A prototypic implementation of an optimizing network expansion planning model considering the value perspective of the company and the effects of monopoly regulation in the objective function

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Abstract

In recent years several approaches for the electricity network expansion planning problem have been proposed. In the course of the increasing penetration of companies with information technologies first practical applications can be observed. Due to the extensive costs for infrastructure projects optimizations in this field have a substantial economic impact. The problem can be stated as a large-scale, nonlinear, combinatory optimization problem. Derived mainly from operations research and engineering sciences, most models aim at the minimization of the system costs.

However, in regulated natural monopolies the implication that minimizing costs leads to maximizing company value does not hold. This insight is confirmed by regulatory theory and studies basically results from the fact that regulatory systems can never be perfect. For the German market many economical publications deal with the possibilities of regulatory optimization of investment strategies in terms of maximizing revenues or value. In practice, investment evaluation methods as NPV calculations, taking the regulatory system into account, have been applied in recent years leading to an intensive discussion about the sufficiency of the regulatory system and its implicated incentives to invest in network infrastructure.

Taken together the application of cost minimizing objective functions in network planning models neglect the economic calculation schemes that are practically applied in the electricity distribution companies for the evaluation of investments and strategies. It can be assumed that this leads to suboptimal investment decisions.

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The proposed model deals with this problem. For the first time, this modell implements a value oriented economical calculus, considering the effects of the German regulatory system in an optimizing model for the grid expansion planning problem. Firstly, the model shows that a network expansion plan aiming at maximizing the Net Present Value of the investment program can significantly differ from a cost minimizing optimization depending on the expected regulatory framework. Secondly, under specific regulatory conditions the model results equal the empirical investment behavior under incentive regulation systems. Thirdly, it confirms that technical restrictions limit the possibilities of regulatory optimization.

Keywords:

Regulation of natural monopolies

Distribution network expansion planning

Shareholder value

Metaheuristics

Optimization

1 Introduction

1.1 Liberalization in European energy markets

In course of the liberalization process of the European energy markets which started in 1998 the role of distribution network operator companies has changed significantly. Since the introduction of the Energy Industry Act 2005 in Germany, the system operators are legally and economically unbundled from the energy supply companies. Since the Energy Industry Act no longer allows cross-subsidization within the companies. The distribution system operators are responsible for their own economic results [1], [2]. The cost pressure for network operators has increased notably. For securing a sustainable economic position distribution system operators need to consider the economic effects of expenditures in infrastructure in the planning process. As monopolistic part of the value chain distribution system operators are regulated by the national regulatory authority (Bundesnetzagentur) [2], [3]. Above all the introduction of an incentive regulation in 2009 in Germany led to a major change in the economical environment of the companies having significant effects on investment- and maintenance strategies [4].

1.2 Network planning

The network planning process is characterized by high capital intensity and the long useful technical life of the assets. Due to the latter, once taken decisions have long-term consequences on network structures and performance. Hence, restructuring processes cannot be accomplished in a short time [5]. Since an optimal network and investment planning is only possible through computer support, techno-economical energy system models for network planning have been developed by several research facilities in recent years and first applications can be seen in practice [6]. Due to its high complexity the planning process is divided into two stages [7]–[10]. In the static long-term planning future final-state network structures are created with a planning horizon of 20 to 50 years, in most cases independently of the existing network structures. The following planning stage, the dynamical expansion or extension planning, determines the execution times and the order of all construction (or tear down) activities that are necessary to transform the existing network structures into one of the chosen target structures under consideration of given technical restriction and boundary conditions for a planning horizon of 5 – 25 years [8], [9], [11]. Both planning stages can be characterized as large-scale, nonlinear, combinatory optimization problems for which both exact methods as LP, MIP or DP and heuristics as GA, ACO or Tabu Search have been developed. Since problem instances of realistic sizes cannot be solved in a feasible time, heuristics are preferable used in recent years, since they can find a large number of solutions of similar quality in a short time [12].[2] Derived mainly from operations research and engineering sciences, most models thereby aim at the minimization of the system costs [5], [7], [10], [11], [13]–[15].

1.3 Investment evaluation and strategies in regulated monopolies

In regulated natural monopolies the implication that minimizing costs leads to maximizing company value does not hold. While in competitive markets the market price cannot be influenced by a single company in (natural) monopolies this is not the case. It can be shown that the optimal output level of unregulated monopolies exists at the point where marginal costs equal marginal revenues. At this point the monopoly realizes additional profit at the cost of social welfare (death weight loss) [3], [16]. In theory the regulation of natural monopolies therefore aims at minimizing those social welfare losses [17]. In practice a regulatory regime can never be perfect, e.g. due to existing information asymmetries and political influences. In an early publication Averch et al. (1962) showed in their model that a monopoly can compensate regulatory intervention by changing the weight of the production factors work and capital [17], [18]. Since that time many literature has been published related to the influence of regulation on the behavior of firms.

Fig. 1.1 shows a strategic behavior under incentive regulation known as “ratched effect”, which e.g. was observed after the introduction of this system in

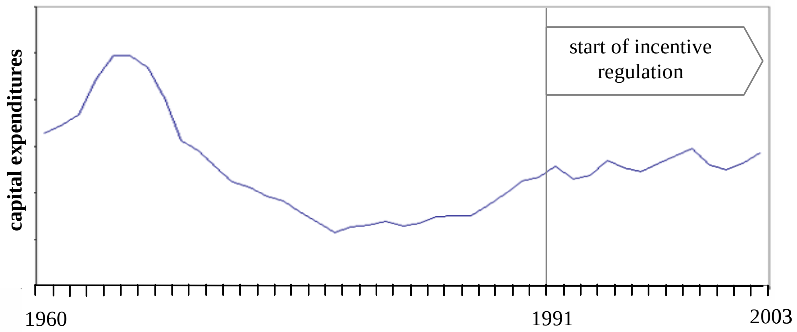

Fig. 1.1: Time Series of Investments in Network Infrastructure in Great Britain and the Ratched-Effect (source: [19])

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[2] See also [9], [10] .

Great Britain. The companies increased their costs at the end of each regulatory period because the revenues in the next period depended on the level of costs in the year of cost audit. The losses in the years with increased costs were overcompensated by the increased revenues in the following period [20].

In course of the introduction of an incentive regulation in Germany in 2009, many scientific and practical publications dealt with the question of achievable rate of returns under this regulatory system. E.g. Ballwieser (2008) showed that due to the time delay between the date of investment and recognition of the derived capital expenditures within the revenue cap the rate of return of a single investment depends on its timing and other regulatory parameters [21]. Other publications proposed optimization strategies whereby the regulatory oriented optimization of the asset base has been identified as one the most relevant strategies [22]–[26].

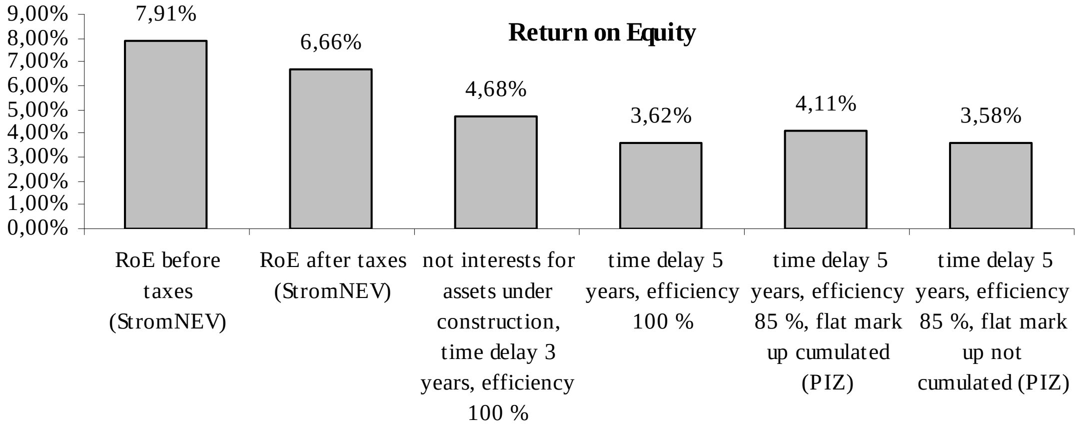

Fig. 1.2: Resulting Rate of Returns on Equity depending on the timing of investments and other regulatory parameters (source: [21])

Summarized it can be shown that electricity distribution companies aim at maximizing their profit or company value while considering the effects of the applied regulatory framework. The maximization of value is thereby not necessarily in line with cost reduction. Therefore it can be assumed that planning models aiming at minimizing system costs lead to suboptimal investment decisions in regulated environments.

Only a few authors considered value oriented measures in technical planning approaches so far. E.g. Fritz et al. (2002) et al. and Lehman et al. (2010) identified planning alternatives on the basis of network models that are afterwards evaluated by profitability measures or cost-revenue analysis. The evaluation is thereby restricted to a few manually chosen plans [23], [27].

2 Modeling Approach

2.1 Overview

The here proposed techno-economical model integrates the economical evaluation of investments under consideration of revenues from regulated network fees with a technical network planning model of the high voltage layer. Main drivers of the model are the given supply task and the limited useful lifetime of the equipment in the existing network. Typically, in most network planning approaches, the planning task is separated into two subsequent stages, the long-term planning and the expansion planning. The results of the static long term planning represent the input variables of the expansion planning where the detailed actions for the transformation of the existing grid into the future network structures are determined.

2.2 Network Model

The network and its economical and technical relevant components are modeled on two layers. On the upper layer the network structure is described as an undirected graph where nodes represent the transformer stations and edges the routes between those stations. In the stations and on the routes the network equipment is situated. Within the stations (nodes) transformers and switch gears and at the routes (edges) overhead lines, cables, masts and trenches are localized [12]. For each equipment class several types can be chosen and characterized by their specific economical and technical parameters. The parameters are vendor specific and represent individual constraints of the planning problem (see Chapter 3).

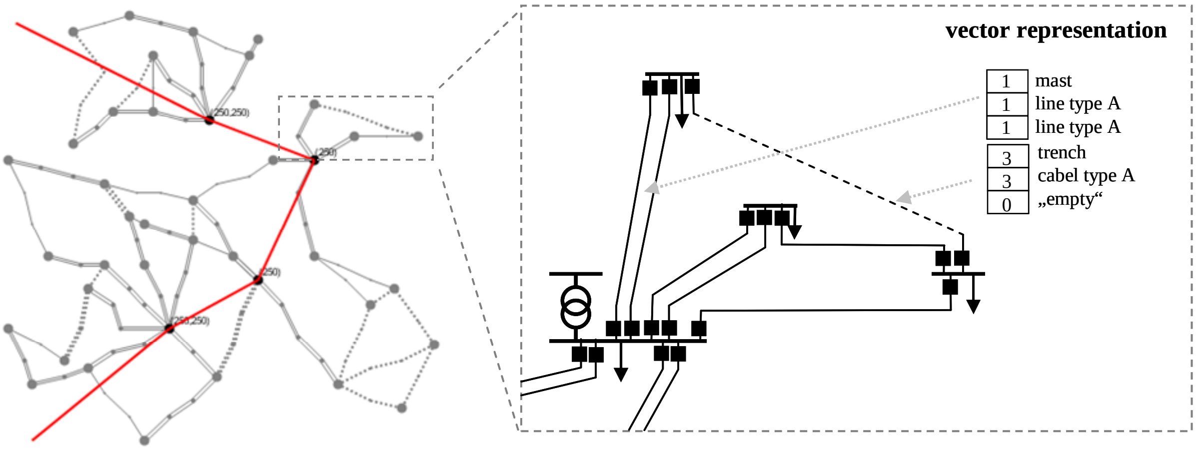

Fig. 2.1: Network Model

2.3 Objective Function

Both the static long term planning problem and the expansion planning problem can be described as assignment problems. Due to the fact that the advances proposed in this paper are referring to the planning stage of expansion planning consecutively only the objective functions of this planning stage will be described. While the traditional approaches aim at minimizing system costs or the present value $PV_{Ex}(x_e)$ of all expenditures CF_{Ex_t} the here proposed objective function is to maximize the net present value $NPV(x_e)$ based on the free project cash flows FCF_{E_t}. The alternative planning approaches for the expansion planning problem can therefore be formulated as:[3]

Minimize:

$$PV_{Ex}(x_e) = \sum_{\forall t \in EH} \frac{CF_{Ex_t}}{(1+i_{r_t})^t}$$

Maximize:

$$NPV(x_e) = \sum_{\forall t \in EH} \frac{FCF_{E_t}}{(1+i_{r_t})^t}$$

Subject to:

$$b_{place,t} \in ZBMK_{place,t}$$

locally allowed equipment types

$$R_{node}(G_{ne}) = V(G_{ne})$$
$$R_{node}(G_{ne,\,failure}) = V(G_{ne,\,failure})$$

structural (n-1)-constraint: all substations have to be connected to the network in steady state and case of failure

$$sl_{ds,t} \leq max\_length_t$$
$$a_{ds,t} \leq max\_st_t$$

maximum of allowed length of double spur lines and number of substations in double spur lines

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[3] An overview about indices, indices sets, parameters and variables is given in the apendix.

$$In0_{line,t} \leq I_{max\,n0}{}_{linetype}$$
$$Sn0_{transf,t} \leq S_{max\,n0}{}_{transftype}$$
$$In1_{failure,line,t} \leq I_{max\,n1}{}_{linetype}$$
$$Sn1_{failure,transf,t} \leq S_{max\,n1}{}_{transftype}$$

maximum allowed capacity use of lines, cables and transformers in steady state (n-0) and case of failure (n-1)

$$U_{min\,n0} \leq Un0_{node,t} \leq U_{max\,n0}$$
$$U_{min\,n1} \leq Un1_{failure,node,t} \leq U_{max\,n1}$$

allowed range of voltage levels in all stations (nodes) in steady state (n-0) and case of failure (n-1)

$$S''_{min}{}_{sgtype} \leq S''_{node,t} \leq S''_{max}{}_{sgtype}$$

allowed range of short circuit current in switch gears

$$\forall place \in PLACE; \forall t \in OZ; \forall node \in NODE; \forall failure \in FAILURE; \forall ds \in DS(G_{ne,t});$$
$$\forall conductor \in CONDUCTOR; \forall tranf \in TRANSF$$

While the relevant expenditures can be directly derived from load flow calculations and equipment parameters the network fees have to be calculated in reference to the assumed regulatory system(s). Due to the fact, that those systems can be very complex, e.g. as in the case of the German regulatory system, the complexity of the evaluation function in this approach exceeds the complexity of existing cost oriented approaches noticeably. Due to this complexity the objective function cannot be described in detail in this paper. Fig. 2.2 shows its conceptual structure.

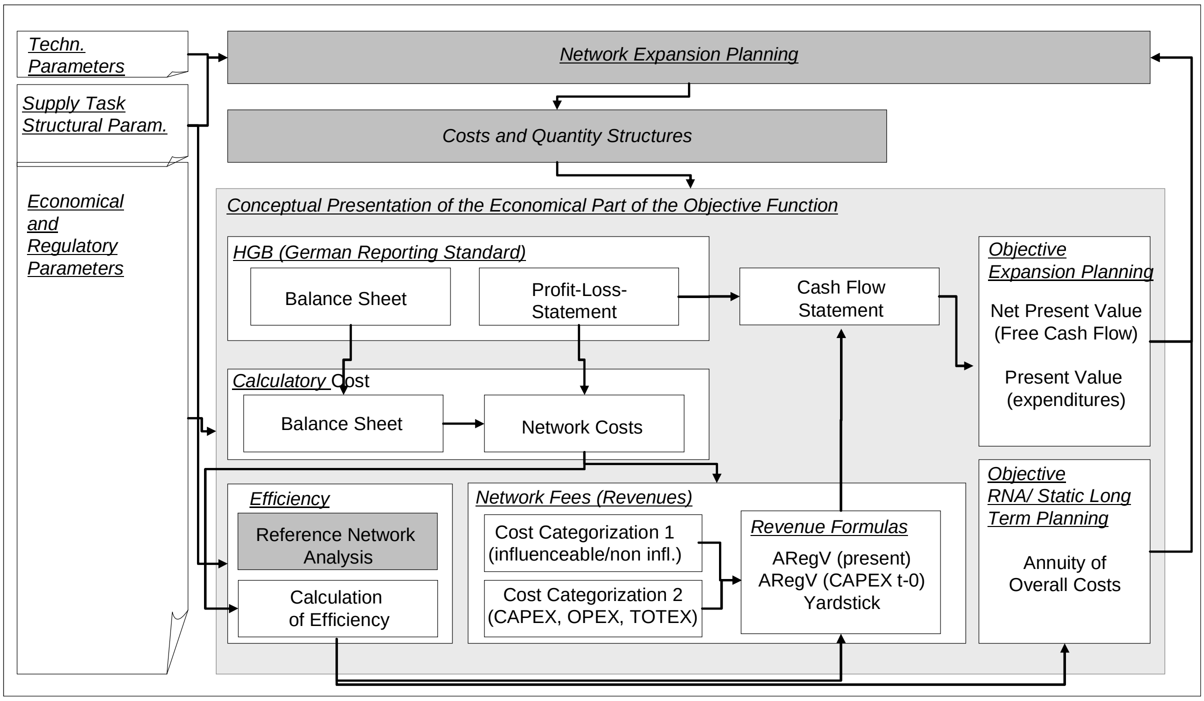


Fig. 2.2: Conceptual Description of the implemented Objective Function(s).

2.4 Optimization Approach: Ant Colony Optimization

Both optimization problems (static long term planning and dynamic expansion planning) can be stated as large scale, nonlinear, combinatory optimization problem. Within the developed model prototype the static long term planning is realized by Genetic Algorithm (GA) in reference to existing approaches which will not be described further [12], [15]. The focus of this chapter lies on the dynamic expansion planning problem. Although exact optimization algorithms as (stochastic) dynamic programming exist for sequential problems as presented here, they are limited to relatively small instances of the problem (curse of dimensionality) [9]. Furthermore, due to the time dependent objective function and in opposition to existing cost oriented models the objective function used here is path depended and therefore not temporal separable. Due to the fact, that latter characteristic is a prerequisite for the application of dynamical programming, this method is not applicable. Instead a heuristic Ant Colony Optimization Algorithm (ACO) is used to solve the expansion planning problem. The problem is formulated as assignment problem where every investment or divestment decision has to be assigned to one year of the optimization period. A remotely similar algorithm has been already successfully applied to this problem by Paulun (2007) [9].

Ant Colony Optimization (ACO) is a metaheuristic for solving hard combinatorial optimization problems. Analogous to real Ant Colonies ACO is based on indirect communication via pheromone trials within a colony of simple agents, the artificial ants (stigmertic system). Each ant represents a solution of the problem. The pheromone trails serve as distributed, numerical information, that is used by the ants to probabilistically construct solutions and which is adapted during the iterative optimization process to reflect the search experience of the ants. The here developed algorithm follows the ACO-metaheuristic as presented by Dorigo et al (2009) but is extended in order to match the specific characteristics of the optimization problem [28]. Due to the many constraints only a very few of the constructed solutions are technically valid. Therefore repair algorithms are applied trying to fix violations based on an analysis of the violated constrains [9]. The second extension takes into account, that some modeled equipment classes are relevant for the electrical functionality of the constructed network, e.g. transformers and lines, and some are not, e.g. trenches. Additionally there exists interdependencies between the equipment, e.g. between masts and overhead lines.

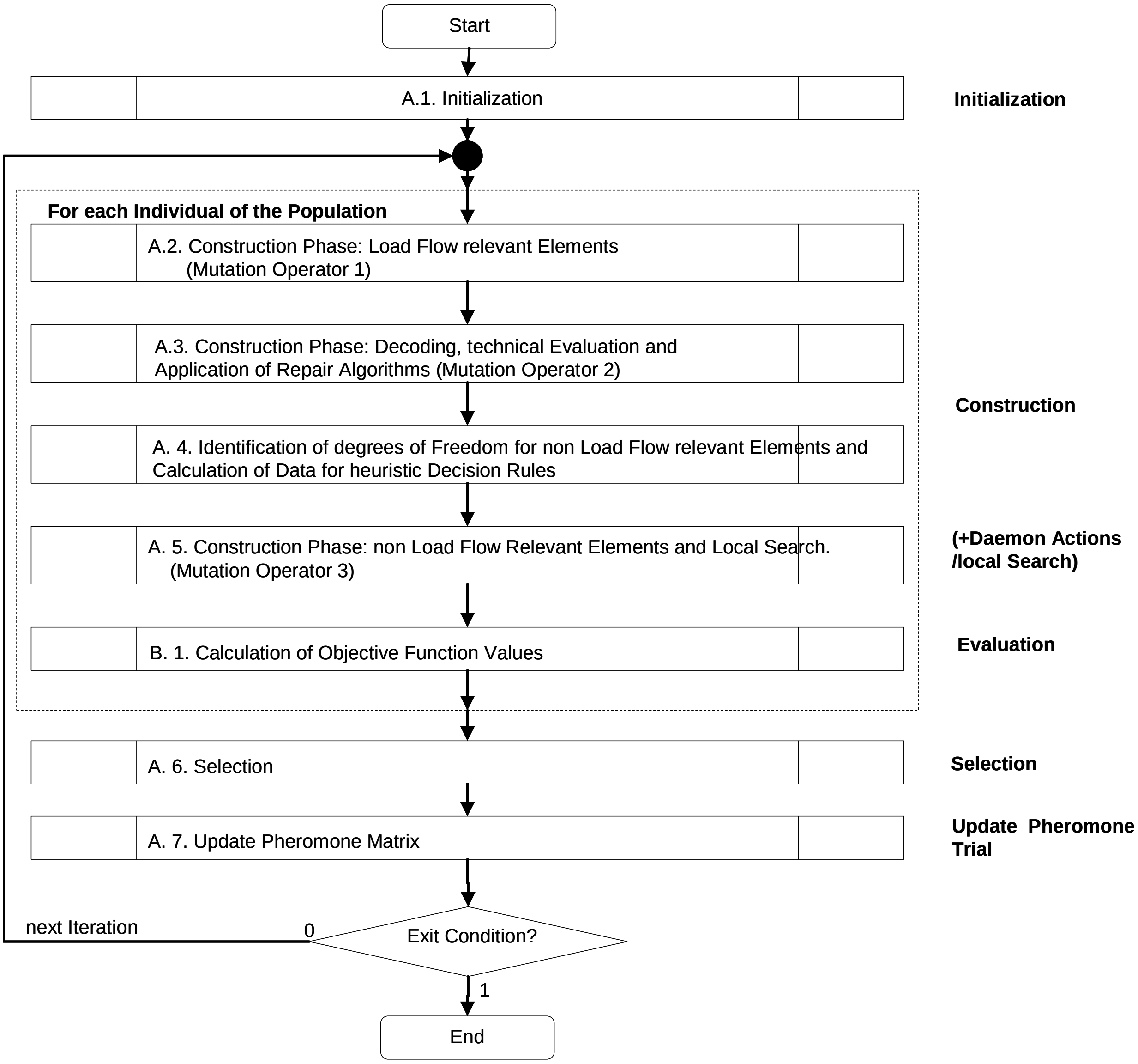


Fig. 2.3: Basic Structure of the ACO-Algorithm

To take those aspects into account, the solution construction is done successively starting with electrical relevant and independent parts followed by electrical non relevant and dependent parts of the solution. E.g. the ACO-constructor decides at the first place where and when a power line is built. Afterwards it is decided when the related masts and switch gears have to be constructed/tore down (Fig. 2.3).

The difference vector between the vector representations of the existing network end the vector representation of one target network structure defines the set of projects e for which a decision has to be made concerning the time of project execution. In the given example the model contains about 500 integer decision variables.

If the equipment type at one place in the target network structure equals the equipment type of the existing network then the variable in the difference vector represents a replacement decision. Otherwise it represents an expansion or restructuring decision. For each project a decision variable x_e is defined whereby the possible range of values consists of all years j of the optimization period plus a value that represents a non-decision. The corresponding pheromone matrix $\tau_{e,j}$ spans over all single decisions and all years of the optimization period.

During the process of successive solution construction a probability $P(x_{e,j})$ for each allowed value of every decision variable is calculated composed by a factor $\tau_{e,j}$ derived from the pheromone trail and a factor $v_{e,j}$ derived from a myopic rule. E.g., a myopic rule can represent the logical deduction that before the lines are installed the masts have to be constructed. The weight of both factors is determined by the algorithm parameters α and β. Alternatively with a certain probability Q a so-called pseudo-random-proportional-rule is applied that gives the value $x_{e,j}$ of the decision variable that has the highest related pheromone value a probability of 100%. When probabilities for all values of all decision variables are calculated, a monte-carlo-selection is used to select one value for each variable. This process is repeated for all ants of the colony [29].

$$P(x_{e,j}) = \left\{ \begin{array}{ll} if \quad rnd > Q: & \dfrac{\tau_{e,j}^{\alpha} \cdot v_{e,j}^{\beta}}{\sum\limits_{\forall k \in OZ} \tau_{e,k}^{\alpha} \cdot v_{e,k}^{\beta}} \\ if \quad rnd \le Q: & \left\{ \begin{array}{l} 1: j = \underset{\forall k \in OZ}{argmax}\left[\tau_{e,k}^{\alpha} \cdot v_{e,k}^{\beta}\right] \\ 0: else \end{array} \right\} \end{array} \right\}$$

$\tau_{e,j}$	pheromon trial of each value for each decision variable
$v_{e,j}$	myoptic rule
α,β	weight factors
$P(x_{e,j})$	selection possibility of each value of the decision variable
$0 \le Q \le 1$	application probability of the pseudo - random - proportional - rule

After a solution for each ant is constructed one or more ants are chosen to update the pheromone matrix. All elements of the solution space $x_{e,j}$ that are represented by a chosen ant lead to updates in the corresponding places in the pheromone matrix $\tau_{e,j}$. Additionally a weathering factor ρ is applied emulating the evaporation of the natural pheromone trial and weakens the influence of older solutions [29]. By forgetting and refreshing the „collective knowledge“ represented by the pheromone matrix is updated iteratively to the actual state. In order to avoid the dominance of some few solutions, a reversion coefficient φ is applied that implicitly defines upper and lower boundaries for the pheromone values.

$$\tau_{ej} = \tau_{ej} \cdot (1-\rho) + \rho \cdot \left\{ \begin{array}{ll} \dfrac{1}{f(x_{e,j})} & \forall (e,j) \in AP_{phero} \\ 0 & \forall (e,j) \notin AP_{phero} \end{array} \right\}$$

$$\tau_{ej} = \tau_{ej} \cdot (1-\varphi) + \varphi \cdot \tau_0 \qquad \forall (e,j) \in AP_{phero}$$

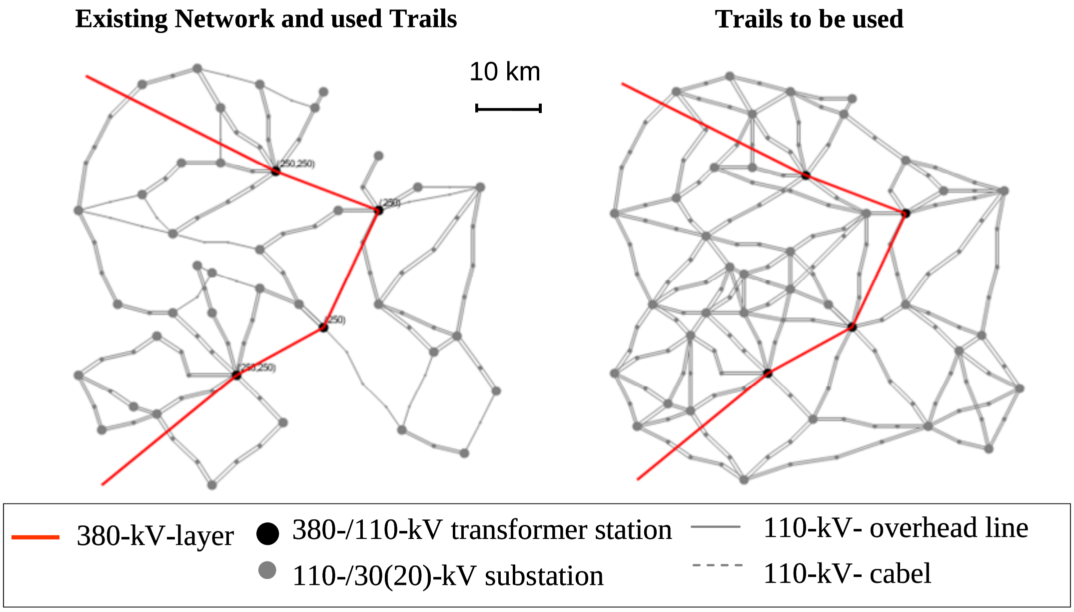
$x_{e,j}$	values of all decisions
AP_{phero}	Ants chosen for updating the pheromon trials
$\tau_{e,j}$	value of a pheromon trial in the phreromon matrix
τ_0	initial pheromon value
ρ	weathering factor
φ	weathering coefficient

During the optimization process a large number of different network structures is created and subjected to technical and economical evaluation. The technical constrains are tested on basis of load flow calculations, short circuit calculations and structural tests. The latter tests are mostly based on algorithms applied to the network graph. Thereby each network structure is tested for the steady state and cases of failure (n-1). Only structures or -in case of the dynamic expansion planning- cues of yearly structures that are identified as technical valid are subjected to economical evaluation.

3 Synthetic Case Study

3.1 Planning/Supply task and constrains (synthetic data)

To demonstrate the effects of different objective functions on the planning results, the here proposed model prototype has been applied to the 110-kV layer of a synthetical energy network. The supplied area covers 3300 km^2 of partly urban and rural character. The 110-kV layer is supplied by four transformer stations from the 380-kV overlay grid. The 110-kV layer itself distributes the electrical energy via 40 substations to the 20-kV/30-kV medium voltage layer. The current 110-kV layer is built as meshed structure complemented by double spur lines (Fig. 3.1, left). As typical for German energy networks the 110-kV layer grew significantly in the seventies of last century resulting in an average asset age of 28 years.


Existing Network and used Trails

Trails to be used

Fig. 3.1: Existing Network Structure and Trails available to be used

Preceding the planning process, the main planning principles have to be determined and preliminary assessments have to be made [8], [11]. The results of this step represent the boundary conditions of the planning problem the model has to incorporate in the optimization.

One of the main drivers of the planning process is the expected load development in every substation within the planning horizon. Due to the lack of data, general prognoses of load developments have been used in the past. In general the load prognosis should be done for each node/substation individually [14]. For the planning task an increase of app. 0,5% per year is presumed, whereat the prognosis differ significantly for particular nodes. In order to increase reliability the maximum length of double spur lines is reduced from 8 km to 3 km at the end of the planning horizon. If new trails are used only cable lines are allowed. Additionally, it is planned to exchange the overhead lines in the urban area in the south east stepwise for cable lines if it is economically feasible. In order to reduce short circuit currents the industrial dominated area in the north shall be galvanically decoupled. Generally the network has to be constructed in compliance with the n-1 security measure and the current must exceed 108-kV in steady state and 99-kV in case of failure. For simplification of the planning task only a few standardized equipment types are permitted to be used (Table 3.1, Table 3.2).

Table 3.1: Equipment Parameters of Overhead Lines, Cables, Masts and Trenches

equipment type	**Al/St 150/25 mm^2**	**VPE Cu 400**	**mast type 1**	**trench type 1**
I max (n-0) [A]	470	600	-	-
I max (n-1) [A]	515	660	-	-
R’ [Ω/km]	0,11	0,05	-	-
X’ [Ω/km]	0,4	0,12	-	-
acquisition and production costs (100% recognition as assets) [Euro]	35.000	400.000	150.000	90.000
Ø cost of operation and maintenance [% of AaP costs/a]	0,9%	0,3%	0,9%	0,3%
cost of deconstruction [% of AaP costs/a]	1%	9%	5%	9%
market value [% calc. depreciated book value]	50%	50%	60%	0%
useful life [a] (HGB / calc./ techn.)	35/40/50	35/40/60	35/40/50	35/40/100

Table 3.2: Equipment Parameters of Transformers and Switch Gears

equipment type	**transformer 250 MVA**
S max (n-0) [MVA]	250
S max (n-1) [MVA]	325
U (kr) [%]	0,16
U (Rr) [%]	0,004
acquisition and production costs (100% recognition as assets) [Euro]	3.800.000
Ø cost of operation and maintenance [% of AaP costs/a]	0,26%
cost of deconstruction [% of AaP costs/a]	4%
market value [% calc. depreciated book value]	100%
useful life [a] (HGB / calc./ techn.)	20/40/40
equipment type	**outdoor switchgear AIS 31,5 kA**
I’’ min [kA]	1,5

I’’ max [kA]	31,5
acquisition and production costs (100% recognition as assets) [Euro]	480.000
Ø cost of operation and maintenance [% of AaP costs/a]	0,84%
cost of deconstruction [% of AaP costs/a]	1%
market value [% calc. depreciated book value]	100%
useful life [a] (HGB / calc./ techn.)	20/25/25

3.2 Economical and Regulatory Parameters

As proposed, the network planning process should be enhanced by an economical evaluation aiming at the maximization of the company value. Therefore next to the technical assessments the preliminary determination of economical and regulatory parameters is necessary for the planning process. By this the evaluation of expansion- and replacement strategies becomes a subjective individual task depending on company specific parameters and expectations concerning the national regulatory system. To demonstrate the effect of different optimization objectives, technical restrictions and the impact of the (expected) regulatory framework, the dynamic expansion- and replacement planning optimization is executed under different regulatory scenarios. These scenarios are described by some dozen parameters and different revenue formulas that cannot be described to full extent in this paper. E.g., important parameters are the allowed regulatory interest rate for equity, the general applied regulatory system or the industrial wide efficiency requirement (x-gen).

Table 3.3: Overview of the analyzed regulatory scenarios and related objective functions

Scenario	Objective	Regulatory system	Restrictions
infinite incentive regulation, full restrictions	NPV-->Max	- incentive regulation (2012-2023) - actual regulatory input parameters	- electrical and structural - max. technical life - equipment compatibility - project resource and investment budgets restrictions
infinite incentive regulation, relaxation of restrictions	NPV-->max	- incentive Regulation (2012-2023) - actual regulatory input parameters	- max. technical life - equipment compatibility
cost minimization, full restrictions	Cost --> min	- irrelevant	- electrical and structural - max. technical life - equipment compatibility - project resource and investment budgets restrictions
economical realistic, full restrictions	NPV-->Max	- incentive regulation (2012-2023) - yardstick-regulation (2024-) - actual regulatory input parameters	- electrical and structural - max. technical life - equipment compatibility - project resource and investment budgets restrictions

economical positive, full restrictions	NPV-->max	- incentive regulation (2012-2023) - no time delay for CAPEX since 2013 - positive regulatory input parameters	- electrical and structural - max. technical life - equipment compatibility - project resource and investment budgets restrictions

3.3 Stage 1: static long term planning

In the first planning stage three cost efficient target network structures for a planning horizon of 20 years are computed using reference network analysis. These networks in combination with the presently existing network structure represent the input variables for the subsequent dynamic expansion planning. The expansion planning algorithm automatically chooses the most appropriate target structure.[4]

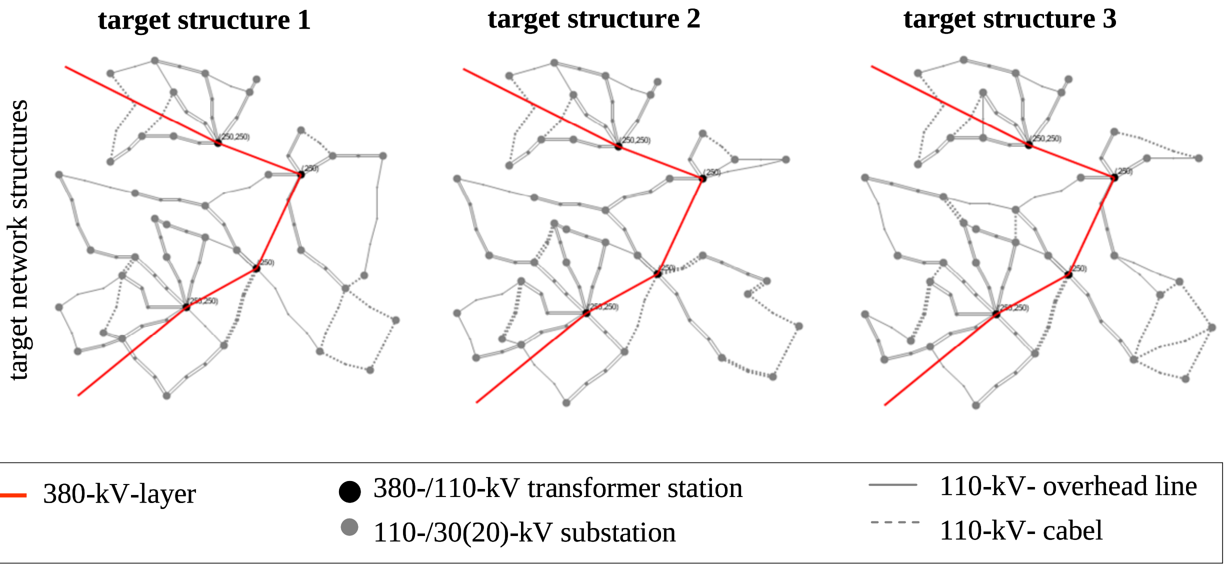


Fig. 3.2: Computed Static Target Structures

3.4 Stage 2: Expansion (Restructuring and Replacement) Planning

For the first two regulatory scenarios, the since 2009 applied German incentive regulation is presumed to last at least for the evaluation horizon of app. 60 years. Fig. 3.3 shows the computed investment

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[4] Because of the increasing decission space the planning results improve with the number of given alternative target structures. For demonstration purposes this number is limited to three in this example.

time series for all expansion, restructuring and replacement investments within the optimization horizon of 15 years. The most visible pattern of investment strategies under incentive regulation systems is the above described “ratched effect”. In both scenarios this effect is confirmed and equals the historical patterns that have been observed, e.g. in Great Britain. Further the model confirms the practical experience that regulatory optimization is restricted by technical necessities. While scenario (2), where only selected restrictions are applied, shows a very significant ratched effect pattern, this pattern is blurred but still significant in scenario (1) where all technical restriction are taken into consideration.

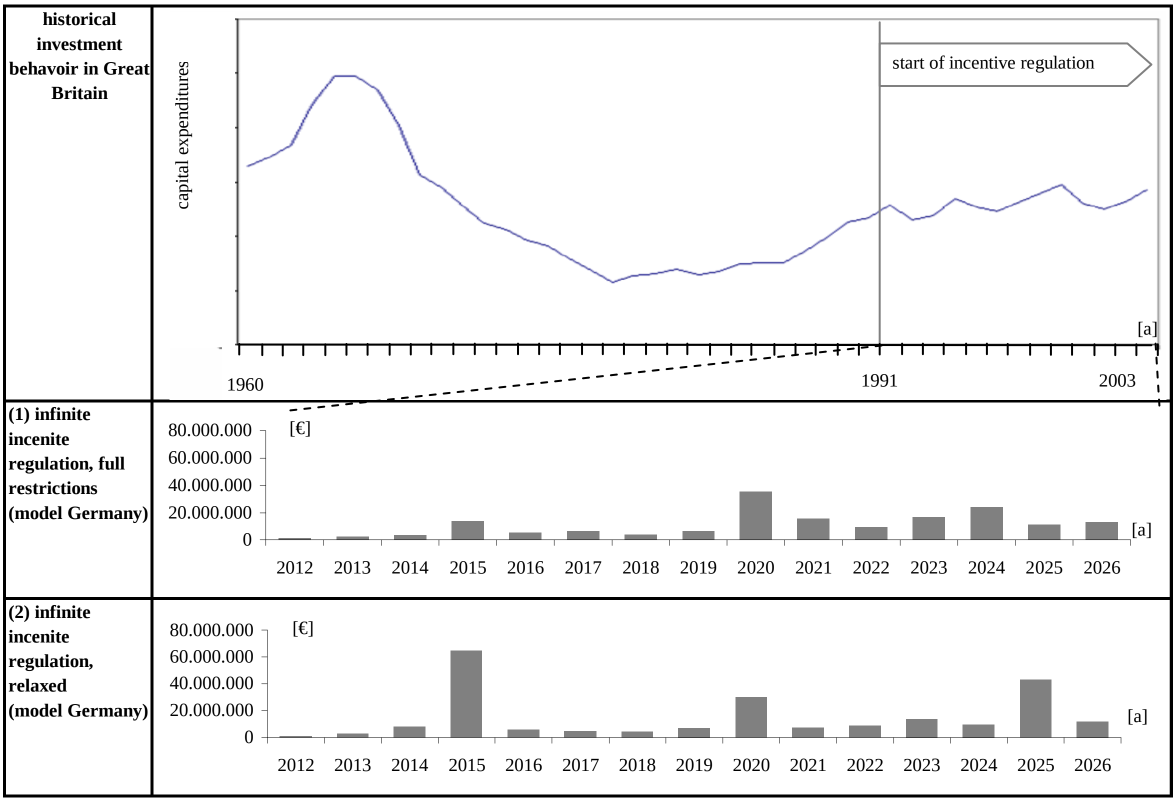


Fig. 3.3: Computed Investment Strategies in Scenarios (1) and (2)

In a second group of scenarios (3-5) a “cost minimizing” strategy (3) is compared to strategies aiming at maximizing the NPV under consideration of revenues earned via network fees (4-5). The latter two strategies differ by differences in the assumed regulatory framework. In scenario (4) a real present and expected future framework and in scenario (5) an economical positive framework, where positive NPV can be easily achieved, are modeled.

As expected due to the optimization objective, out of all scenarios scenario (3) shows the lowest PV of expenditures (-94,01 Mio.). This is realized by avoiding and postponing investments as long as no technical restriction is violated. The increase of investments from year 2020 can be explained by necessary investments due to the end of life of a significant share of assets and electrical and structural restriction, e.g. the stepwise reduction of the allowed length of double spur lines. The rate of return (equity) of 4,09 % and the negative NPV pinpoint to the fact, that the present regulatory system is not sufficient from an investment point of view. The model thereby confirms the statement of practitioners and newer studies that companies facing growing investments, either for replacement investments driven by historical investment cycles or by growth or restructuring investment driven by the change of the supply task, can be economically disadvantaged by the present regulatory system [30].

The fact, that even with optimization positive NPV cannot be achieved has a significant impact on the value maximizing strategy as showed in scenario (4). Since positive values cannot be created, every investment is similar to value destruction, hence the best strategy to “maximize” the value is to minimize expenditures.

The postponing of investments in scenario (4) is also caused by expectations concerning the future regulatory system whereupon a yardstick regulation starting in 2023 is assumed (in comparison to scenario (1), where an infinite incentive regulation is modeled). Due to the fact that growth and restructuring investments lead to more sufficient revenues when executed under a yardstick regulation compared to the present German incentive regulation there is an additional incentive to postpone investments. The model thereby shows that not only the present regulatory system but also the expected future system determines the investment behavior of value maximizing distribution system operators. In short the results in scenario (4) are only slightly different to the PV minimizing strategy. Nevertheless, even under the described conditions, a regulatory optimization aiming at the incentive regulation period can be seen in year 2015.

For a better demonstration of the effects of the regulatory system on investment behavior an artificial economical advantageous environment is modeled in scenario (5), where e.g. CAPEX are refunded without time delay and the regulatory interest rate on equity that is used in network fee calculations is set to 12%. As limiting factors remain technical restrictions and efficiency measures that avoid the so-called effect of “golden plating” by a certain extent.

As can be seen by the present value of expenditures of -112.0 Mio. €, earlier and more investments are undertaken in this scenario. Hence, the optimal value maximizing investment strategy in an economical preferable environment (5) thereby differs significantly from an expenditure minimizing strategy (3). It also differs from a value maximizing strategy in a non preferable economic environment (4). Both comparisons confirm the influence of the regulatory system on investment behavior.

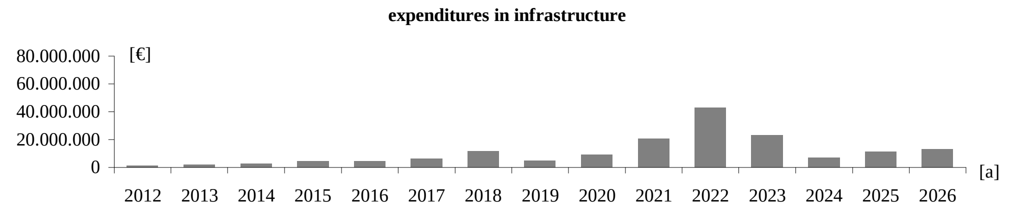
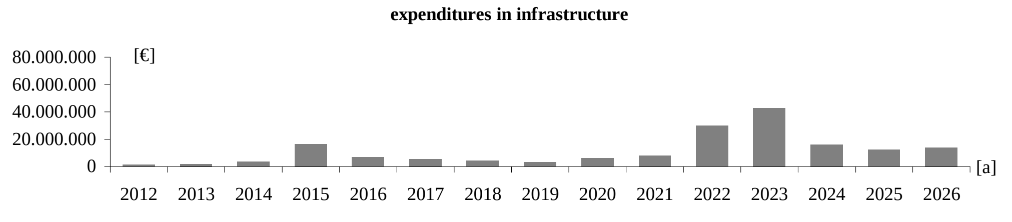
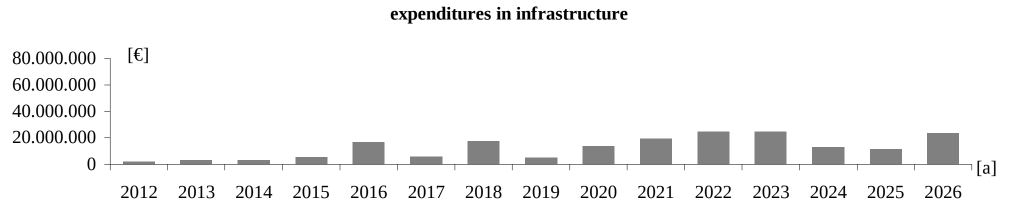
<table>
<tr><th colspan="4">Szenario</th></tr>
<tr><td rowspan="3">cost minimization, full restrictions</td><td colspan="3"> </td></tr>
<tr><td>Present Value of Expenditures</td><td>Rate of Return</td><td>Net Present Value</td></tr>
<tr><td>-94.012.928 €</td><td>4,09%</td><td>-15.544.827 €</td></tr>
<tr><td rowspan="3">economical realistic, full restrictions</td><td colspan="3"> </td></tr>
<tr><td>Present Value of Expenditures</td><td>Rate of Return</td><td>Net Present Value</td></tr>
<tr><td>-97.196.568 €</td><td>4,39%</td><td>-14.390.584 €</td></tr>
<tr><td rowspan="3">economical positive, full restrictions</td><td colspan="3"> </td></tr>
<tr><td>Present Value of Expenditures</td><td>Rate of Return</td><td>Net Present Value</td></tr>
<tr><td>-111.969.720 €</td><td>9,82%</td><td>7.165.653 €</td></tr>
</table>

Fig. 3.4: Computed Investment Strategies in Scenarios (3) to (5)

4 Integration of Uncertainty and Flexibility

4.1 Methodology

Although the presented approach incorporates risk by discounting all cash flows by a risk adjusted discount rate, from a modeling point of view the model works under certain expectations. Since uncertainties exists in most real world applications, many approaches as scenario-, sensitivity- or Monte-Carlo-Analysis have been applied to capture this uncertainty in optimization processes [31], [32]. However, even with such methods, the existing flexibility of planers and managers to react to future developments is still neglected in the evaluation leading to the possibility of underestimated project values [33]. If a planning problem is characterized by uncertainty, irreversibility and flexibility then the option to change plans in the future according to the existing conditions has a significant value. Since network planning is a successive process in an uncertain environment and investments in infrastructure have high sunk costs, those characteristics are given in expansion planning leading to the need of incorporating flexibility in the evaluation process [34]. Existing approaches in the context of network planning are mostly based upon stochastic dynamical programming as one of the major methods of flexible planning (or real option evaluation). However, this method is limited to relatively small problem instances and numbers of uncertainty parameters. Above all, as stated before, this method cannot be applied due to the characteristics of the here proposed objective function.

This example pinpoints to a problem of the evaluation methods. Although flexible planning (or real option approaches) from a theoretical point of view have clear advantages over traditional static approaches as simple NPV calculation, a lot of difficulties arise in practical implementation [35], [36]. As a result of those difficulties, there are a large number of alternative approaches in the literature ranging from analytical and numerical to merely qualitative approaches.

To incorporate uncertainty and flexibility in the network expansion planning process, a two stage process is used in the presented approach. In a first step one or more optimal planning solutions considering uncertainty but not flexibility are computed, using the above described ACO-algorithm. In a second step a flexibility value is calculated for each computed plan. The planning period of 15 years is therefore divided in only two stages, a fixed period and a flexible period. By this simplification the evaluation problem is reduced to a problem with characteristics of European options which can be solved using stochastic simulation combined with the presented ACO-Algorithm. The advantages of this simplifying approach are that the number of stochastic parameters and their probability distributions are not restricted and that large problem instances can be solved. The main disadvantage is the lack of accuracy. Fig. 4.1 shows the proposed concept, where based on the pre-chosen plan in each stochastic simulation a conditional optimal expansion plan is calculated. Because only the decisions in the flexible period can be changed by the algorithm, each pre-chosen plan is determined by its decisions in the fixed period. The thereby caused limitations of the degrees of freedom lead to different values of flexibility of each plan. Out of all plans with equal project values without flexibility the plan with the highest flexibility value is to be preferred.

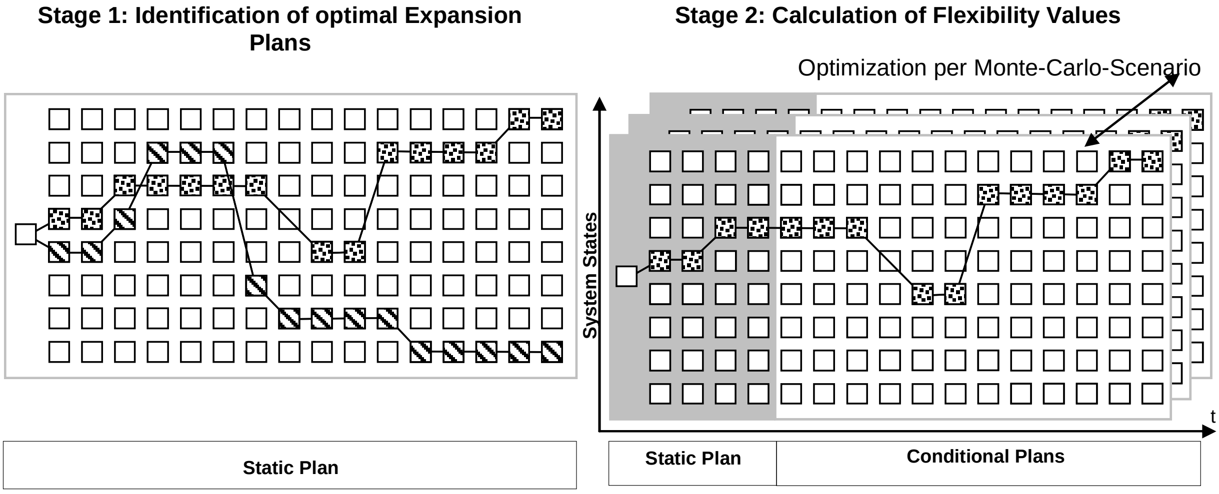


Fig. 4.1: Evaluation of Flexibility Values

4.2 Conceptual example

Existing approaches in network planning mainly deal with uncertainty in load and generation development. For simplification and in alignment with the focus of this paper, the presented model only incorporates regulatory uncertainty that is not been considered so far in network planning. Nevertheless, the chosen approach can also incorporate rather technical uncertainties as load development, useful life of equipment or construction time. The following uncertain regulatory parameters are modeled in the presented example:

Table 4.1: Uncertain Regulatory Parameters

Parameter	**Probability distribution**
regulatory return on equity	geometric Brownian movement initial value = 10,53% Δt = 1 Sigma = 0,1 Drift = 0
healing of the time delay problem	Cumulated probability: 2013 = 20% 2014 = 50%
start of yardstick regulation	Cumulated probability: 2019 = 50% 2024 = 100%
X-gen in the third regulatory period	Cumulated probability: -1,0% = 25% 0% = 50% +1,0% = 25% (from 2024 = 0%)

Fig. 4.2 shows the investment row of a computed expansion plan which has been chosen for further evaluation of flexibility. It is of note that only the decisions in the fixed period are finally fixed, all later decisions are conditional depending on the uncertain development of parameters.

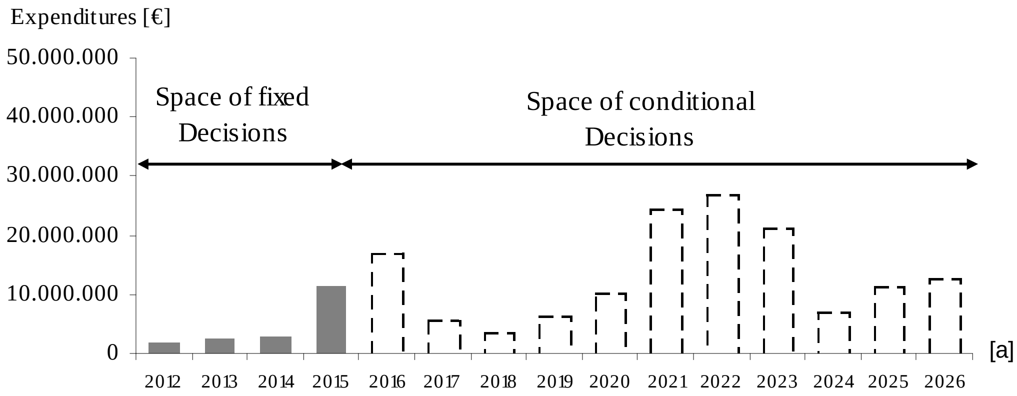


Fig. 4.2: Fixed and conditional Decision Space of the pre-chosen expansion plan

Based on one pre-chosen expansion plan the distribution of project values with flexibility and without flexibility is calculated. As can be seen in Fig. 4.3 the ability to react to future developments of uncertain parameters lead to a change in the distribution of expected project values. The difference between the mean value of the NPV without flexibility (-5,25 €) and the mean value with flexibility (-7,8 Mio. €) represents the value of flexibility in regulatory uncertain environments (+2,55 Mio. €) [37].

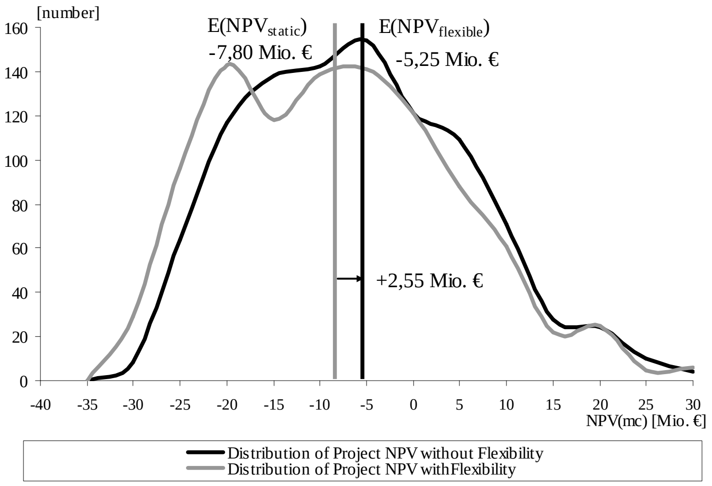


Fig. 4.3: Distribution of Project Values with and without Flexibility

5 Discussion and Outlook

With the presented approach, for the first time a value oriented economical calculus considering the effects of the German regulatory system is integrated with an optimizing model for the network expansion planning problem. By doing so, the model reflects the practical planning process in companies where investment strategies are developed in close cooperation between the asset management, controlling and regulatory department aiming at maximizing company values.

The model results confirm the theoretical predictions and empirical observations of regulatory economy science. As regulatory systems never can be perfect, minimizing costs does not necessarily lead to maximizing the company’s value in natural monopolies. A network expansion plan aiming at maximizing the Net Present Value of the investment program can significantly differ from a cost minimizing optimization depending on the expected regulatory framework. The model further shows that the ability of regulated companies for economical optimizations within a given system is restricted by technical constraints.

A second focus of the presented approach lies on the consideration of uncertainties and flexibility in the planning process. Since the application of standard methods for incorporating flexibility is limited due to the complexity and characteristics of the planning problem, a simplified evaluation method for European options based on stochastic simulation is proposed. In this context the model demonstrates that regulatory uncertainty leads to option/flexibility value and therefore is to be considered in network planning. The comparison of flexibility values of pre-chosen investment plans (expansion strategies) can especially be of significance when decisions/investment in the near future predestinates the development of the network for several years.

Due to the complexity of the underlying planning problem further work could advance the model on several layers. For example:

- From an economical point of view further work is necessary concerning the prognosis and modeling of uncertain regulatory parameters.
- From an operations research perspective future work should aim at the inclusion of the flexibility evaluation into the optimization algorithm leading to a one stage approach instead of the here presented two stage approach.
- From an engineering perspective the technical network model can be more detailed to better reflect the network planning models in use. In first experiments the here presented optimization model has already been connected via interfaces to a commercial network calculation tool.

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Appendix A

Variables

x_e := Decision variables representing the expansion plan

PV_{Ex} := Present Value of all cash outflow in network infrastructure

NPV := Net Present Value of Free Cash Flows

CF_{Ex_t} := Cash Outflow in network infrastructure

FCF_{E_t} := Free Cash Flow

i_{r_t} := Discount Rate

$b_{place,t}$:= Used equipment types at any places of the network at time t

$R_{node}(G_{ne}); R_{node}(G_{ne,\, failure})$:= Set of all sets of interconnected nodes in (n-0) and (n-1) cases in a given network structure

$V(G_{ne}); V(G_{ne,\, failure});$:= Set of all nodes of the network graph

$sl_{ds,t}$:= Length of each double spur line

$a_{ds,t}$:= Number of substations in each double spur line

$I_{n0_{conductor,t}}$:= Current in lines

$I_{n1_{failure,conductor,t}}$

$S_{n0_{transf,t}}$:= Rated power of transformers

$S_{n1_{failure,transf,t}}$

$U_{n0_{node,t}}$:= Voltage level in (sub)stations

$n1_{failure,node,t}$

$S''_{node,t}$:= Short circuit current in all nodes

Parameters

$I_{max\,n0_{linetype}}$:= Maximal Current Capacity of each line type

$I_{max\,n1_{linetype}}$

$S_{max\,n0_{transftype}}$:= rated power of each transformer

$S_{max\,n1_{transftype}}$

$U_{min\,n0}$ $U_{min\,n1}$ $U_{max\,n0}$ $U_{max\,n1}$:= Allowed range of voltage levels in stations

$S''_{min_{sgtype}}; S''_{max_{sgtype}}$:= Allowed range of Short circuit current

EH := Evaluation Period

OZ := Optimization period

max_length_t := Maximal allowed length of double spur lines in year t

max_st_t Maximal allowed number of substations in double spur lines in year t

Indices and sets of indices

$place; PLACE$:= Index and set of all places of equipment

t := Index of time

$ZBMK_{place,t}$:= Set of allowed equipment types at any place of the network at time t

$node; NODE$:= Index and set of nodes in the network graph

$failure; FAILURE$:= Index and set of all failure cases

$ds; DS(G_{ne,t})$:= Index and set of all double spur lines in a given network structure

$line; LINE$:= Index and set of all line

$tranf; TRANSF$ Index and set of all transformers