent ERGEG workshop (11 February 2010) the EU Commission mentioned the publication of an ‘infrastructure package’ including financing issues by the end of 2010.
(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. Art. 22 of Directive 2009/72/EC [6] 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 3rd package itself, ENTSO-E considers the regional level and their development plans as the working horses for the Community-wide plan.[7] Furthermore, the TYNDP has to incorporate supranational aspects, so-called Community aspects. Explicit referral is made to the guidelines for the trans-European energy networks (TEN-E). [8] The latter guidelines including the TEN-E project lists and the Priority Interconnection Plan (PIP) [9] can be considered as today’s the most concrete realization of the supranational viewpoint. Cross-border investments and the lack thereof should also be given sufficient attention in the TYNDP.

It is clear that both a bottom-up approach based on the national development plans and a supranational top-down approach based on the Community needs are combined and complemented with public consultations. An important question is whether both planning approaches can converge or not and whether they have sufficient impact on the resulting plan and, ultimately, on the investments really done or not? Proper regulatory oversight at different levels is key.

Regulatory oversight with respect to the TYNDP is mainly a task of ACER. In Regulation (EC) No714/2009 [4] it is stipulated that ACER has to give its opinion on both the TYNDP (Art. 9(2)) and the national development plans (Art. 8(11)). The complete procedure for the development of the TYNDP by ENTSO-E and the involvement of all stakeholders (including ACER) is still under development [7]. The latter opinion should assess to which there are inconsistencies between the national plans and the TYNDP. ACER can recommend amendments to the national plans which then have to go through the national regulators. At the same time the national regulators have to examine the national development plans and there 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 supranational parties. Indeed, national regulators still play a central role, even in the incorporation of supranational viewpoints. In Art. 22(7) national regulators are given the authority to take certain measures to ensure the that investments planned within a timeframe of 3 years after publication of the national development plan are done when the TSO appears to be reluctant to do it. It is even possible to address third parties to make the investment. However, to what extent can it be expected that national regulators draw the supranational card when the resulting plans are not benefitting to the grid users in their area?

Additionally, will ACER truly act supranationally and will it be as powerful as required to fulfill

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Community needs? According to Art. 2 of Regulation No 713/2009 [5], 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 Commission. Although Art. 13(5) of Regulation No 713/2009 [5] 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 objectives rather than the European viewpoint. This opens the door towards a multilateral nature. However, the Board of Regulators acts by a 2/3 majority (Art. 13(3)). Avoiding unanimous decision-making is an important step towards a supranational ACER.

Furthermore, even if the national development plans and the TYNDP converge to a balanced and acceptable outcome, it is not guaranteed that the plans will be also implemented. Especially supranationally inspired investments can be expected to experience problems. Note that the TYNDP itself is a non-binding document. Only national plans can be enforced, but this has to be done by the Member States themselves (Art. 22(7) of Directive 2009/72/EC [6]). Financing those investments will be difficult, especially when benefits are scattered over different countries and when the ones bearing the investment cost are not those who benefit. Today there is no adequate financing framework for cross-border investments and costs are mostly borne by the grid hosting the new investments. Cross-border links are mostly financed bilaterally by the TSOs at both sides of the interconnector. When national and supranational viewpoints do not match and without an adequate financing framework, supranational investments are facing hard times.

3 Supranational and national planning models

There is a wide spectrum of transmission planning models available in techno-economic literature. An overview is given in [11]. Using the classification of [11], the models used in this paper are mathematical optimization models. No heuristics are applied. The result is an optimum obtained via the minimization of an objective function subject to constraints. With respect to the planning horizon, the second type of classification in [11], the presented models are static, i.e. they plan for a single point in the future (e.g. a single given year). An transmission expansion path using different time frames within a single optimization is not possible in such static models. As a last way to classify planning models, [11] considers

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3 In the context of this paper multilateral has to be understood as the negotiation among different national parties, i.e. national interests are driving this cooperation. In the case of a supranational cooperation, it are (in this case) Community interests that prevail, thereby neglecting the possible interests of different countries.
the incorporation of restructured electricity markets. Here, perfect competition is considered. Section 3.1 provides further details on this issue.

Although there is large variety in planning models concentrating on a single transmission area, the number of publications taking explicitly into account the difference in objective functions between neighboring areas and the resulting transmission plans is very limited. When transmission planning involves more than one zone, a supranational approach is often adopted, e.g. in [12]. By doing so, transmission planning models concentrating on a single area can be used. However, multi-area issues and the use of different objective functions are known in other problems such as multi-area optimal power flow calculation [13] or the behavior of profit-maximizing generation firms in power markets [14].

3.1 Assumptions

Setting up a transmission planning model requires several assumptions with respect to grid issues, generation and demand side, costs and benefits included. . . This section gives an overview of all assumptions underlying both the supranational and the national planner models. Several assumptions are made with the purpose of keeping the objective functions and constraints linear. This improves calculation times and guarantees optimal solutions. In section 3.3.3 extra assumptions specific to the national planner models are discussed.

3.1.1 Grid issues

The representation of the transmission grid in a transmission planning model is a crucial issue. In this paper, a simplistic approach is adopted. Power Transfer Distribution Factors (PTDF) and DC power flow are used to model the flows in the grid. Transmission losses are neglected. This allows for a linear formulation of all grid related constraints. Although it has its limitations, DC load flow is a technique that allows for acceptable results in economic applications.

New investments can only occur on existing links, i.e. the grid topology is considered fixed. New links between two nodes which are not connected yet have to be exogenously added before the model is run. The model can only decide on the increase of the transmission capacity of lines known to the model. Additionally, the PTDF-matrix is assumed to be constant. New investments have no impact on the values in the PTDF-matrix. In reality, this is not the case. For instance, upgrading a link to higher voltage level would have an impact on the PTDF-matrix. Taking this into account would render a non-linear model.

The models in this paper allow for a continuous increase of transmission capacity. In reality, transmission investments are lumpy. Therefore, a discrete approach would be better. Although, it would not complicate the models too much, computation times can plummet in such case. For the purpose of this
paper, i.e. indicating the potential divergence between national and supranational planners, these assumptions are acceptable as it is the difference between both approaches that matter and not the specific result of a single plan itself.

3.1.2 Generation issues

It is assumed that both the national and supranational planners act as so-called reactive planners. A reactive transmission planner acts after the generation side has decided on the location of generation facilities. However, the model can be used to assess the impact of different scenarios varying in the location and amount of generation (e.g. varying levels of wind power at different locations). In this paper, there is no uncertainty on the location and the capacity of generation facilities.

With respect to the underlying market design, the models adopt a viewpoint of perfectly competitive markets. Using an Optimal Power Flow (OPF) approach based on marginal costs, is equivalent to marginal cost bidding.

3.1.3 Demand issues

The demand side is considered price-inelastic, i.e. size and location of demand is fixed and exogenously determined. However, by using a multi-period approach it is possible to introduce different levels of demand. For instance, section 5 uses a two-period setup representing a peak and off-peak period. The weight of each period is determined by the number of hours that the conditions of that period occur during a year. As the models solve for a single representative year the sum of all weights should be 8760 hours. The multi-period approach should not be misunderstood. It entails no dynamic planning model.

3.1.4 Costs and benefits

At the cost side, the models only include generation dispatch costs and transmission investments cost. Generation dispatch costs are based on marginal production costs, i.e. fuel costs. Transmission investments costs are implemented using a fixed charge per kilometer per MW-increase. Annuited investment cost are used in order to be able to solve for a single year. Costs are linearly increasing with the output, i.e. constant marginal costs. This allows for a linear objective function.

No specific assumptions are made on the TSO structure. In reality TSOs have their own profit functions which depends on its structure (ISO, TSO, ITO...). In the presented models it is assumed that planners maximize welfare independent of their own business model. This can be thought of as a perfectly regulated TSO with perfect incentives.

Only economic benefits and costs are accounted for. Benefits or costs related to reliability and sustainability are not included.
3.2 Supranational planners

The supranational planner considers all areas together as one single area. For the supranational planner there is no difference between nodes in different areas. He can decide on transmission investments in all transmission lines. As long as the global situation improves, it is possible that some areas loose welfare while others gain. Two different models are proposed. The first type of supranational planner (section 3.2.1) maximizes total welfare by minimizing total generation dispatch costs. The second type of supranational planner (section 3.2.2) only considers consumer surplus, i.e. total price paid by demand is minimized.

3.2.1 Supranational planner type 1: minimizing total dispatch costs

An extended OPF closely following Kirschen et al. [15] is used for the supranational planner. A DC OPF algorithm expanded with transmission investment costs is the core element. It is formulated as a linear program (LP). Instead of minimizing generation cost, the sum of generation cost and an annuitized investment cost of grid expansions is minimized. As a consequence not only generation dispatch, but also the ratings (MW) of the different lines in the grid are the result of the decision variables. One can understand the proposed problem as given a generation park and the existing rights of way between different nodes, which lines should be built and how should generation be dispatched. There is a trade-off between investing in extra transmission capacity or dispatching more expensive generation units.

For the supranational planner the entire grid is considered as one single zone. Generation facilities or transmission lines are not earmarked as belonging to a specific country. The objective function maximizes the supranational welfare by minimizing total dispatch costs plus transmission investment costs. All generator outputs and transmission line ratings are variable. The supranational planner is indifferent to the fact that some countries might lose welfare and others might gain welfare. The problem solved by the supranational planner is the following linear optimization problem:

\[
\begin{array}{ll}
\min_{\{xcap_l, P_{g,p}\}} & \left\{ \sum_p \left[ duration_p \sum_g c_g P_{g,p} \right] + \sum_l c_l length_l xcap_l \right\} \\
\text{subject to:} & \\
\forall p, g & P_{p,g} \leq P_{g,p}^{max} \\
\forall p, l & |\sum_b PTDF_{l,b} (P_{g,p} - dem_{b,p})| \leq ecap_l + xcap_l \\
\forall p & \sum_g P_{g,p} - \sum_b dem_{b,p} = 0 \\
& xcap_l, P_{g,p} \geq 0
\end{array}
\]
\( P_{g,p} \) and \( xcap_l \) are the decision variables. In each period the output of each generation facility is limited by its installed capacity in constraint \( (2) \). As enforced by constraint \( (3) \), in each period flows are limited by the lines’ thermal rating. This thermal rating is however a variable to the model. Next, constraint \( (4) \) ensures that in each period system balance is maintained. Finally, non-negativity of all variables is guaranteed by constraint \( (5) \). This LP is solved using CPLEX 12.1.0 in GAMS.

### 3.2.2 Supranational planner type 2: minimizing price paid by demand

The second type of supranational planner focuses on consumer welfare. The first part of the objective function \( (6) \) minimizes the price paid by demand in each node (the Locational Marginal Prices (LMP)) multiplied by demand. The second part of the objective function dealing with transmission investments remains unchanged. The LMPs and the generation dispatch are determined by an underlying DC OPF.

The entire problem is modeled as a bi-level problem. The approach is similar to a Stackelberg-game with a leader and follower. In this context we consider the supranational planner deciding on the transmission capacity of his transmission lines as the leader. The determination of the optimal dispatch and the LMPs, i.e. the underlying DC OPF, in each period is then the following problem.

\[
\begin{align*}
\min_{xcap_l, P_{g,p}, \mu_{p,g}^+, \mu_{p,g}^-, \lambda^+_p, \lambda^-_p, \mu_{p,l}^+ \mu_{p,l}^-} & \left\{ \sum_p \left[ \text{duration}_p \sum_b \text{dem}_{p,b} \text{LMP}_{p,b} \right] + \sum_l c_l \text{length}(l) \ xcap_l \right\} \\
\text{subject to:} & \\
\forall p, b & \quad \text{LMP}_{p,b} = \lambda^+_p + \lambda^-_p - \sum_l \text{PTDF}_{(l,b)} \left( \mu_{p,l}^+ + \mu_{p,l}^- \right) \\
\forall p, g & \quad P_{p,g} \geq 0 \quad \perp c_g + \mu_{p,g}^\text{max} + \lambda^+_p - \lambda^-_p \\
& \quad - \sum_l \text{PTDF}_{(l,g)} \mu_{p,l}^+ + \sum_l \text{PTDF}_{(l,g)} \mu_{p,l}^- \geq 0 \\
\forall p, g & \quad \mu_{p,g}^\text{max} \geq 0 \quad \perp - P_{p,g} + P_{p,g}^\text{max} \geq 0 \\
\forall p & \quad \lambda^+_p \geq 0 \quad \perp - \sum_g P_{p,g} + \sum_b \text{dem}_{p,b} \geq 0 \\
\forall p & \quad \lambda^-_p \geq 0 \quad \perp \sum_g P_{p,g} - \sum_b \text{dem}_{p,b} \geq 0 \\
\forall p, l & \quad \mu_{p,l}^+ \geq 0 \quad \perp \sum_b \text{PTDF}_{(l,b)} P_{p,b} - \sum_b \text{PTDF}_{(l,b)} \text{dem}_{p,b} + \text{ecap}_l + xcap_l \geq 0 \\
\forall p, l & \quad \mu_{p,l}^- \geq 0 \quad \perp \sum_b \text{PTDF}_{(l,b)} \text{dem}_{p,b} - \sum_b \text{PTDF}_{(l,b)} P_{p,b} + \text{ecap}_l + xcap_l \geq 0
\end{align*}
\]

\[
\begin{align*}
xcap_l, P_{p,g}, \mu_{p,g}^+, \lambda^+_p, \lambda^-_p, \mu_{p,l}^+, \mu_{p,l}^- \geq 0
\end{align*}
\]
Acap, \( P_{p,g}, \mu_{p,g}^{\max}, \lambda_+^p, \lambda_-^p, \mu_+^{p,l}, \mu_-^{p,l} \) are the decision variables. Constraints (8) to (13) form the supranational OPF. The OPF is written as a set of linear complementarity constraints. The LP notation of the supranational OPF is given in Appendix B. Equation (7) defines the LMPs based on the dual variables of the OPF and constraint (14) ensures non-negativity of all variables.

Such a bi-level program formulated with complementarity constraints is called a Mathematical Program with Equilibrium Constraints (MPEC). MPECs are much harder to solve than LPs as the complementarity constraints make the problem non-convex. The particular problem defined here is a Linear Program with Complementarity Constraints (LPCC). Both the objective functions and the constraints are linear, this opens the door for specific solution methods.

The LPCC is solved using a technique that converts the problem to a Mixed Integer Linear Program (MILP), which can be directly solved using CPLEX 12.1.0 in GAMS. This technique that guarantees a globally optimal solution (under certain conditions) is described in [16]. At the core of the technique are a set of binary variables, one for each complementarity constraint. By doing so, it can be enforced that both parts of the constraint cannot be zero at the same time. The disadvantage of the MILP-approach is the long computation time.

3.3 National planners

National planner interests differ from a supranational planner. Only national welfare matters. The consequences for other areas are not accounted for. Two types of national planners are described in this section. They vary in the set of transmission lines they can decide upon. The first type is the “Pure national planner” (section 3.3.1). He can only increase the rating of the lines in his area and the interconnections adjacent to his area. The “Alternative national planner” (section 3.3.2) has more options. He can also decide on investments in transmission lines in all areas, like the supranational planners.

3.3.1 Pure national planner

The problem solved by the pure national planner is similar to the supranational planner (type 2). Whereas the supranational planner (type 2) considered demand and LMPs in all nodes (index \( b \)), the pure national planner is only concerned about the price paid by demand in the nodes in his area (index \( nb \)). The price for demand in nodes in other areas is irrelevant. The second part of the objective function (15) again deals with transmission investments. However, now only the transmission lines within the area of the national planner and the interconnections adjacent to this area are decision variables (index \( nl \)). The transmission capacity of the other lines is fixed.

\(^4\text{nl and nb are respectively national lines (including interconnections) and national nodes.}\)
National welfare is determined from a consumer’s point of view. National consumer surplus is maximized when the price paid by the consumers is minimized. By keeping demand price-inelastic and by not including producer’s surplus, the objective function can be kept linear. Therefore, the pure national planner only focuses on the LMPs multiplied by demand in the national buses and the investments in national lines.

As for the supranational planner (type 2), LMPs and the generation dispatch are determined via an underlying DC OPF. This DC OPF considers all areas, it is a supranational DC OPF. This can be interpreted as assuming that the national planner is confronted with a perfectly competitive supranational market.

Compared to the formulation of the model of the supranational planner (type 2) (equations (6) to (5)) only the objective function has changed. The problem is again an MPEC and is solved likewise. The national planner’s objective function is:

$$\min_{xcap_{nl}, P_p, g, \lambda_p, \mu_p} \left\{ \sum_p \left[ \text{duration}_p \sum_{nb} \lambda_p, \mu_{p,nb} \right] + \sum_{nl} c_{nl} \text{length}(nl) xcap_{nl} \right\}$$

(15)

3.3.2 Alternative national planner

A pure national planner only considers the transmission lines within their own area and the interconnections adjacent to their area. However, it can be useful to analyze which investments a national planner would propose when he can decide over all lines in the grid, including lines in other (even non-adjacent) areas. The advantage of such approach is that it can be easier to merge all national plans into a single plan. For instance, an investment in a line in a particular area can also be beneficial to other areas, especially when loop flows occur.

Mathematically, the alternative planner’s objective function keeps the middle between the pure national planner and the supranational planner (type 2). Only the price paid by demand in nodes in his own area (index $nb$) matters, but all transmission lines (index $l$) are open for investments. The objective function is given by equation (16).

$$\min_{xcap_l, P_p, g, \mu_{l,p}, \lambda_p, \mu_{p,l}, \mu_{p,l}, \mu_{l,p}} \left\{ \sum_p \left[ \text{duration}_p \sum_{nb} \lambda_p, \mu_{p,nb} \right] + \sum_l c_l \text{length}(l) xcap_l \right\}$$

(16)

Table 1 summarizes the differences between all objectives functions discussed. Notice the clear difference
between supranational planner (type 1) and the other planners. Whereas the former focuses on total welfare by minimizing generation dispatch costs, all other planners only consider consumer surplus via the impact on LMPs.

<table>
<thead>
<tr>
<th>Planner Type</th>
<th>Variable lines</th>
<th>Relevant Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supranational planner (type 1)</td>
<td>All ( xcap_l )</td>
<td>All ( P_{p,g} )</td>
</tr>
<tr>
<td>Supranational planner (type 2)</td>
<td>All ( xcap_l )</td>
<td>All ( LMP_b )</td>
</tr>
<tr>
<td>Pure national planner</td>
<td>National ( xcap_{nl} )</td>
<td>National ( LMP_{nb} )</td>
</tr>
<tr>
<td>Alternative national planner</td>
<td>All ( xcap_2 )</td>
<td>National ( LMP_{nb} )</td>
</tr>
</tbody>
</table>

Table 1: Objective functions: summary

3.3.3 Extra assumptions

The above models for national planners require extra assumptions. First, the models are solved for each involved national planner. These plans have to be merged. How to deal with interconnections is a crucial issue. A simple, but naive solution is to only accept those investments that are agreed by all involved parties. This assumptions implies taking the minimum of all outcomes. For instance, if planner A wants to invest 100 MW in a link and planner B desires 200 MW, the result will be the minimum, i.e. 100 MW. Of course, this solution is clearly not correct as limiting the capacity on one line can have adverse effects on flows and prices elsewhere in the grid.

Second, as the pure national planner can only decide on the capacity of his national lines, assumptions on the capacity of the foreign lines are needed. Different scenarios are possible. For instance, foreign lines can remain unchanged, they can be expanded according to the supranational planner’s result... This is exogenous to the model. The model for the alternative national planner can improve chances for easy merger, but no convergence between the different national planners is guaranteed.

Both assumptions can be relaxed when the different national planner’s models are solved simultaneously and result in an equilibrium. This would make the problem an Equilibrium Problems with Equilibrium Constraints (EPEC) instead of an MPEC. Solving EPECs is more complex. This goes beyond the scope of this paper.

4 Example 1: A 3-node network with one variable line rating and one time period

In this section, the models representing the supranational and national planners are applied to a 3-node network. In order to get grips to the models’ behavior, only one time period is considered. Moreover, the capacity of only one line is variable and open for investment. The network and generation data are given in figure 1. Assume all lines have equal impedance and have a length of 100 km. Transmission
investment cost is 50 €/(MW.km.year). Line 1-2 is the only line on which capacity can be increased. The situation without any investment is given in figure 1b. This is the result of a DC OPF on the starting grid. The dotted line indicates congestion. It is clear that consumers in node 1 are suffering most from congestion. Their price equals 60 €/MWh and the generator in node 1, the most expensive one, generates at maximum capacity.

4.1 Supranational planners

Type 1: minimizing generation dispatch cost

This supranational planner minimizes total generation dispatch costs and transmission investment cost. In figure 2a the result is given. The supranational planner (type 1) invests an extra 2500 MW in line 1-2 resulting in a transmission capacity of 3000 MW. The result is a single price in all zones, 45 €/MWh. Total welfare increases, but it are especially consumers in node 1 that clearly benefit from this result. Their price decreased, whereas consumers in node 2 see a higher price (45 €/MWh instead of 30 €/MWh). The price in node 3 remains unchanged.

Producers are affected differently. Whereas the generator in node 1 produces at full capacity in the initial situation and makes a profit of 10 €/MWh, his output is set to 0 MW in the supranational planner’s result. Generator 2 has an increased profit compared to the initial situation where he produced at marginal cost. Furthermore, his output increased to maximum capacity. Generator 3 continues producing at marginal cost, but his output increased with 2500 MW.

\[\text{Note, however, that it is not necessary optimal to eliminate all congestion.}\]

Figure 1: 3-node network
**Type 2: Minimizing the price paid by demand**

This supranational minimizes the price paid by demand (LMP) multiplied by demand. As not only the price itself, but also the level of demand matters, nodes with a higher demand have a higher impact on the objective function value. The result for the 3-node network is given in figure 2b. In this case, an extra 500 MW is invested in line 1-2 compared to the initial situation. Compared to the supranational planner (type 1) the invested capacity is 2000 MW lower.

The impact on consumers is different for each node. The LMP in nodes 1 and 3 decrease compared to the initial situation, whereas the price in node 2 is unchanged. Consumers in nodes 2 and 3 are better off compared to the solution of the supranational planner (type 2). Due to the limited increase of the rating of line 1-2, node 1 is unable to reach the best possible outcome in this solution. It’s price drops to 50 €/MWh, but with a higher transmission capacity a decrease to 45 €/MWh is even possible.

Generation dispatch has changed compared to the result of the supranational planner (type 1). The expensive generator in node 1 generates at maximum capacity, whereas the generator in node 3 has a zero output. Note that producer surplus is not taken into account by the supranational planner (type 2).

### 4.2 National planners

Whereas the supranational planners maximized welfare for all areas at once, national planners only consider their own area. Three planners are modeled in this example, one for each node. Each planner minimizes the price paid by demand in his node and the transmission investment cost for expanding line 1-2. The impact on generation profit is neglected.

In section 3.3 two types of national planners are described. In this 3-node example only one line
rating is variable to keep results simple. It is assumed that each national planner can decide on the rating of line 1-2. The difference between “pure” and “alternative” planners cannot be demonstrated by this example. The planner in node 3 acts as an alternative national planner. The planners in nodes 2 and 3 are in fact pure national planners.

In figure 3 the result for each planner is given. The result of Planner 1 is the same as the supranational planner. He invests an extra 2500 MW in line 1-2, thereby decreasing the price in node 1 to 45 €/MWh. Planner 2 prefers not to invest in line 1-2. By keeping the line rating at 500 MW, the price in node 2 remains 30 €/MWh. Planner 3 wants to increase the line rating to 1000 MW, yielding a price of 40 €/MWh.

Note that although Planners 2 and 3 have different opinions on the optimal line rating of line 1-2, Planner 2 would not mind to increase the capacity to 1000 MW (which is in favour of Planner 3), as long as he has not to pay for it. In both cases the price in node 2 is 30 €/MWh. Also Planner 1 is better off in this situation compared to the initial situation. His price drops from 60 to 50 €/MWh. He might be willing to participate in the costs for an increase to 1000 MW.

5 Example 2: Benelux network with multiple variable line ratings and two periods

The models from section 3 are now applied to the network in figure 4 consisting of 15 nodes and 28 transmission lines roughly representing the Benelux. It is a modified version of the configuration used in [17]. A supranational planner considering Belgium and the Netherlands at once is compared to both a Belgian and a Dutch planner.
5.1 Calibration

Load and generation data are given in table 2. Only one time period (8760 hours) is considered. Especially nodes 1 to 7 are important, they carry all demand and generation. Nodes 8 to 15, i.e. the ones surrounding the Benelux, are there to keep the power flows right. Nodes 1 and 2 are “supernodes”, aggregating the remainder of the grid.

Table 3 presents generation cost data. Two scenario’s are given. They vary in the assumed CO$_2$-price, namely 20 and 100 €/tonne. The results in section 5.3 are entirely based on a price of 20 €/tonne. Only in the sensitivity analysis in section 5.4 a higher CO$_2$-price is used for comparison. Fuel prices are largely based on the Fossil Fuel Reference and Higher Prices Sensitivity Scenario of the 2009 World Energy Outlook (IEA). Common assumptions on plant efficiency and emissions are used. Compared to the situation with a CO$_2$-price of 20 €/tonne, a price of 100 €/tonne causes a switch in the merit order.

The grid used is the same as in [17]. Initial flows, line ratings, distances are given in table 4. Flows on congested lines are printed in italic. Transmission cost data are based on [19] which reports annual capital charges (€/km.MW.year) based on a bottom-up costing model. A constant cost of 50 €/(MW.km.year) is used as a base case. Sensitivity to this cost figure is discussed in section 5.4. Lines L21 to L28 connecting nodes 1 and 2 have very high line ratings and investment costs, they are not open for investments and cannot be congested. The initial LMPs are given in table 5.

In the model an upper bound to the extra investment in a particular line is set to 4000 MW.
Table 2: Demand and installed generation per node (in MW)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>n1</th>
<th>n2</th>
<th>n3</th>
<th>n4</th>
<th>n5</th>
<th>n6</th>
<th>n7</th>
<th>n8-n15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>78813</td>
<td>73540</td>
<td>6156</td>
<td>6318</td>
<td>6655</td>
<td>5151.6</td>
<td>2854.8</td>
<td>0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>20340</td>
<td>58288</td>
<td>2713</td>
<td>449</td>
<td>0</td>
<td>2618</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lignite</td>
<td>10883</td>
<td>580</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Coal</td>
<td>28664</td>
<td>15822</td>
<td>2474</td>
<td>3968</td>
<td>253</td>
<td>1134</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CCGT</td>
<td>7758</td>
<td>0</td>
<td>350</td>
<td>249</td>
<td>0</td>
<td>910</td>
<td>1705</td>
<td>0</td>
</tr>
<tr>
<td>Gas</td>
<td>10634</td>
<td>124</td>
<td>575</td>
<td>4872</td>
<td>1510</td>
<td>1432</td>
<td>2768</td>
<td>0</td>
</tr>
<tr>
<td>Oil</td>
<td>5517</td>
<td>11130</td>
<td>560</td>
<td>111</td>
<td>0</td>
<td>1865</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hydro</td>
<td>1271</td>
<td>14381</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Generation cost data (in €/MWh)

<table>
<thead>
<tr>
<th>CO₂ = 20 €/t</th>
<th>CO₂ = 100 €/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>6.3</td>
</tr>
<tr>
<td>Lignite</td>
<td>29.4</td>
</tr>
<tr>
<td>Coal</td>
<td>36.9</td>
</tr>
<tr>
<td>CCGT</td>
<td>53.9</td>
</tr>
<tr>
<td>Gas</td>
<td>78.1</td>
</tr>
<tr>
<td>Oil</td>
<td>121.8</td>
</tr>
<tr>
<td>Hydro</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4: Line ratings (in MW), distances (in km) and initial flows for a CO₂-price of 20 €/t (in MW)
Table 5: Initial situation: Locational Marginal Prices for a CO\textsubscript{2}-price of 20 €/t (in €/MWh)

<table>
<thead>
<tr>
<th>Node</th>
<th>Area</th>
<th>LMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1</td>
<td>D</td>
<td>78.1</td>
</tr>
<tr>
<td>n2</td>
<td>F</td>
<td>36.9</td>
</tr>
<tr>
<td>n3</td>
<td>B</td>
<td>53.9</td>
</tr>
<tr>
<td>n4</td>
<td>N</td>
<td>78.1</td>
</tr>
<tr>
<td>n5</td>
<td>N</td>
<td>157.4</td>
</tr>
<tr>
<td>n6</td>
<td>B</td>
<td>77.5</td>
</tr>
<tr>
<td>n7</td>
<td>N</td>
<td>102.8</td>
</tr>
<tr>
<td>n8</td>
<td>D</td>
<td>98.6</td>
</tr>
<tr>
<td>n9</td>
<td>D</td>
<td>105.6</td>
</tr>
<tr>
<td>n10</td>
<td>D</td>
<td>57.0</td>
</tr>
<tr>
<td>n11</td>
<td>D</td>
<td>51.2</td>
</tr>
<tr>
<td>n12</td>
<td>F</td>
<td>46.3</td>
</tr>
<tr>
<td>n13</td>
<td>F</td>
<td>38.3</td>
</tr>
<tr>
<td>n14</td>
<td>F</td>
<td>20.1</td>
</tr>
<tr>
<td>n15</td>
<td>F</td>
<td>42.9</td>
</tr>
</tbody>
</table>

5.2 Scaling issues

The different planning problems inherently suffer from bad scaling properties, which can lead to numerical difficulties when solving. At least two elements are at the root of this problem. Firstly, the objective function value is very high compared to the variables and the constraints. Whereas the objective function values is of the order 10\textsuperscript{8}, most variables are of the order 10\textsuperscript{0} to 10\textsuperscript{4}. A very small change of a variable can cause a large change in the objective function values. This can be solved by re-scaling the objective function, e.g. by multiplying all objective function coefficients with 10\textsuperscript{-5}.

Secondly, and more fundamental to the problem, is the large discrepancy between between the two parts of the objective function. The part dealing with transmission investments is very small compared to the part dealing with dispatch costs (supranational planner (type 1)) or the price paid by demand (all other planners). For the results in section 5.3 total transmission investments costs are 1000 times smaller than the other part of the objective function. This implies that with a small transmission investment cost a high impact on prices and generation dispatch can be created. This scaling problem is inherent to the problem and cannot be removed as exactly this trade-off is searched for by the optimization. This issue is further discussed in section 5.4 on sensitivity to cost figures.

In GAMS the CPLEX-solver options tackling scaling issues and precision (i.e. scaind and numericalemphasis) are used in order to have more qualitative results.

5.3 Results

The models of section 3 are applied to the Benelux-grid. The nodes and lines in France and Germany mostly serve to keep the flows acceptable in Belgium and the Netherlands. Therefore, the focus lies on Belgium and the Netherlands only. Line ratings in Germany and France (i.e. L2, L3, L5 and L16 to L28)
are considered fixed, even for the supranational planners. Only Belgian and Dutch lines, their mutual interconnections and the interconnections with Germany and France can be open for investments. Also, only Belgian and Dutch national planners are implemented. The former focuses on nodes 3 and 6, the latter takes into account nodes 4, 5 and 7.

In table 6 the impact of the different planners on consumer welfare is given. The total price paid by consumers is compared to the initial situation. The total price paid by demand equals $\sum \{LMP_{dem}\}$.

In table 7 the total generation dispatch cost is given. This includes generators in France and Germany and not only those located in Belgium or the Netherlands. Note that only for the supranational planner (type 1) generation costs are part of the objective function. For the other planners, the generation costs are only in the objective function of the Stackelberg-follower, i.e. the underlying DC OPF.

The transmission investments done by the different planners are shown in table 8. Foreign transmission lines not available to pure national planners are indicated with “n/a”.

Pure versus alternative national planners

From table 8 it can be learned that the pure national planners clearly disagree on the investments to be done. This is not surprising as they have partly different decision variables. The investment done in the interconnections between Belgium and the Netherlands (lines L9 to L11), which they have both in their set of decision variables, is clearly different. Whereas the pure Belgian planner hardly invests, the pure Dutch planner increases the transmission capacity between both countries. Moreover, as can be seen in table 8 the total price paid by Belgian demand even increases in the case of the pure Dutch planner compared to the initial situation. This is not true for the pure Belgian planner. In that case Dutch demand also benefits, even more than in case of a pure Dutch planner. The pure Belgian planner clearly has decision power over transmission lines with more price impact in this case.

Alternative national planners always score better than pure national planners. The decrease in price paid by demand is always larger. This makes sense as an alternative planner has more degrees of freedom, i.e. more transmission lines open for investment.

Very interesting is the fact that results of alternative national planners are not as diverging in this case study as one might expect. Firstly, all parties always profit. Table 6 indicates that Belgian demand now also profits (to a limited extent) in case of a Dutch planner. Moreover, the price paid by Dutch demand in case of a Belgian alternative planner, is only 4.82% lower than in case of a Dutch alternative planner. Secondly, proposed transmission investments are less diverging in case of alternative national planners. Both planners agree on the increase of transmission capacity between France and Belgium (table 8). However, with respect to the Belgian-Dutch and the Dutch-German border the Belgian alternative planner prefers a smaller increase. Thirdly, the alternative national planners are able to achieve a cheaper
generation dispatch than pure national planners (table 7). Note that the alternative Dutch planner almost equals the generation dispatch cost of the supranational planner (type 1) without having it in its objective function.

**National planners versus supranational planners**

Not only convergence between national planners is relevant, taking into account the process underlying the TYNDP discussed in section 2 envisages convergence between national and supranational planners. When national planners do not only take into account their own transmission grid, but when they also consider investments outside their control area, chances can be higher to obtain a result that is more acceptable for a supranational planner. Especially in highly meshed interconnected grid like in Europe, investments in parallel paths to the ones in the own control area can be more fruitful. Acting supranational can clearly be beneficial from a national point of view.

Analyzing the result obtained by the alternative Dutch planner learns that there is a strong match with the result obtained by the supranational planner (especially type 1). As mentioned above, he also scores very well with respect to generation dispatch costs. The Belgian alternative planner rather agrees with the supranational planner (type 2). Belgian demand clearly profits, but also Dutch demand is much better off. What in the end will be the outcome, cannot not be judged based on the provided data and models. As mentioned in section 3.3.3 an EPEC-like model is required for answering that question.

**5.4 Sensitivity analysis**

In this section sensitivity of the results to the cost data used in briefly analysed. The focus lies on the impact on the invested transmission capacities. Firstly, transmission investment cost data have been. For both types of supranational planners and the alternative national planners, table 9 shows the lowest cost first causing a change in the invested transmission capacities. The alternative Belgian planner is the first to decrease its level of transmission investments when the cost rise. However, this only happens when the investment costs increase more than 15 times compared to the reference case. The reference case of 50 €/MW.km.year was based on the values reported in [19] for a double circuit 380 kV overhead line. Although for a single circuit line, underground cables or for lower voltage the costs per MW.km.year increase, ICF2002 does not report such high values. Results can therefore be thought to be rather insensitive to transmission investment costs. Note that [19] only takes into account pure investment costs and does not value the social cost of a new line. From such a NIMBY-perspective, such high costs might sometimes be acceptable.

Secondly, sensitivity to generation cost data is limited in this case. The a higher CO₂-price caused the merit order to change in favour of CCGT (table 3), this has hardly any impact on transmission
Table 6: Benelux results: hourly price paid by demand

<table>
<thead>
<tr>
<th>Description</th>
<th>Belgium</th>
<th>Netherlands</th>
<th>B &amp; NL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial situation</td>
<td>731277</td>
<td>1834355</td>
<td>2565631</td>
</tr>
<tr>
<td>Supranational (type 1)</td>
<td>6.29%</td>
<td>-32.61%</td>
<td>-21.52%</td>
</tr>
<tr>
<td>Supranational (type 2)</td>
<td>-30.97%</td>
<td>-33.32%</td>
<td>-32.65%</td>
</tr>
<tr>
<td>Pure Belgian planner</td>
<td>-27.19%</td>
<td>-27.41%</td>
<td>-27.34%</td>
</tr>
<tr>
<td>Pure Dutch planner</td>
<td>20.76%</td>
<td>-17.36%</td>
<td>-17.36%</td>
</tr>
<tr>
<td>Alt. Belgian planner</td>
<td>-30.97%</td>
<td>-31.93%</td>
<td>-31.65%</td>
</tr>
<tr>
<td>Alt. Dutch planner</td>
<td>-3.06%</td>
<td>-36.75%</td>
<td>-27.15%</td>
</tr>
</tbody>
</table>

Table 7: Benelux results: generation dispatch cost (€/hour)

investments done by the different planners. The values of table 8 remain valid. This can be explained by the fact that demand was high in the presented case. When demand is high, a lot of generation facilities have to be running anyway, making the merit order shift less relevant. In a two-period setup also featuring an off-peak case or in a situation with lower demand, results can be very different. As transmission investment are rather cheap compared to the gains in generation dispatch cost or price paid in demand they can create, planners would prefer to invest in transmission capacity enabling cheaper generation facilities to produce during low demand periods, even when they are not located close to demand. During high demand periods in a meshed grids with generation facilities spread throughout the grid, this is a less crucial issue.

Table 8: Benelux results: transmission investments

<table>
<thead>
<tr>
<th>Line</th>
<th>Area</th>
<th>Initial (MW)</th>
<th>Extra capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Supra 1</td>
<td>Supra 2</td>
</tr>
<tr>
<td>L13</td>
<td>B/F</td>
<td>898</td>
<td>+955</td>
</tr>
<tr>
<td>L14</td>
<td>B/F</td>
<td>1207</td>
<td>+761</td>
</tr>
<tr>
<td>L15</td>
<td>B/F</td>
<td>267</td>
<td>+336</td>
</tr>
<tr>
<td>L12</td>
<td>B</td>
<td>1842</td>
<td>0</td>
</tr>
<tr>
<td>L9</td>
<td>B/N</td>
<td>641</td>
<td>+145</td>
</tr>
<tr>
<td>L10</td>
<td>B/N</td>
<td>641</td>
<td>+849</td>
</tr>
<tr>
<td>L11</td>
<td>B/N</td>
<td>936</td>
<td>+3</td>
</tr>
<tr>
<td>L6</td>
<td>N</td>
<td>1842</td>
<td>0</td>
</tr>
<tr>
<td>L7</td>
<td>N</td>
<td>1842</td>
<td>0</td>
</tr>
<tr>
<td>L8</td>
<td>N</td>
<td>1842</td>
<td>0</td>
</tr>
<tr>
<td>L1</td>
<td>N/D</td>
<td>2971</td>
<td>0</td>
</tr>
<tr>
<td>L4</td>
<td>N/D</td>
<td>896</td>
<td>+1537</td>
</tr>
</tbody>
</table>
Table 9: Transmission investment cost sensitivity: lowest cost causing investment change (in €/MW.km.year)

<table>
<thead>
<tr>
<th>Supra 1</th>
<th>Supra 2</th>
<th>Alt. Belg.</th>
<th>Alt. Dutch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1240</td>
<td>3720</td>
<td>790</td>
<td>1950</td>
</tr>
</tbody>
</table>

6 Conclusion

The European transmission grid requires new investments in the (near) future. This is necessary to attain policy goals with respect to RES deployment, reliability and further market integration. Until now, the available legislative framework did not fully support such development. However the adoption of the 3rd package creates new opportunities. Especially with respect to network planning a clear European voice is heard. Network development plans at regional and European scale have to published on regular basis. The incorporation of both European viewpoints (top-down) and national elements (bottom-up) in the development plans drafted at different levels, is a crucial element.

However, it remains to be seen whether on the one hand the TYNDP, the Community-wide development plan, is truly able to incorporate both European and national needs and not just one of them. On the other hand, the implementation of the plan, i.e. actually constructing new lines, will take place as the TYNDP is non-binding. The implementation crucially depends on national TSOs regulated by national regulators. Will they be able to take up the European viewpoint and invest for the European benefit or only when this is in line with their own interests? The problem of a mismatch between costs borne and benefits reaped by a transmission investment is unfortunately not addressed by the 3rd package.

Different mathematical optimization models for static transmission planning are presented in this paper. They vary in complexity, ranging from LPs to MPECs. Supranational planners not differentiating between different areas are compared to national planners who only focus on the benefit for their area. The multi-area context is explicitly taken into account. Planners have to face a regional perfectly competitive market. The market outcome is endogeneous to the model, the planners influence the market outcome by their investments and vice versa.

As illustrated by two examples in this paper, it is not self-evident that all national and supranational interests coincide. Planners at different levels clearly can have different preferences. Drawing general conclusions from the two examples is difficult and dangerous. A different setup can yield other results. However, the most promising result when looking for convergence can be found with the so-called “alternative national planners”. By allowing national planners to look at possible investments outside their control area, better solutions can be found. If co-financing of investments outside control areas would be possible, conflicting interests could be tempered.
Acknowledgments

The authors are grateful for the support of Leonardo Meeus, Hannes Weigt, Marcelo Saguan and Erik Delarue. Discussing these issues with them was quite revealing. Also the expertise of Jeroen Tant in the field of optimization is highly appreciated. However, all remaining errors are the sole responsibility of the authors.

References


A Appendix: Nomenclature

All variables and parameters are declared in the table below.

- $b$: buses or nodes
- $nb$: national buses
- $g$: generators, a subset of $b$
- $l$: transmission lines
- $nl$: national transmission lines, a subset of $l$
- $p$: time periods
- $xcap_l$: investment in line $l$ (MW)
- $P_{p,g}$: generated power by generator $g$ in period $p$ (MW)
- $LMF_{p,b}$: locational marginal price in node $b$ in period $p$ (€/MWh)
- $\mu_{p,g}^{max}$: dual variables associated with maximal generation output constraints
- $\lambda_+^{p}, \lambda_-^{p}$: dual variables associated with the balance constraints
- $\mu_{p,l}^{+}, \mu_{p,l}^{-}$: dual variables associated with the maximal flow constraints
- $dem_{p,b}$: demand in bus $b$ in period $p$ (MW)
- $duration_{p}$: number of hours in period $p$ (hours)
- $length_{l}$: length of line $l$ (km)
- $c_l$: investment cost of line $l$ (€/MW.km.year)
- $P_{p,g}^{max}$: maximum generation output of generator $g$ in period $p$
- $PTDF$: matrix with dimensions $(l, b)$ containing power transfer distribution factors

B Appendix: Supranational OPF written as an LP

The supranational OPF determines the optimal dispatch at supranational level, given transmission capacity limits, generation output limits, demand and generation costs. Based on the dual variables (Greek notation), LMP’s can be calculated.

$$\max_{\{P_{g}\}} \left\{ \sum_{g} c_{g} P_{g} \right\}$$
subject to:

\[ \forall g \quad P_g \leq P_{g_{\text{max}}}^{\text{max}} \]

\[ \forall l \quad \left| \sum_l P_{TDF_l}(P_b - \text{dem}_b) \right| \leq e_{\text{cap}_l} + x_{\text{cap}_l} \quad [\mu_l^+, \mu_l^-] \]

\[ \sum_g P_g - \sum_b \text{dem}_b \geq 0 \quad [\lambda^+] \]

\[ \sum_g P_g - \sum_b \text{dem}_b \leq 0 \quad [\lambda^-] \]

\[ \forall g \quad P_g \geq 0 \]

This LP can be written as a set of complementarity constraints by using its Karush-Kuhn-Tucker (KKT) conditions. In [14] (page 72) the link between the LP and the KKT conditions is given.

The above formulation does not consider any time period. For each period, this LP has to be solved, resulting in a set of complementarity constraints for each period.