Optimal Investment Appraisal under Price-Cap Regulation

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Abstract

This paper develops a new methodology for evaluating the combined price and quality performance of new electricity network investments under price-cap regulation. The basic idea is to simulate a large number of possible network configurations and use these as the benchmark for evaluating the distribution firm's own investment proposal. The results of a case study indicate that the network simulation tool may provide the regulator with valuable information regarding the preferred network characteristics for the given supply area.

Keywords: Regulation; Quality; Electricity; Benchmarking; Investments.

JEL Classification: L15; L51; L94

1. Introduction

Background

This paper deals with the issue of integrating quality into a regulatory price-cap system when use is made of the building blocks approach. Under the building blocks approach, the firm proposes certain investments to the regulator who in turn needs to determine whether these should be charged to the consumers. Allowed investments are included into the Regulatory Asset Base (RAB) and prices reflect an allowance for their depreciation as well as a rate-of-return on these investments. Under an approach where the firm's returns depend on the level of investments allowed into the RAB, there is a risk of the overcapitalisation or Averch-Johnson effect. In this particular case, the Averch-Johnson effect takes the form of inflated investment projections. In the spirit of price-cap regulation, the firm has an incentive to reduce investment levels if it can retain (part of) the difference between the forecasted and actual investment level. This creates a natural tendency for the firm to inflate its investment proposals. That is, the firm increases its profits by inflating the size of the RAB but not necessarily undertaking these projected investments.

An important regulatory task under building blocks is to ensure that the firm invests at an appropriate level. This level should also be reflected in the determination of the RAB. At the same time, the regulator also needs to ensure that the investments undertaken by the firm provide consumers with a desirable quality level. However, due to his inferior information position, it is difficult for the regulator to evaluate whether a given investment proposal is effective. That is, to assess whether the investment is conducted in a cost-efficient manner and whether it results in a socially optimal level of quality.

Benchmarking is an important regulatory tool for dealing with the informational problem (Ajodhia 2006). Models for opex benchmarking are nowadays widely applied. The application of traditional benchmarking models (such as DEA) is however limited in the area of investment evaluation. The heterogeneous character of investments makes it difficult to construct a comparable and sufficiently large data sample. On the one hand, each investment is characterised by unique demand and supply conditions, which leads to substantial differences in both cost as quality performance. This makes it difficult to compare individual investments in a straightforward way. Although structural differences could possibly be captured in the benchmarking model, this would require an even larger sample size in order to maintain the discriminative power of the analysis. At the other hand, firms have some flexibility in the timing of the investment. This not only further reduces the sample size but also creates some scope for strategic allocation of investments over time.

The problem of evaluating investment performance is further complicated by the observation that it is important to consider the integrated costs and quality performance of the investment. Investments conducted at low costs may not necessarily be effective as they may provide consumers with too low quality. Similarly, very expensive investments may be associated with an oversupply of quality. The regulatory challenge lies in the integrated evaluation of both price and quality performance of each investment and in assuring an optimal balance between these two variables. Thus, investment appraisal is one of the areas where the regulatory informational disadvantage becomes most clear.

At the same time, capital costs generally form a substantial part of the firm's total costs and investment decisions have a significant impact on the network's quality. Ensuring that investments are undertaken at least costs and that they deliver a socially optimal quality level can generate significant benefits to society. A tool that enables the regulator to effectively measure the performance of investment proposals in both the price and quality sense is therefore an important regulatory asset.

The objective of this paper is to develop a benchmarking methodology that can be used for integrated price-quality assessments of network investments. In particular, the methodology considers investments in new distribution networks. This novel methodology is implemented in the form of a software tool programmed under Matlab – the Network Simulation Tool (NST). The NST is based on the idea of comparing the performance of the firm's investment proposal to that of a large number of artificially constructed alternatives. These alternatives are generated through simulation and represent possible solutions that the firm might have considered instead of the one being proposed. The performance of an investment is measured in terms of its total social costs (sotex), which is defined as the sum of network costs and interruption cost. Comparing the performance of the actually proposed investment and the artificially constructed alternatives provides information that can be used by the regulator to determine the RAB and subsequently set the X-factor under the price-cap scheme.

Paper Outline

This paper is structured as follows. Section two starts with a general description of the NST and reviews the NST in the light of existing network models. Section three presents a more detailed description of the NST. Section four applies the NST to a case study of a fictive Greenfield distribution network. Conclusions and policy implications are presented in section five.

2. General Design

Network Simulation Tool: General Design

Rather than comparing a given network investment proposal to other actual investments, the NST determines the possible alternative solutions for the investment under scrutiny, and evaluates whether these alternative solutions perform better than the proposed one. Starting from a given Greenfield supply area, the basic idea of the NST is to construct a large number of network designs and choose the most effective one from these. In constructing the network alternatives, as much as possible variation in characteristics of the networks are allowed thus increasing the probability of arriving at the true optimal network. If one could enumerate and evaluate all theoretically possible networks for a given Greenfield area, the best alternative could simply be identified and subsequently used as the benchmark. However, the total number of alternatives that need to be analysed tends to increase exponentially as a function of the size of the network. Consider for example a simple network consisting of 10 connections (e.g. cables) whose routing is fixed and where the only decision variable is the type of cable. If there are five possible cable types to choose from, the total number of networks would already be equal to 5^{10} = 9.7 million. If, in this simple example, a computation time of 10 microseconds per network is assumed, the total computation time for the analysis would be more than one day. If a more realistic network is considered, taking into account, for example, additional connections, routing possibilities, protection, variations in equipment types, the number of networks would increase at an exponential rate. For relatively small networks, the total number of possible networks to consider would quickly grow very large and lead to unpractical computation times.

An approach where one enumerates and evaluates all possible networks is not practical due to the constraints in computation power. It is however important to recognise that it is not necessary to consider all possible networks. The number of networks – and therefore computation time – can be substantially reduced by adopting a smart selection of networks. From the full set of all possible networks, only a small selection will be truly suitable for consideration in practice. Most networks will either be too expensive or provide a too low level of quality. Only a relative small portion of all possible networks will offer a proper balance between price and quality i.e. will be effective in the integrated price-quality sense. By limiting the analysis to these networks only, the number of network alternatives to be considered can be significantly reduced and hence computation time improved.

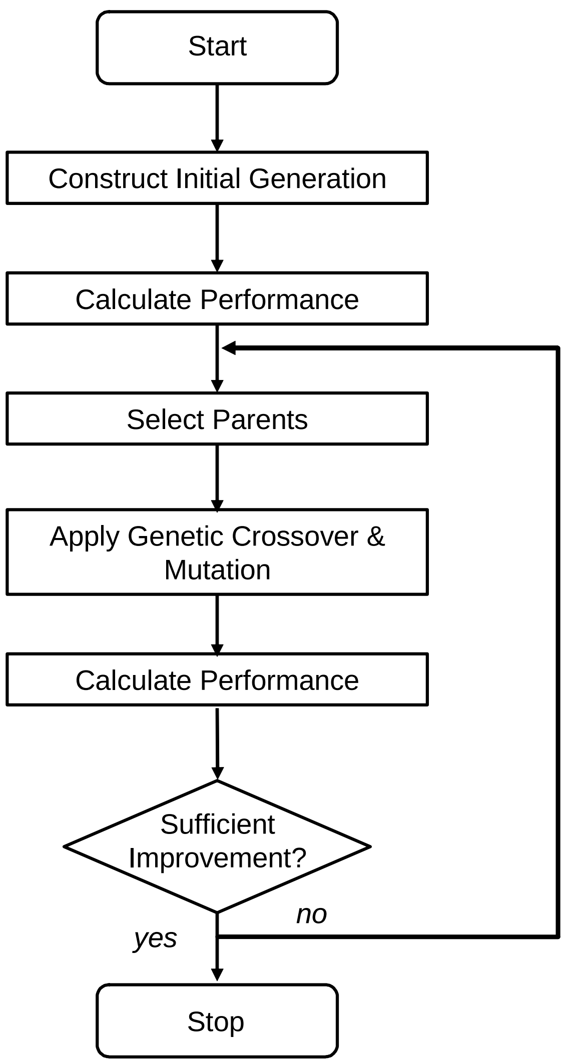

Figure 1. Basic steps of the NST.

Particularly, a faster convergence towards the theoretically optimal network can be realised by choosing an iterative approach where one narrows down the scope of the analysis to network types that exhibit superior performance. For this purpose, a genetic algorithm as shown in Figure 1 can be applied. The first step of the algorithm consist of constructing an initial set of networks that could be used for a given newly to be supplied Greenfield area. Each initial network has a given set of basic features, which may relate to aspects such as the number of feeders, the choice for a radial or meshed design, the type and quality of assets, the protection system, etc. In principle, as much flexibility in the basic features of networks is allowed in this stage of the process.

These initial networks are denoted the parents. In the next round, a new set of networks - the children - is constructed through the combination of parental networks. This new generation of networks inherits certain key features from the parent networks. However, not all initial networks are used in the process of creating the next round of networks. Each initial network is assigned a certain probability of being considered a parent network. Networks that exhibit superior performance – that is, have low levels of sotex – have a higher probability of being selected as parent than networks who perform poorly.

The construction of new networks takes place by using a genetic crossover technique where the basic features of the two parental networks are randomly combined in order to create a new network. Furthermore, for maintaining genetic diversity, a mutation operator is applied. Here, a certain probability is introduced for one or more basic features of the new network to change its value beyond the constraints of the genetic crossover.

Calculating the sotex performance of each network consists of three steps. Firstly, a reliability analysis of the network is conducted. From this, interruption costs experienced by consumers can be obtained. Secondly, the cost of the network itself is determined on the basis of the quantity and price of the network assets as well as the cost of losses. Finally, summing up interruption and network costs provides the measure of total social costs or sotex. The process of creating subsequent generations of networks is repeated for a number of times until no substantial improvement in the performance of networks is noticed.

Experiences with Network Models

The idea of using a model to construct artificial networks for benchmarking is not new. Network models for electricity distribution are, among others, used by regulators in Sweden, Chile, and Spain. These models are now briefly discussed.

The Swedish regulator has developed a network model known as the Network Performance Assessment Model (NPAM).[1] The NPAM constructs a single fictive network based on several input data regarding the geographical location of the loads, electricity consumption, and connections to other networks. The fictive network consists of multiple voltage levels. Starting with the low voltage network, consumers are grouped and connected to a transformer. This grouping is performed on the basis of different conditions such as the expected voltage drop and the consumer's distance to the transformer. Constructing the network starts by putting a transformer in the so-called electricity gravity centre for the given consumer group. Consumers belonging to this group are subsequently connected to this transformer. This process starts with the connection to the transformer of the consumer that is closest to it. Then, each subsequent consumer is connected to the transformer or to an already connected consumer, whichever is closest. This process is repeated for all groups until all the consumers within each group have been connected to a transformer. The same principle is then used to connect the different transformers to a transformer positioned in the electricity gravity centre of the next voltage level. Eventually, through this cascading approach, a fictive network is constructed which forms the basis for calculating network performance.

The calculation of the network performance, which is the main output of the NPAM, takes place in two steps. The first step provides the network cost. This consists of opex, capex, and network losses. Opex is estimated as the sum of administration, operation, and maintenance costs. The administrative cost is assumed proportional to the number of clients and covers the cost of meter depreciation, meter reading, invoicing, and processing. Other operational and maintenance costs are assumed proportional to the asset value. Capex is estimated on the basis of the purchase price of the assets in the fictive network and includes an allowance for depreciation as well as a rate-of-return. Network losses are estimated for each connection point using functions that depend on the density of the fictive network and are valued at a standard price.

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[1] At the time of writing, the Swedish regulator had not yet formally implemented the NPAM. See Gammelgard and Larsson (2003) or Larsson (2003) for a description of the Swedish network model.

The second step in calculating the network performance consists of calculating the quality cost. This is done by considering the interruption cost incurred by consumers on the basis of the reliability level they experience. The cost of quality is thus not derived from the quality performance of the fictive network, but from the actual quality level that consumers experience. The reason for this, according to Gammelgard and Larsson (2003), is that quality is regulated separately outside the NPAM. In determining the quality cost, a distinction is made between consumers based on the density of the network. The principle followed is that interruptions are more expensive for consumers located in dense networks (e.g. urban areas) and that unannounced interruptions are more expensive than announced ones. Based on this, the total interruption cost for the network is calculated. The network total performance is then defined in terms of the sum of the network cost and the interruption cost. This is the benchmark against which firms are compared and prices are envisaged to be set by the regulator.

In Chile, network models are an important aspect of the regulatory process. Here, an ideal firm is constructed based on the actual demand and the expected load growth. Rudnick and Raineri (1997) and Rudnick and Donoso (2000) provide descriptions of the Chilean network model. Starting from the existing grid configuration and assets, a model is applied to optimise the maintenance, operations, and management of the firm. The model takes into account fixed costs such as administration, invoicing and user service expenses as well as variable costs, which include network losses, investments, operational costs, and maintenance costs. In order to maintain comparability between firms, different network zones (high density, urban, semi rural and rural) are identified where each zone represents an area of homogeneous technical and economic conditions. For each firm, the network model determines the cost that would be incurred by an efficient firm supplying electricity to a mixture of zones corresponding to the actual firm. As far as known, quality is not directly considered in the optimisation process.

Both the Chilean regulator and the distribution firms perform optimisation studies using different sets of models. The cost corresponding to an efficient firm is defined as the weighted average of the regulator’s estimation of the optimal cost and that of the firm where the weights are set at 2/3 and 1/3 respectively. The results of these studies form the basis for determining the firm’s income. The models used for the analysis are however not public and the technical details of the calculation of the cost incurred by the model firm are not disclosed due to the highly detailed nature of the analysis. However, the fact that different studies are conducted and that these studies tend to generate different results indicates that there is not a common optimisation methodology but rather different methodologies are employed. For example, Rudnick and Raineri (1997) report that some firms claimed a level of optimal costs that was twice as high as the regulatory estimate. This is not surprising as one may assume firms to have an incentive to inflate their estimation of costs in order to receive higher revenues.

Under the Spanish regulatory framework, use is made of a network model known as BULNES (Sumicsid 2003). The BULNES model determines the optimal network cost for each distribution firm based on information regarding the geographical position of consumers, demand levels, and the connecting nodes to the transmission network. Using this information, optimisation algorithms are applied to determine the location of transformers, routing of lines and cables, etc. The cost of this optimal network is then derived using assumptions on the price of the assets and the unit cost of preventive maintenance, corrective maintenance, and operations. Furthermore, prices are adjusted to the particular case of each firm to reflect different conditions affecting the operation of the system that are related to ice, salt, precipitation, altitude, and rights of way. BULNES does not consider interruption costs incurred by consumers. Rather, reliability is considered in the form of the cost of carrying out corrective maintenance based on the expected number of interruptions and the associated repair costs.

The information provided by BULNES is used by the regulator to determine the efficient cost of distribution corresponding to each firm and to allocate the total revenues to be perceived by the distribution firms among them. Revenues are allocated proportionately to the efficient cost for each firm. The total income level for the industry is predetermined on the basis of agreements between the regulator and the industry. The purpose of the BULNES model is thus to allocate this income amongst the different firms rather than determine the absolute level of the income.

Another network model developed in Spain is proposed by Peco and Gomez (2000). This model is similar to the BULNES model except for the fact that it explicitly considers quality. The model constructs an optimal distribution network based on the exact geographical location of the consumers and their associated demand.

For each service area, the model constructs the optimal network and calculates the associated network costs. This optimal network links loads with generation sources assuming there are no equipment failures; its configuration is optimised as far as the cost of investments and losses are concerned. The optimisation process is subject to operational constraints on the feeder capacity and the magnitude of voltage drops. It makes use of heuristic algorithms that design a radial network linking sources and consumers. This network is built from scratch minimising both the investment and the cost of network losses. In doing so, possible constraints imposed by the geographical location of nodes (e.g. right-of-way) are also taken into account.

Once the optimal radial network has been obtained, a second optimisation process decides the number, location, and size of feeder reinforcements and new feeder sections that create alternative routes of supply to the loads. This process also determines the optimal level of investment in switching and protective devices. This second optimisation stage is aimed at minimising the total social cost associated with the network taking into account the cost of interruptions. During this process, network reinforcements are included and discarded until the sum of network and interruption costs cannot be further reduced, i.e. the least cost network from a social point of view has been obtained.

NST versus Traditional Models

There are several differences between the NST and the traditional network models mentioned above. The outcome of traditional models is a single network that results from an optimisation process. In contrast, the NST is not based on optimisation but rather on the principle of simulating a large number of networks, out of which the most optimal one can be selected. The advantage of this approach is that it recognises the limitations connected to the use of optimisation algorithms and leaves – in principle – full flexibility in the choice of network characteristics. In the literature, a number of algorithms for optimisation of the design of electricity distribution networks have been presented.[2] There are important differences between these algorithms as these are based on different assumptions regarding the desired network topology. The choice

[2] For an overview of optimisation algorithms in distribution network planning see for example Khator and Leung (1997) or Brown (2002) pp. 291-353.

of optimisation algorithm a priori constrains the outcome of the analysis. For example, certain algorithms only consider networks with a radial design thus automatically exclude meshed networks as a viable outcome. However, it may well be that in the particular case a meshed network performs better.

Another and perhaps more important feature of the NST is that it considers costs and quality in a fully integrated fashion. Networks are evaluated both in terms of their cost and quality performance. Traditional models either ignore quality or consider quality only in a second stage. For example, the Swedish model does not consider the quality performance of the optimised network but assesses the network performance on the basis of the number and duration of the actual interruptions experienced by consumers. The model by Peco and Gomez (2000) is the one that comes closest to being an integrated price-quality approach. Here, quality enters the analysis in the second stage by adjusting the network that was obtained in the first stage of the optimisation process. This is an important limitation as the outcome of the second stage of the process, where quality performance is considered, is conditioned by the outcome of the first stage. For example, a certain network may initially be regarded as expensive when only the cost side is considered but may well turn out to provide a better price-quality trade-off than other networks. This network might however not be considered in the second-stage of the analysis if it had already been discarded in the first stage.

The NST on the other hand considers price and quality performance simultaneously. The performance of a network is defined in terms of the total social cost. Subsequent networks are constructed and evaluated while optimising the total social cost. This allows the search process to consider all types of networks as long as their overall performance, as measured by the total social cost, is satisfactory. Table 1 summarises the main differences that exist between the NST and traditional network models.

Table 1. Summary of differences between traditional models and the NST.

	Basic approach	**Treatment of Quality**
Sweden (NPAM)	Cascading algorithm	No
Chile	Unknown	No
Spain (BULNES)	Optimisation algorithms	Indirectly
Spain (Peco and Gomez 2000)	Optimisation algorithms	Second stage optimisation
NST	Simulation	Integrated with price

3. Detailed Design

Construction of Initial Networks

The NST considers only the distribution network; transmission and low voltage networks as well as production facilities are excluded from the analysis. The assumption is that the network consists of one main feeding point (represented by a HV/MV substation) and a variable number of MV substations. Furthermore, loads are assumed to be represented by a number of MV/LV transformer stations. Each MV substation is supplied by the HV/MV substation through one or two primary feeders. The MV/LV transformer stations are in turn supplied by the MV substations via the secondary feeders. The location of the MV/LV transformers as well as information about demand characteristics are input data to the NST. Figure 2 provides a schematic representation of the type of system the NST is applicable to.

The construction of networks essentially takes the form of combining the basic features of two parent networks. These features can be represented in terms of a string of bits where each bit contains information about the network characteristics.[3] Generally speaking, two types of bits can be identified. Firstly, a number of bits represents key characteristics of the network. Secondly, a variable number of bits contains information about the connections in the network. This in turn consists of information regarding the existence of an electrical connection between two nodes as well as information about the type of connection assumed (e.g. cable or line and the capacity, reliability and resistance of that cable or line).

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[3] In genetic terms, this string of bits could be considered the network's chromosome.

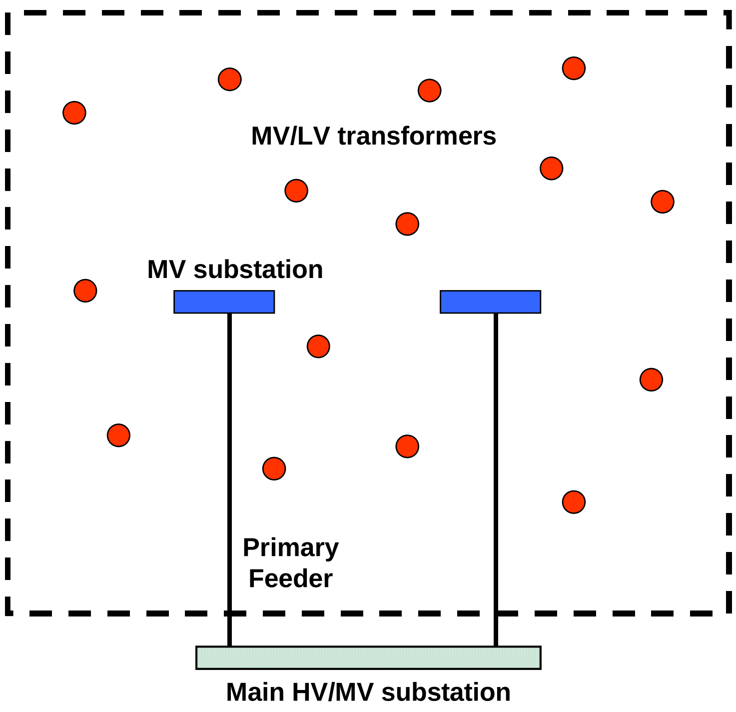


Figure 2. Schematic overview of the scope of the NST.

In the construction of new networks, the strings of bits of the two parental networks are randomly combined into a single one. The combination of bits – that is, the construction of the new network – however takes into account a number of constraints. To begin with, there is the adequacy constraint, which requires that all loads are supplied in the base situation, i.e. when no faults have occurred in the network. Furthermore, there are some physical constraints that need to be taken into account: The resulting current flows in the network will dictate the minimum capacity of each feeder and consequently limit the choice of the cable or line type. An overview of the possibilities regarding the key characteristics of networks is shown in Table 2.

Table 2. Overview of choices with respect to the key characteristics of the network.

Key characteristic	**Allowed Range**
Number of MV substations	1, 2, 4
Number of primary feeders per MV substation	Single or Double
Number of secondary feeders per MV substation	1 – 31
Basic network topology	Radial or Meshed
Protection for primary feeders	Yes / No
Protection for secondary feeders	Yes / No

By combining the key characteristics of the network as well as varying the routing within the network, different networks can be constructed. Each network will perform differently with respect to costs and quality. Generally, adding more redundancy to the network increases quality but also comes at an additional cost. For example, doubling the number of primary feeders leads to an increase in quality since a failure in one of the feeders no longer leads to an interruption (assuming that each feeder has sufficient capacity to supply all load). Similarly, increasing the number of secondary feeders leads to relatively shorter feeders. This at the one hand reduces the impact of an interruption while at the other hand, shorter feeders also lead to a lower probability of an interruption taking place in that feeder. Conversely, reducing protection increases the impact of the interruption while designing the network in a radial way results in longer interruptions due to the lack of possibility to reroute power flows in the case of interruptions.

Clearly, there are a large number of possibilities to choose from, but not every quality improving or reducing measure will be effective from the social point of view. The underlying idea of the NST is to consider the impact of these different choices regarding the design of the network and, on the basis of this information, enable the regulator to more effectively evaluate the performance of a given investment proposal.

Genetic Crossover and Mutation

For selecting networks that will act as parents for the subsequent generation of networks, a mix of the elitist class and tournament selection methods is used.[4] Under the elite class method, networks are sorted in order of their sotex performance and a selection is made of the best performers, which become part of the so-called elite. For example, the elite can be defined as the 10 percent best performing networks. This selection method makes sure that alternatives with relatively high performance (i.e. low levels of sotex) are always maintained as parents.

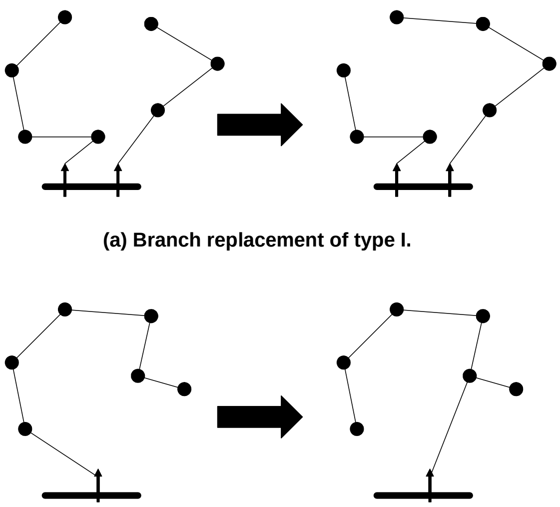
Table 3. Simplified example of genetic crossover to produce two children.

Key characteristic	Parent I	Parent II	Child A	Child B
Number of MV substations	1	2	1	2
Number of primary feeders per MV substation	1	2	2	1
Number of secondary feeders per MV substation	2	3	3	2

[4] See also Brown (2002, p. 311) for a description of these parental selection methods.

Basic network topology	Radial	Meshed	Radial	Meshed
Protection for primary feeders				
• Primary Feeder 1	Yes	No	Yes	No
• Primary Feeder 2		Yes	Yes	
Protection for secondary feeders	Yes	No	No	Yes

The elitist method however has the disadvantage that genetic diversity is reduced over time. To counteract this potential problem, an additional set of parents is selected through the tournament selection method. Here, a random selection of two networks is made and the one with least sotex is classified as a parent. The probability for better performing alternatives to be selected is thus higher while at the same time, poor performers still maintain a chance to be selected and transfer their genetic information to subsequent generations. Note that a given network may be selected as parent more than once. For example, an elite network is not excluded from participation in the tournament and thus may be selected under both the elitist class and tournament. Furthermore, a given network can also be selected multiple times under the tournament method.



(a) Branch replacement of type I.

(b) Branch replacement of type II.

Figure 3: Example of type I and type II branch replacement techniques.

Once parent networks have been chosen, a genetic crossover is applied to create a new generation of networks. Each combination of two parents produces two children. The binary string of the new network is determined by a random selection between the binary strings of the two parent networks. The new network thus inherits the combined characteristics of the two parent networks. An example of this procedure is shown in Table 3.

In addition to genetic crossover, the newly constructed network is exposed to mutation. The importance of mutation lies in the fact that it provides for a constant supply of fresh networks thus increasing genetic diversity. In this case, two types of mutation are applied. Firstly, a small probability is introduced for any of the network's main characteristics to randomly change its value. Secondly, mutation is applied to the network's routing scheme through branch replacement techniques. Here, the network's routing scheme is randomly reconfigured. Two types of branch replacements techniques are used. Changes of type I modify the network's routing such that a given load point is supplied through a different feeder. Here, only a single feeder segment is adjusted at one time. Under branch replacements of type II on the other hand, two feeder segments are modified at the same time. Each branch replacement takes into account the constraint that supply to all loads is maintained. Figure 3 provides an example of each of the two respective branch replacement techniques.

Reliability Analysis

The reliability analysis provides information about the frequency and duration of interruptions experienced by each consumer.[5] This information can then be used to calculate the level of interruption costs which is one of the components of the network alternative's sotex performance. For an individual consumer *i*, annual interruption costs *ic* can be defined as follows:

$$ic_i = ENS_i \cdot ICENS_i \tag{1}$$

And total interruption costs *ic* can be derived from:

$$ic = \sum_i ENS_i \cdot ICENS_i \tag{2}$$

Here, *ENS* stands for Energy Not Supplied and is the annual amount of energy not supplied to consumers. *ICENS* is the interruption costs incurred per kWh of *ENS* and is an input parameter of the NST. The annual *ENS* per consumer in turn can be approximated by:

$$ENS_i = f_i \cdot d_i \cdot PD_i \cdot LF_i \tag{3}$$

The frequency *f* and duration *d* of interruptions affecting consumer *i* are the output of the reliability analysis. The parameters *PD* and *LF* are input parameters and denote respectively the peak load and the load factor for

[5] For a detailed treatment of electricity network reliability analysis, see for example Meeuwsen (1998b).

consumer *i*.

For calculating the reliability performance of the network, a computer program named Distrel has been integrated into the NST.[6] Distrel is based on a probabilistic approach to reliability analysis that has as a starting point the failure of network components. This failure behaviour can be modelled as a Markov process. Here, a given network component is thought to be in either one of two states namely the UP-state (the component is functioning normally) or the DOWN-state (the component has failed). Moving from the UP-state to the DOWN-state means that the component fails and conversely, moving from the DOWN-state to the UP-state implies that the component has been repaired. Moving from one state to the other occurs with a certain probability and can be expressed in terms of the failure rate and the repair rate.

The failure rate reflects the probability of moving from the UP to the DOWN state and can be determined empirically by observing the actual performance of that component during a long period of time. If F_k is the number of failures of a component *k* observed during a predefined period (typically one year) and $t_{u,i}$ is the time a component *k* is in the UP-state, the failure rate can be defined as:

$$\lambda_k = \frac{F_k}{\sum_{i=1}^{F_k} t_{u,i}} \tag{4}$$

Once a component has failed, it will not remain in the DOWN-state but will be brought back to the UP-state by repairing it (or replacing the component by a new one). The repair rate reflects the probability of a given component to move from the DOWN to the UP state. From this, the repair time can be derived, i.e. the average time taken to repair the component. If $t_{d,i}$ is the time that the component *k* resides in the DOWN-state, then its repair time can be defined as:

[6] Distrel was developed by the Power Systems Laboratory of the Delft University of Technology. See Meeuwsen (1998a) for a detailed description of Distrel.

$$\mu_k = \frac{\sum_{i=1}^{F_k} t_{d,i}}{F_k} \tag{5}$$

In the case of meshed networks, there is usually the possibility to restore supply by means of rerouting power via alternative feeders. The faulted component can then be electrically isolated and repaired while supply is already restored. The time the component resides in the down state is then reduced. Generally, it is helpful to make a distinction between repair time and switching time where the latter replaces the former in case of rerouting possibilities.

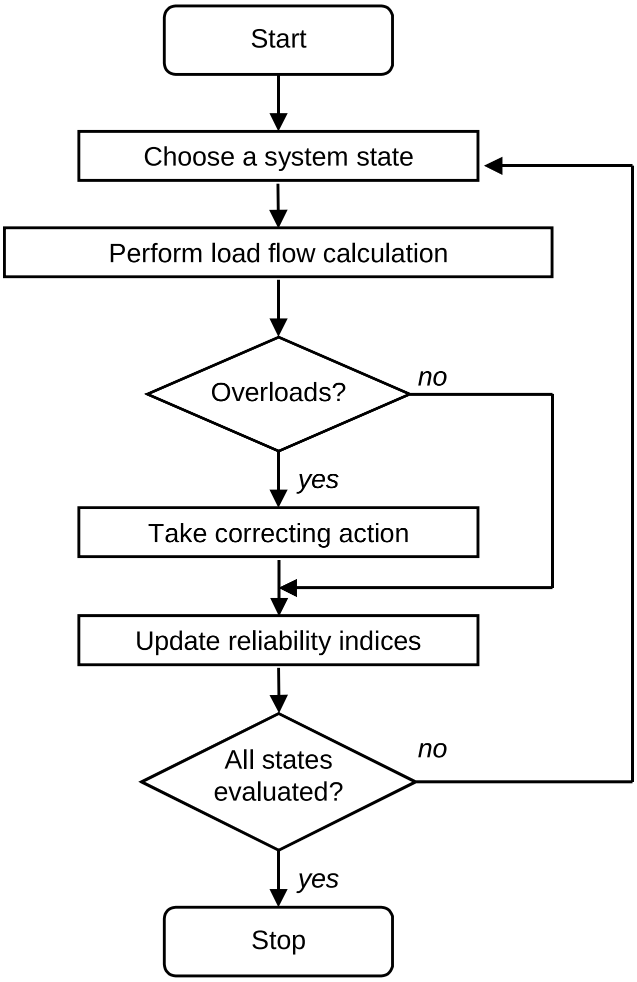


Figure 4. Basic steps involved in conducting a reliability analysis under Distrel.

The failure rate will generally not be constant but will vary with the age of the component. Typically, the failure rate behaves in line with the so-called bathtub curve with the probability of failure being higher during the early and later years of the component lifetime (Klaassen et al. 1988). In the intermediate period, which is the largest part of the component lifetime, the failure rate is more or less constant. For practical purposes, this constant failure rate is used in the application of reliability analysis. Similarly, the repair or switching time may vary as a function of different factors but for the purpose of the analysis is here assumed constant.

The failure and repair characteristics of an individual component represent the probabilities of moving from one state to the other. By considering all network components simultaneously, a system state can be defined. A system state is defined as a combination of the states of all individual components and consists of components being either in the DOWN or UP state. Each system state may or may not involve interrupted consumers. If the number of system states is equal to *N*, then probability *Pr* for a certain system state occurring can be derived by solving the following set of equations (Meeuwsen 1998a):

$$Pr(l)\cdot\sum_{m\in N}\tau_{lm}=\sum_{m\in N}Pr(m)\cdot\tau_{ml},\quad l=1,2,3,...\mathrm{N} \tag{6}$$

Here, *Pr* is the probability of a certain state to occur and τ_{lm} is the transition rate from state *l* to state *m*, which follows from the failure and repair times of the different components. The average duration *Du* of residing in a certain state is equal to:

$$Du(l)=\frac{1}{\sum_{m}\tau_{lm}} \tag{7}$$

And the frequency of being in that state is:

$$Fr(l)=\frac{Pr(l)}{Du(l)} \tag{8}$$

From this information, the cumulated interruption frequency and duration indices (respectively *f* and *d*) for each consumer can be obtained. The steps involved in carrying out this analysis are shown in Figure 4. Firstly, a certain system state – which is defined as a combination of the states of all individual components – is selected and it is assessed whether any consumers would be interrupted in the given system state. This can be done by conducting a load flow analysis. If a certain component (or combination of components) has failed, then this may or may not lead to any interrupted consumers. Furthermore, other components may become overloaded and thus correcting actions will need to be applied. This may also lead to additional consumers being interrupted as the system’s protection will automatically disconnect these overloaded components. The duration of the interruption in turn depends on the possibilities to restore power through switching actions or be driven by the time it takes to repair the faulted components. This process is repeated for all possible states in order to eventually determine the interruption frequency and duration for each consumer.

It is clear that, when the number of components increases, the number of system states grows exponentially and consequently, the computation time required to perform the reliability analysis may become very long. In order to reduce the computation time, here, only first order states are considered. That is, for a given system state, only one component is assumed to fail at any given point in time. By excluding states where multiple component faults occur, the number of system states to be analysed can be reduced substantially. At the same time, this does not have large impact on the accuracy of the results obtained, as the probability of two or more components failing at the same time is relatively low.[7]

Cost Analysis

The second part of the sotex evaluation consists of computing the costs of the network itself. Network costs can be divided into investment costs and the costs of losses occurring in network cables and lines. Investment cost comprises the cost of assets belonging to the following categories:

- Substation buildings;
- feeder bays including breakers and disconnectors;
- feeder protection systems;
- primary and secondary feeders (km cable or lines).

The number of substations, feeders, disconnectors, and protection systems follows from the network's configuration. For determining the length of the feeders, the distance between each pair of connected nodes (being either a MV substation or a MV/LV transformer station) needs to be considered. Feeders generally

[7] Note that in the case of a transmission network, the analysis of multi-order faults would be more important as the level of redundancy in these networks is typically higher.

follow roads, streets or property boundaries which means that the feeder's segments are built along a rectangular pattern of roads and streets rather than the shortest path between two given points (x_1,y_1) and (x_2,y_2). The Euclidean Distance consequently tends to underestimate the length of the feeder (Willis 1997, p. 291). Therefore, the Lebesque or "taxicab travel" distance ($|x_1-x_2|+|y_1-y_2|$) is used since it is a more reliable estimate of the length of the feeder.

The prices and volume of assets determine the total investment cost (*capex*) that will need to be recovered during the lifetime of the assets. Capex can be divided into two parts, namely depreciation and return. The depreciation costs refer to the initial purchase price of the asset while the return is associated with the capital costs of the asset. The costs of capital consist of both the costs of debt (interest) and the costs of equity (dividends). For comparison purposes, it is helpful to express capex in terms of an annuity. If a lifetime of *n* years is assumed, then the annual levelised *capex* for a given asset of type *a* can be given by Willis (1997, p. 209):[8]

$$capex_a = \frac{ror \cdot (1+ror)^n}{(1+ror)^n - 1} \cdot p_a \cdot q_a \qquad (9)$$

Where *ror* stands for the weighted average of debt and equity costs, *p* is the price of the asset and *q* is the number of assets installed.

In addition to investment costs, the firm will also face the costs of network losses. Due to the inherent resistance of connections, there will be ohmic losses in the network. The losses for each connection *c* can be approximated by Willis (1997, p. 32):

[8] Note that the impact of taxes is ignored. Furthermore, the assumption is that the complete investment is undertaken at a single moment in time. In reality, the construction time of a new network may span a significant period of time with some assets being installed earlier than others. Given however that the time scope of the analysis is very long (the lifetime of assets in electricity distribution is typically around 30 years), the impact of this assumption will be restricted.

$$losses_c = \hat{I}_c^{\,2} \cdot \Omega_c \cdot 8760 \cdot LF_c^{\,2} \tag{10}$$

Where $\hat{I}c$ stands for the peak current through the connection in normal operating conditions, Ω is the resistance of the connection, and *LF* is the load factor. The cost of losses can be calculated by multiplying the total amount of losses (in kWh) by the purchase price per kWh for these losses. Assuming a fixed price per kWh, the expression of total network cost then becomes:

$$nc = \sum_a capex_a + p_L \cdot \sum_c losses_c \tag{11}$$

Where p_L is the price paid for one kWh of losses. The annual social cost of the network can finally be defined as follows:

$$sotex = ic + nc \tag{12}$$

4. Case Study

Input Data

The NST has been applied to a fictive Greenfield supply area of 10x10 km consisting of 58 consumers (represented by MV/LV transformer stations) serving clusters of residential and commercial consumers. Figure 5 provides a schematic overview of the Greenfield supply area.

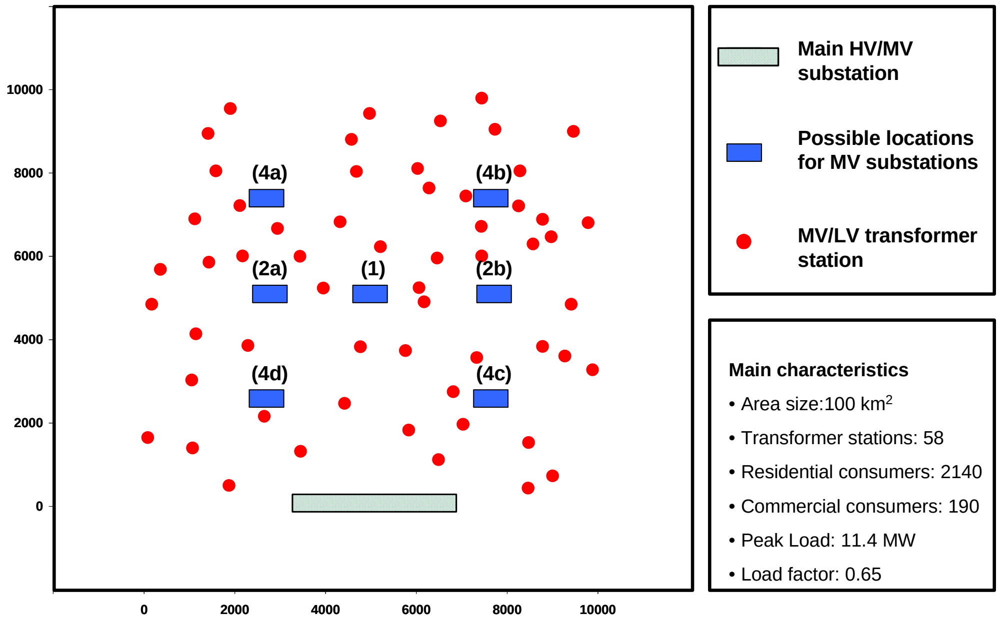


Figure 5. Overview of Greenfield supply area. Distances are in metres

As the analysis deals with distribution networks only, industrial consumers are excluded from the analysis. Residential consumers and commercial consumers are supplied by 250 kVA and 400 kVA transformers, respectively. A peak load of 5 kVA and 40 kVA for these two respective consumer types is assumed. In total, the distribution network serves 2140 residential and 190 commercial consumers. This results in a non-coincidental peak load of around 15 MVA. In reality, not all consumers will demand their peak load at the same time. To capture this effect, the non-coincident peak load is multiplied by a coincidence factor of 0.8, which brings the coincident peak load to approximately 12 MVA. Furthermore, a power factor of 0.95 is assumed, which results in an active power coincidental peak of 11.4 MW. Throughout the analysis, a load factor of 0.65 is assumed.

The MV/LV transformers are supplied via the MV substations and are defined as input data for the model. The number of MV substations is a decision variable in the analysis and can be either one, two or four. The location of these MV substations depends on this number, the different options are shown in Figure 5 for each of the three respective cases of one, two or four MV transformers.

Each MV substation in turn is supplied by a single main HV/MV substation whose location is fixed at 5000 metres below the centre of the supply area. The network consists of underground cables only. The assumption is that each two kilometres of cable contains one joint. Joints connect two parts of a cable within the network and are also subject to failure. Thus, the inclusion of joints decreases the reliability of the network.

Information on prices for network components has been obtained from Ajodhia (2006) and inflated to 2005 levels. A rate-of-return of 10 percent and a lifetime of 30 years has been assumed for all assets. Table 4 shows the price of the different network components as well as the value assigned to network losses.

Table 4. All-in prices for different network components and network losses.

Component	Price	Unit
MV substation building	70,000	EUR / station
Network Cable – AL95	45	EUR / m
Network Cable – AL240	80	EUR / m
Network Cable – AL400	90	EUR / m
Network Cable – AL630	130	EUR / m
Primary feeder breaker	39,000	EUR / feeder
Secondary feeders breaker	11,000	EUR / feeder
Feeder protection	8,000	EUR / feeder
Disconnector	4,000	EUR / disconnector
Network Losses	35	EUR / MWh

Component failure data are obtained from Dutch statistics and are based on a compilation by Meeuwsen (1998a). Table 5 shows the failure rates and repair and switching times assumed for cables and joints. All other components (e.g. breakers, rail sections, and protection systems) are assumed perfectly reliable.

Table 5. Failure data for cables and joints used in the case study.

Component	Failure Rate	Repair Time	Switching time
Cables	0.0018 outages / km per year	24 hours	1 hour
Joints	0.0023 outages per year	8 hours	N/A

For the calculation of interruption costs, use has been made of the value of non-delivered energy as applied by the Norwegian regulator NVE (Langset et al. 2001). A distinction is made between residential and commercial consumers. Table 6 shows the cost per kWh of non-supplied electricity for each type of consumer.

Table 6. Interruption cost data used in the case study.

Consumer Type	Interruption costs per kWh non-supplied
Residential	0.40 EUR / kWh
Commercial	4.50 EUR / kWh

Simulation Results

Total calculation time for the case study is about one hour when the model runs on a PC with a Pentium 4 (1.8 GHz) processor. The result of the analysis for the given Greenfield supply area is shown in Figure 6, which displays the annual sotex for each network alternative as a function of quality (measured by SAIDI). This Figure also provides an approximation of the sotex curve, which can be drawn by enveloping the points representing those networks whose sotex is lowest for a given quality level. The form of the curve is in line with expectations. Starting from a high quality level (SAIDI = 0) and moving to the right (higher SAIDI levels), sotex levels first decrease and then increase once the optimal quality level is reached. The sotex curve as drawn here should however be interpreted with care since its shape is biased by the genetic algorithm. In reality, the sotex curve is likely to be less steep than shown in the Figure.

As can be observed, the best performing network alternative has a SAIDI performance of about 3.2 hours per year and an annual sotex of around 430,000 EUR per year. Figure 7(a) shows a schematic representation of the best performing network alternative. As maybe observed, this network has a radial design and consists of a single MV substation and a single primary feeder. In terms of social costs however, the difference between the best performing and subsequent performing networks is very small. This is also shown in Figure 7 where the three subsequent performing networks are also shown.

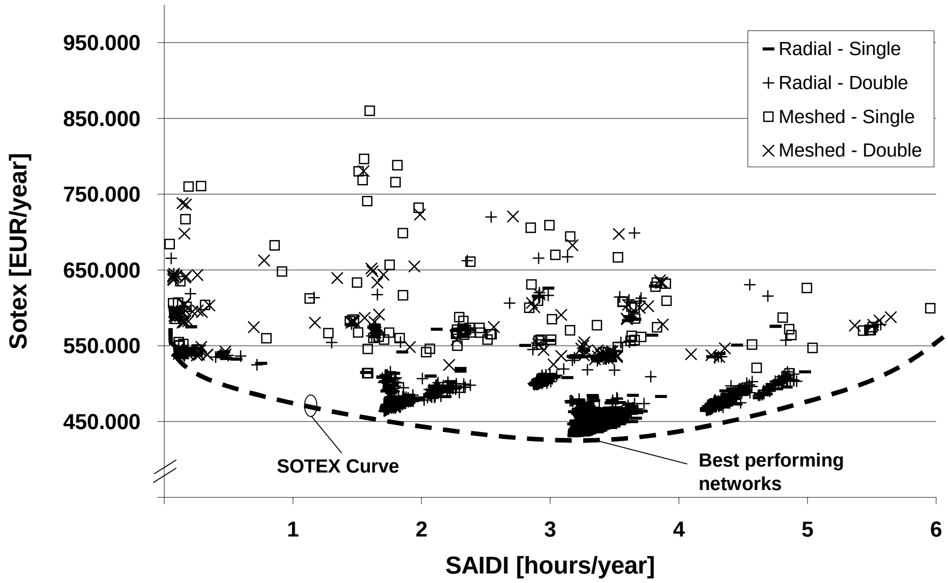
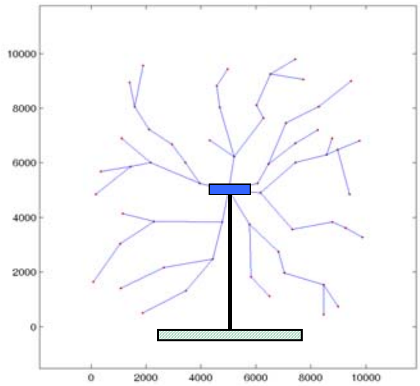


Figure 6. Sotex and quality performance of each (type of) network alternative.

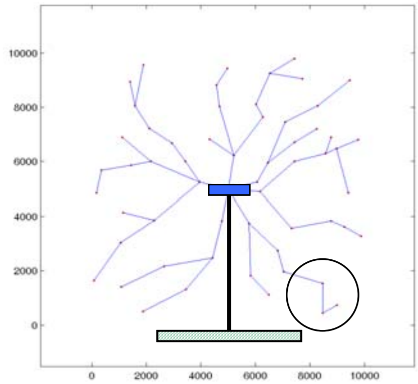
As can be observed, all four networks have the same main characteristics; there are only marginal differences in the routing of these networks. Inaccuracies resulting from uncertainty about the input data and modelling assumptions are likely to eclipse such small differences. Also, due to the partially stochastic nature of the search process, the optimal network, i.e. the best performing network alternative will in principle always be (slightly) different each time the same analysis is performed. Considering these factors, it does not seem appropriate to consider the resulting best performing network as the true optimal one. Rather, the main outcome of the analysis should be an identification of the characteristics of an optimal network.

In this respect, it is helpful to make a classification of networks along two dimensions, namely whether the network consists of radial or meshed feeders, and whether a single or double primary feeder is being used. A graphical presentation of the performance of the four resulting classes of networks is provided in Figure 6. The average performance of each class of networks is presented in Figure 8. As can be seen, the quality performance of radial networks is – on average – lower than that of meshed networks. This is caused by the shorter average restoration times. When a network is meshed, there is the possibility to reroute power flows if an interruption occurs. This causes the duration of an interruption to decrease. On the other hand, meshed networks are more expensive than radial ones. There are two reasons for this. Firstly, a meshed design consists of more connections than a radial network. Secondly, the capacity of connections in meshed networks is typically higher than in a radial network in order to enable the rerouting of power flows in the case of a fault. If a certain feeder is rerouted, the loading of the feeder segments that remain in operation generally increases. This leads to the need to install feeders of higher capacity in meshed networks and therefore leads to higher costs.

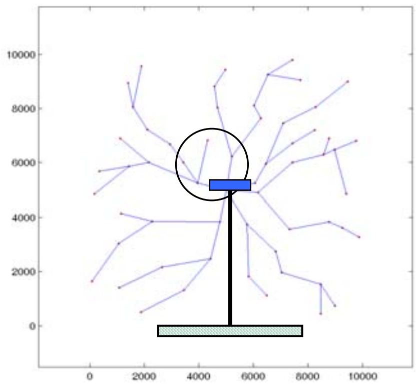
For the given Greenfield supply area, the difference between radial and meshed networks in terms of network costs is, on average, around 150,000 EUR/year. On the other hand, the decrease in interruption costs when choosing a meshed network instead of a radial one averages only 26,000 EUR/year. Thus, for this particular supply area, it seems uneconomic to opt for a meshed design since the reduction in interruption costs does not outweigh the additional network costs. Although there may be individual meshed networks that perform better than certain radial ones, radial networks on average provide a better price-quality trade-off. Furthermore, as can be seen in Figure 6, networks that are close to the bottom of the sotex curve are primarily of a radial design.



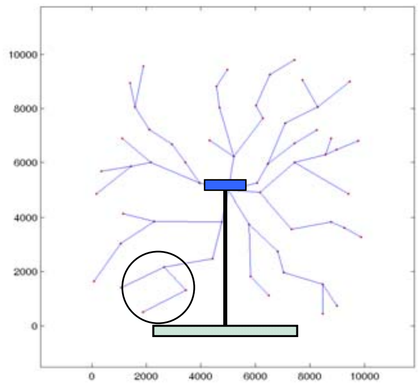
(a) Alternative #1



(b) Alternative #2



(c) Alternative #3



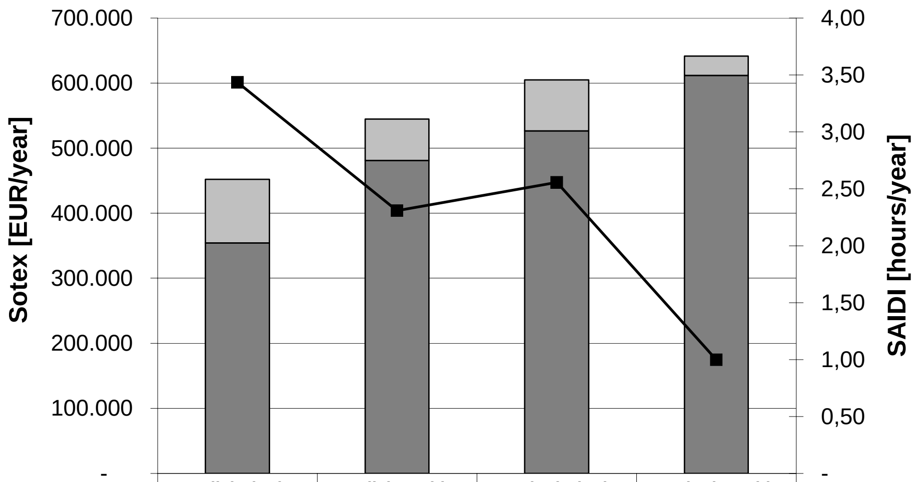
(d) Alternative #4

Alternative:	1	2	3	4

Number of MV substations	1	1	1	1
Basic Topology	Radial	Radial	Radial	Radial
Number of primary feeders per MV substation	1	1	1	1
Total number of secondary feeders	6	6	6	6
Protection Primary Feeder 1	1	1	1	1
Protection Primary Feeder 2	1	1	1	1
Protection for secondary feeders	1	1	1	1
SAIDI	3.19	3.19	3.19	3.19
Network Costs	342,108	342,009	340,091	342,285
Interruption Costs	89,217	89,395	91,314	89,134
Sotex	431,320	431,404	431,404	431,419

Figure 7. Overview and main characteristics of the four best-performing network. The circles indicate the difference between the best and subsequent performing networks.

A similar comparison as above can be made between networks with a single or a double primary feeder. Installing an additional primary feeder between the main HV/MV substation and the MV substations leads to an increase in quality as faults in one of the primary feeders no longer result in an interruption. If one primary feeder fails, electricity can still be supplied through the second feeder. However, the associated decrease in interruption costs (approximately 40,000 EUR/year) is not sufficient to cover the cost of the second primary feeder (approximately 105,000 EUR/year). This suggests that, in this particular case, installing a single primary feeder is the most efficient option as this represents a better trade-off between cost and quality.



	Radial-Single	Radial-Double	Meshed-Single	Meshed-Double
Sotex	452.061	544.789	605.023	641.519
Interruption Costs	97.627	63.677	78.441	29.761
Network Costs	354.434	481.112	526.581	611.759
SAIDI	3,44	2,31	2,56	1,00

Figure 8. Summary of results for four classes of networks.

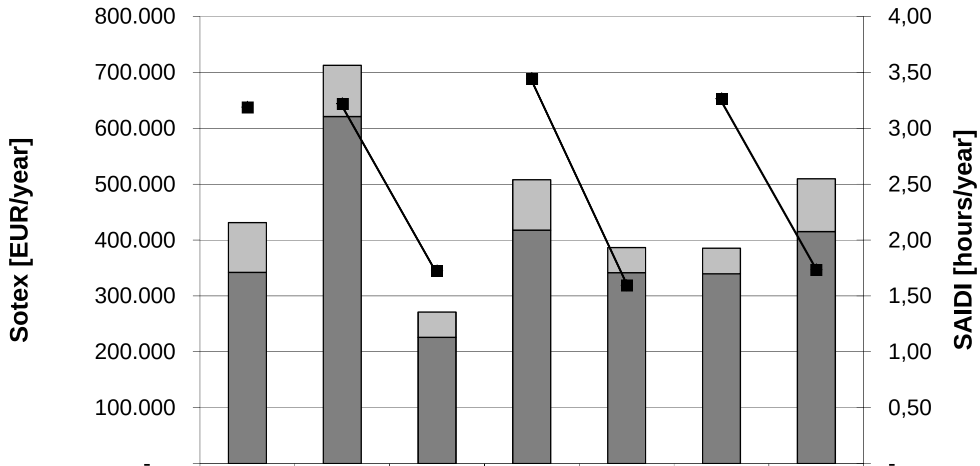
In summary, a radial network comprising a single primary feeder is the network design that best adapts to the Greenfield supply area given. This type of network provides the best trade-off between quality and cost. As can be seen in Figure 7, such a configuration results in a SAIDI value of 3.2 hours per year and a sotex value around 430,000 EUR/year. Using this information, the regulator would be able to evaluate the firm's investment proposal in a more effective way. For example, if the firm proposed a meshed network with double primary feeders, the regulator could argue that – even though that design would lead to a higher quality level – the firm's proposal will be too expensive from the social point of view. On the other hand, if the main characteristics of the network proposed by the firm are similar to those of the best networks identified by the NST tool but the cost of the former is significantly higher than that of the latter, the regulator could request the firm to explain this difference.

Sensitivity Analysis

The outcome of the NST is conditioned by a number of assumptions regarding the input data. More specifically, prices and failure parameters of network components play a key role. The same also holds for interruption cost data. A change in these input parameters can influence the outcome of the analysis. In order to assess the sensitivity of the optimal price-quality trade-off with respect to these parameters, a number of scenarios have been analysed. Eight additional scenarios have been created where the input parameters have been either increased or decreased by a factor of two. The input parameters whose effect on results has been monitored are prices of network components, the failure rate of cables and joints, the repair and switching time of cables and joints, and the interruption costs per kWh. Figures 9 and 10 graphically illustrate the impact of the change in input parameters on the price-quality trade-off. An overview of key results, as compared to those for the base scenario, is shown in Table 7. A discussion of the results now follows.

Decreasing the price of network equipment leads to an increase in the optimal quality level i.e. a lower SAIDI level. If prices are low enough, it becomes economic to install additional primary feeders. This leads to an increase in reliability since interruptions affecting a primary feeder no longer result in interruptions. A decrease in equipment prices thus leads to an increase in the optimal quality level. From a more general point of view, reducing network costs leads to socially better outcomes, which comes in the form of lower prices and higher quality levels. If the firm is able to operate in a more efficient manner, the cost of adding redundancy to the network decreases and consequently quality goes up. In the converse case, i.e. if the firm is operating less efficiently, then it becomes more expensive to provide a higher quality level. Overall, consumers then pay more while they are provided with relative lower levels of quality.

In this particular case, an increase in equipment prices has little impact on the optimal quality level relative to the base case. The explanation for this is the limited possibilities to further reduce the redundancy of the network. The main cost saving measure that could be taken is removing protections from feeders. This however has a substantial negative impact on quality while the associated cost savings are relatively low. As may be observed, doubling component prices does not justify undertaking savings on protection as the resulting increase in interruption costs would then exceed the decrease in network construction, operation and maintenance costs.



	Base Case	Expensive	Cheap	Low Reliability	High Reliability	Low Quality Demand	High Quality Demand
Interruption Costs	89.217	91.527	45.509	90.423	45.006	45.569	94.128
Network Costs	342.108	621.016	225.731	417.769	341.583	339.650	415.290
SAIDI	3,19	3,22	1,73	3,45	1,59	3,26	1,73

Figure 9. Optimal price-quality trade-off under different scenarios.

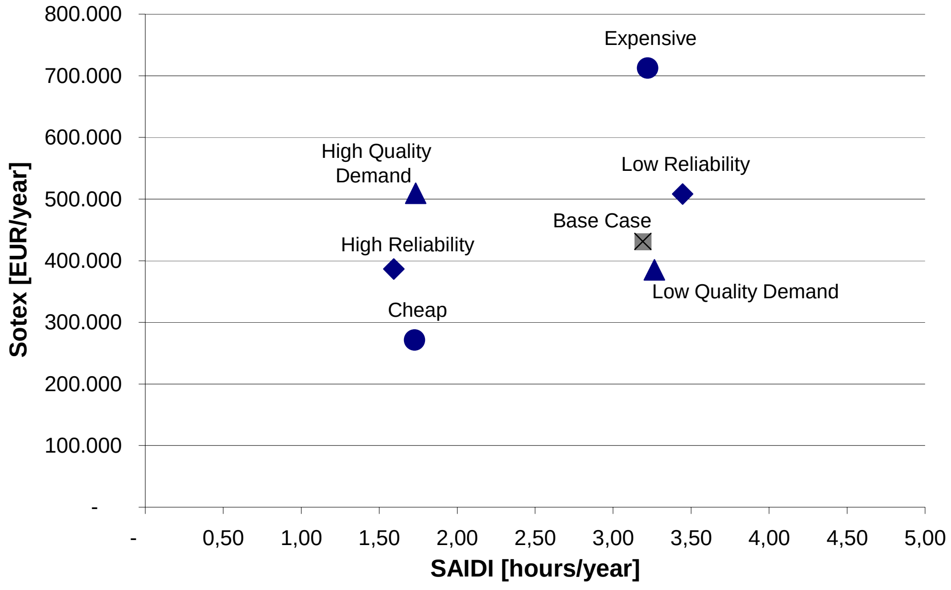


Figure 10. Graphical representation of the optimal price-quality trade-offs under different scenarios.

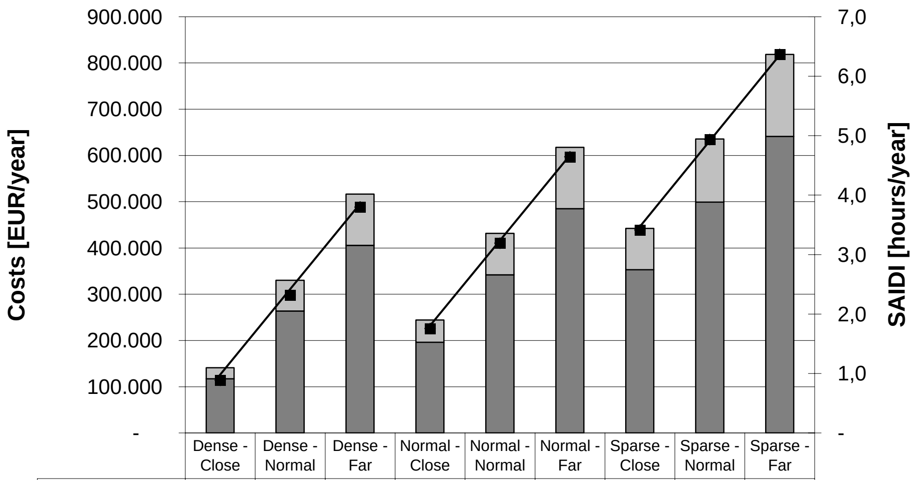
Increasing the failure rate and repair and switching times of network components leads to respectively more frequent and longer interruptions. On the one hand, a higher failure rate implies that components fail more frequently and therefore, the probability of an interruption to occur also increases. Increasing the repair and switching time of components means that it now takes longer to restore supply either by repairing the component or through rerouting measures. Less reliable components thus lead to an increase in interruption costs. Being confronted with low quality components, at some point it becomes economic to increase the redundancy by installing an additional primary feeder. This can be interpreted as follows. The primary feeder has substantial impact on the overall quality of the network as a fault in this feeder results in an interruption affecting all consumers. If the reliability of the primary feeder decreases, then the frequency and duration of faults affecting this feeder increases accordingly. Consequently, interruption costs increase and it becomes more economic to invest in a second primary feeder. This leads to a substantial improvement in service quality as a fault in a single feeder no longer causes interruptions. In this particular case, net savings are high enough to justify the investment in an additional primary feeder.

Overall, however, consumers are still worse off if component reliability is lower. At the one hand, the optimal quality level is reduced (due to less reliable network components) while at the other hand, network costs increase due to the investment in an additional primary feeder. This is in line with expectations since the use of less reliable network components (at constant prices) makes the provision of quality more expensive; this implies a lower optimal quality level. Conversely, the use of more reliable network components – represented by a decrease in the failure rate and repair and switching times – leads to an increase in the optimal quality level while total network costs remain more or less the same. At the same time, interruption costs are now lower and this leads to a net reduction in the total level of sotex. Consumers thus benefit in the sense that they are provided with a higher quality service for the same cost. Note also that the use of high quality components reduces the need to add additional redundancy to the network. For example, doubling the number of primary feeders leads to a relatively small increase in quality if the reliability of the feeder is very high. The additional feeder would however still come at significant costs.

Scenario	Base Case	Equipment Price		Failure Rate		Repair / Switching Time		Interruption Costs	
		Expensive	Cheap	Low Reliability	High Reliability	Low Reliability	High Reliability	Low Quality Demand	High Quality Demand
Nr. of MV substations	1	1	1	1	1	1	1	1	1
Basic Topology	Radial	Radial	Radial	Radial	Radial	Radial	Radial	Radial	Radial
Nr. of primary feeders per MV substation	1	1	2	2	1	2	1	1	2
Nr. of secondary feeders	6	6	7	7	6	7	6	5	7
Protection Primary Feeder 1	1	1	1	1	1	1	1	1	1
Protection Primary Feeder 2	1	1	1	1	1	1	1	1	1
Protection for secondary feeders	1	1	1	1	1	1	1	1	1
SAIDI [hours/year]	3.19	3.22	1.73	3.42	1.60	3.47	1.59	3.26	1.73
Network Costs [EUR/year]	342,108	621,016	225,731	416,985	341,078	418,552	342,087	339,650	415,290
Interruption Costs [EUR/year]	89,217	91,527	45,509	90,208	45,394	90,638	44,617	45,569	94,128
Sotex [EUR/year]	431,320	712,550	271,240	507,190	386,480	509,190	386,700	385,220	509,420

Table 7. Performance of best performing networks under different scenarios.

A change in consumer demand for quality is reflected in the level of interruption costs per kWh of non-supplied energy. An increase in quality demand can thus be approximated by increasing the level of interruption costs per kWh. As consumers place a higher value on quality, it becomes more economic to improve quality levels as the costs to do so are less than the resulting benefits. In this case, the cost of adding a second primary feeder leads to a reduction in interruption costs, which justifies the cost of that extra feeder. The increasing demand for quality justifies the fact that now consumers have to pay a higher price for the distribution service. On the other hand, if interruption costs decrease, the optimal quality level and network costs decrease as well thus leading to a net improvement in sotex levels.



	Dense - Close	Dense - Normal	Dense - Far	Normal - Close	Normal - Normal	Normal - Far	Sparse - Close	Sparse - Normal	Sparse - Far
Interruption Costs	23.652	66.566	110.750	47.973	89.217	132.800	89.509	136.530	177.110
Network Costs	117.467	263.470	405.560	196.222	342.108	484.920	352.919	499.054	641.330
SAIDI	0,9	2,3	3,8	1,8	3,2	4,6	3,4	4,9	6,4

Figure 11. Results for the best performing network alternative under different density and distance scenarios.

Apart from assessing the impact of changing parameter values on the outcome of the analysis, it is also interesting to look at the impact of changes in the structural characteristics of the supply area itself. Two factors have been considered, namely the density of demand and the location of the main HV/MV substation. With respect to demand density, two cases can be identified namely a “dense” network and “sparse” network. These two cases respectively correspond to a situation where the size of the supply area has been respectively contracted and expanded by a factor two. With respect to the location of the HV/MV substation, the distance of this substation to the centre of the supply area has been modified. In the base case, the HV/MV substation is located 5,000 metres below the centre of the supply area. For the purpose of the sensitivity analysis, this distance has been changed to 10,000 metres in one case and zero metres in the other.

These two cases are denoted as “close” and “far”, respectively. Only the vertical position of the substation has been modified; the horizontal position has been maintained at the centre of the supply area.

The results reveal that changing the load pattern or the substation position does not alter the basic characteristics of the optimal network for the Greenfield area under consideration. The best performing alternative remains a radial network with a single primary feeder in all cases. However, the changes do have some impact on the trade-off between cost and quality. As shown in Figure 11, moving the HV/MV substation further away from the supply area centre leads to higher network costs as well as higher interruption costs. Longer distances imply longer cables and therefore higher cable costs. At the same time, the probability of a failure increases with the length of the cables and therefore leads to a decrease in service quality. It however remains uneconomic to install an extra primary feeder. The costs of this extra feeder are still higher than the accrued benefits in terms of a decrease in interruption costs.

The effect of demand density on results has also been assessed. Demand density can be defined as the average distance between loads and the centre of the supply area. As can be observed in Figure 11, network costs decrease in the case of a dense network as the average length of feeders is reduced. At the same time, shorter feeders also lead to an improvement in quality. Sparse networks on the other hand are more expensive due to the longer distances that feeders need to cover. In addition, there is a decrease in quality as the probability of a feeder being exposed to a fault is also higher due to longer feeder length. A supply area with high load density is thus more attractive to serve as this can be accomplished at relatively lower costs while at the same time, a higher quality level can be obtained.

5. Conclusions

This paper has developed a new methodology for evaluating the combined price and quality performance of a new network investment under the building blocks framework. The basic idea is to identify the best possible network design for a given supply area and use this as the benchmark for evaluating the distribution firm’s own investment proposal. The results of the case study indicate that the NST may well be an important tool in the process of investment appraisal. The NST can provide the regulator with valuable information regarding the preferred network characteristics for the given supply area. What is more, it allows the regulator to analyse the impact of changes in input parameters and supply area characteristics on the price-quality trade-off. In doing so, the NST takes into account possible spatial differences in the demand for quality across the network. The resulting optimal network reflects a trade-off between price and quality for the system as a whole but, at the same time, considers the fact that consumers located in different places will place different values on the quality of service. Lastly, instead of considering cost and quality separately as other models do, the NST adopts an integrated approach in making the trade-off between these two aspects of network performance.

The limitations of the NST should however also be recognised. The NST is only a model and therefore an imperfect representation of reality. The outcome of the analysis is driven by the assumptions made in the modelling process. Similarly as with optimisation tools, simulation approaches like the NST run the risk of arriving at a local rather than a global optimum. Making fewer assumptions increases the probability of identifying the true optimal network but at the same time, also leads to longer computation times. Thus, achieving a trade-off between the realism and the practicality of the analysis is essential. In the face of the modelling restrictions, it is unlikely that the best network identified by the NST will coincide with the true optimal network. Furthermore, uncertainties in parameters as well as in the input data may adversely influence the NST outcome.

Recognising these limitations, it is more appropriate to consider the NST as a tool aimed at revealing information about a range of investments and the desirable properties of a network rather than providing an exact prescription of what should be the optimal network for a given supply area. For example, the NST results should not be used to discuss specific routing details of the network. Such specific considerations would also not fit within a price-cap framework and tend to lead to micro-management by the regulator. Rather, the detailed technical design of the network should be left at the firm’s discretion as long as it complies with the general constraints imposed on the basis of the information revealed by the NST.

Rather than getting involved in the details of the firm’s operations, price-cap regulation aims to provide socially desirable outcomes by means of sending incentives. In the spirit of price-cap regulation, it is not desirable for the regulator to intervene in the investment planning process of the firm but rather, to set price and quality targets that are considered appropriate from a social point of view. The NST provides regulators with an – albeit imperfect – instrument to obtain information about the performance of a given investment proposal. This can be realised without the need to perform detailed engineering assessments while the amount of data required for the analysis is relatively small. The information revealed by the NST can then be fed into the process of assessing the desirability of investments or, more generally, in the determination of the RAB.

References

- Ajodhia, V.S. (2006). "Regulating beyond price. Integrated price-quality regulation fof electricity distribution networks.” PhD dissertation, Delft University of Technology, Delft (forthcoming).

- Brown, R.E. (2002). "Electric Power Distribution Reliability." Marcel Dekker, Inc., New York, Basel.

- Gammelgard, M. and M. Larsson (2003). "The challenge of regulating natural monopolies in electrical distribution - Experiences from Sweden." Proceedings of CIRED 2003, Barcelona.

- Khator, S.K. and L.C. Leung (1997). "Power Distribution Planning: A review of models and issues." IEEE Transactions on Power Systems 12 : 1151-59.

- Klaassen, K.B., Van Peppen, J.C.L. and A. Bossche (1988). "Bedrijfszekerheidstechniek Theorie en Praktijk." Delftse Uitgeversmaatschappij, Delft.

- Langset, T., Trengereid, F., Samdal K. and J. Heggset (2001). "Quality Dependent Revenue Caps - A Model for Quality of Supply Regulation." Proceedings of CIRED 2001, Amsterdam.

- Larsson, M.B.O. (2003). "The network performance assessment model - Regulation with a reference network." Proceedings of the Elforsk Market Design Conference, Stockholm, 17 June.

- Meeuwsen, J.J. (1998a). "Handleiding Distrel." Technische Universiteit Delft, Faculteit Informatietechnologie en Systemen, Afdeling Elektrotechniek.
- Meeuwsen, J.J. (1998b). "Reliability evaluation of electric transmission and distribution systems." Technische Universiteit Delft, Delft.
- Peco, J. and T. Gomez (2000). "A Model for Planning Large Scale MV Networks considering Uncertainty in Reliability Modeling." Proceedings of PMAPS 2000, Portugal.
- Rudnick, H. and J.A. Donoso (2000). "Integration of price cap and yardstick competition schemes in electrical distribution regulation." IEEE Transactions on Power Systems 15 : 1428-33.
- Rudnick, H. and R. Raineri (1997). "Chilean distribution tariffs: Incentive Regulation." in: (De)Regulation. and competition: The electricity industry in Chile. Iiades-Georgetown Unversity pp. 223-257.
- Sumicsid (2003). "Norm models." Report to NVE, February.
- Willis, H.L. (1997). "Power distribution planning reference book." Marcel Dekker, Inc., New York, Basel.