Network Modelling for Regulatory Purposes

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1.1 Introduction

1.1.1 Background

This paper deals with the issue of integrating quality into the 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 or not these should be charged to the consumers. Allowed investments are included into the 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 can increase its profits by inflating the size of the RAB but this does not necessarily mean that it actually undertakes the projected investments.

An important regulatory task under building blocks is to assure 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 assure that these investments 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. Models for opex benchmarking are now widely applied by regulators. 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 suitable and sufficiently large data sample. At 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 by the inclusion of environmental factors in the benchmarking model, this requires an even larger sample size as otherwise the discriminative power of the analysis would be reduced. At the other hand, firms also 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 both 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 to assure an optimal balance between these two. Investment appraisal thus is one of the areas where the regulatory informational disadvantage becomes most clear. On the other hand, 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. Assuring that investments are undertaken at least costs and deliver a socially optimal quality level can generate significant benefits to society. The ability 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 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 the total social costs (sotex), which is defined as the sum of network costs and interruption cost. A comparison of the performance of the actually proposed investment and the artificially constructed alternatives provide information that can be used for determining the RAB and subsequently setting the X-factor under the price-cap scheme.

1.1.2Paper Outline

This paper is structured as follows. Section two starts by presenting the methodology of the NST. Section three compares the NST to other already existing network models. A case study of a fictive newly to build distribution network is presented in section four.

1.2 NST Methodology

1.2.1Basic Approach

Rather than comparing a given network investment proposal to other actual investments, the NST considers what possible alternative solutions for the given investment exist, and whether these perform better than the proposed one. If one could enumerate and evaluate all theoretically possible alternatives, the best possible alternative could be identified and subsequently used as the benchmark. However, the total number of alternatives that would need to be analysed tends to increase at an exponential rate. Consider for example a simple network consisting of ten connections (e.g. cables) whose location 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 network alternatives would already be equal to 5^{10} = 9.7 million. If, in this simple example, a computation time of ten microseconds per alternative were assumed, the total time for the analysis would be more than one day. If a more realistic network is considered, taking into account additional connections, routing possibilities, protection, variations in equipment types, etc. then the number of network alternatives would lead to unpractical computation times and make the analysis an unfeasible one.

It is however important to recognise that it is not necessary to consider all, but rather only a subset of the complete set of network alternatives. The number of alternatives – and therefore computation time – can be reduced through a strategic selection of network alternatives. Some (types of) networks will generally perform better than others for a given situation. Rather than considering all possible networks, one could focus only on these superior performing ones and consequently increase the effectiveness and speed of the analysis. More particularly, by choosing an iterative approach where each subsequent round a continuous improvement of network performance is achieved, a faster convergence towards the theoretical optimal network can be achieved. For this purpose, a genetic algorithm can be used where one set of network alternatives is used to construct a new generation of alternatives. Starting from information regarding the supply area and demand characteristics, an initial set of network alternatives (the first generation) is created. Out of this generation, a selection is made of fittest parents i.e. network alternatives that show potential for creating a next and better performing generation of network alternatives. Parental selection is based on performance as measured by the level of sotex for each network alternative. If sotex levels are lower, then the probability of being selected as a parent increases.

The parents of the first generation are used to construct the second generation of network alternatives (the children). Once the second generation has been created, the performance of these network alternatives is evaluated and a new selection is made of fittest parents which are then used to construct the third generation and so on.

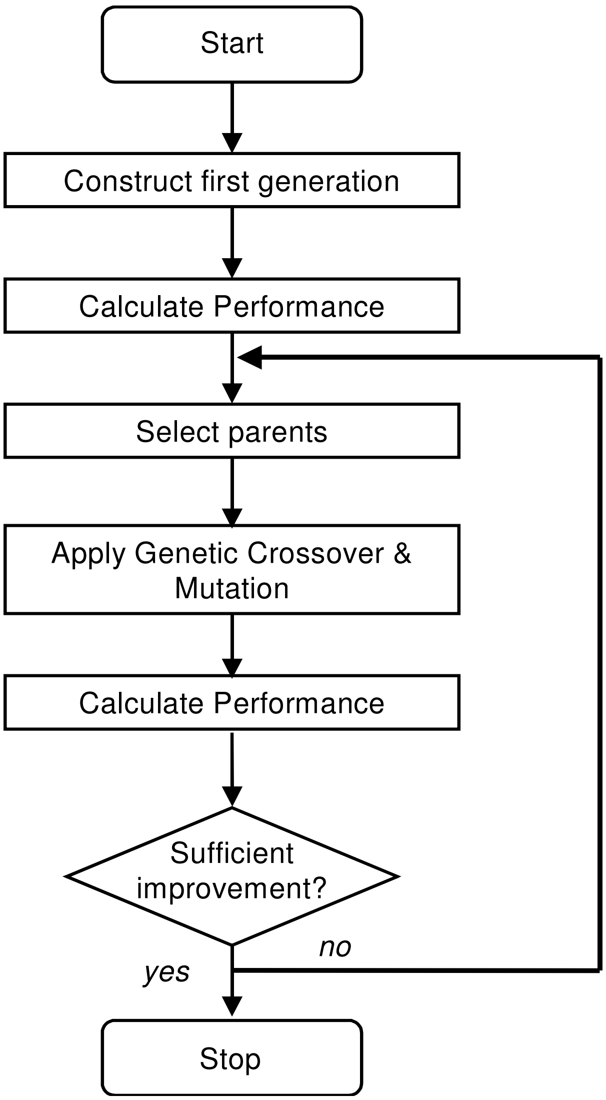


Figure 1. Basic steps of the NST

This process is continued until the improvement in the best performing network alternative has not improved after a certain number of generations.

The generation of subsequent generations of network alternatives takes place on the basis of a genetic algorithm. Each network alternative can be represented by a chromosome, which contains information about the network characteristic such as the type and configuration of equipment as well as the routing scheme of the network. Each subsequent round, combining the chromosomes of two parents creates a next generation of network alternatives. This is done through a genetic operator crossover where each child inherits a random mix of the chromosomes of two parent networks. Furthermore, in order to maintain genetic diversity, a mutation operator is applied where some elements of the child's chromosome are assigned a certain probability to change their value. A more detailed description of the NST now follows.

1.2.2 Construction of Network Alternatives

The NST constructs and evaluates the performance of a large number of possible network alternatives for a given Greenfield area. The NST considers only the distribution network; transmission and low voltage networks as well as production facilities are excluded from the analysis. The network is thought to consist of one main HV/MV substation and a variable number of MV substations. Furthermore, there are a number of MV/LV transformer stations, which represent the load of the network. Each MV substation is supplied by the HV/MV substation through the 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 for the NST.

As said earlier, the construction of network alternatives essentially takes the form of altering the chromosome of two parent networks. This chromosome contains binary encoded information about the key network characteristics and consists of two main parts. Firstly, a total of thirteen bit positions representing the basic characteristics of the network and the protection scheme of the network. Secondly, a number of bits whose number is variable and which contain information about the routing of the network i.e. the presence of a connection between two nodes. The value for each chromosome bit is not determined in complete random way but will need to comply with certain constraints. Firstly, there is the adequacy constraint that requires that the configuration of each chromosome is such that all loads are being supplied in the base situation i.e. when no faults have occurred in the network. Secondly, there is limit to the number of secondary feeders. Each secondary feeder will need to supply at least to one load. Furthermore, there is a maximum allowed loading of each feeder depending on the available feeder types as contained in the NST's equipment database. An overview of the chromosome encoding is shown in Table 1.

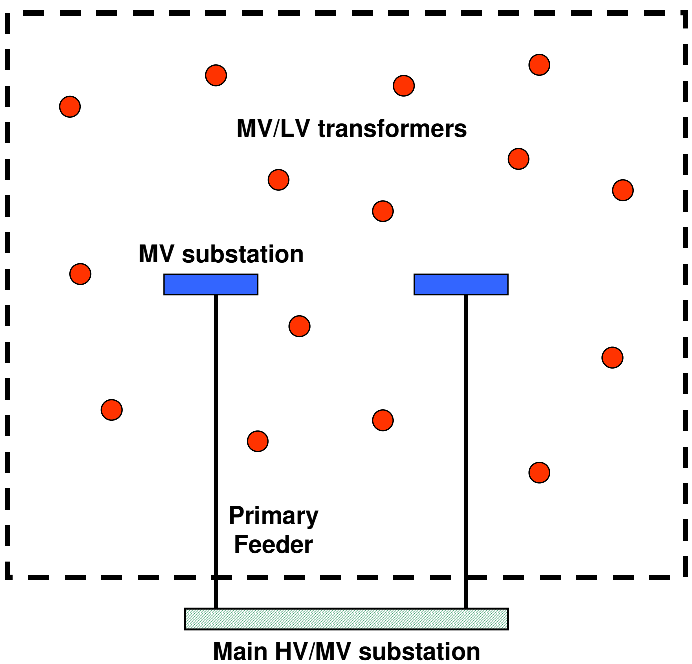


Figure 2. Schematic overview of the scope of the NST.

Table 1. Overview of information encoding for each network alternative chromosome.

Nr.	Genetic Information	Possible Range	Allocated bits	Bit Coding
1	Number of MV substations	1, 2, 4	1-2	00 = 1 01 = 2 10 = 4
2	Number of primary feeders per MV substation	Single or Double	3	0 = Single 1 = Double
3	Number of secondary feeders per MV substation	1 – 31	4-5-6-7-8	00001 = 1 00010 = 2, etc.

4	Routing Scheme	Dijkstra or Travelling Salesman	9	0 = Dijkstra 1=Travelling Salesman
5	Secondary feeder topology	Radial or Meshed	10	0 = Radial 1 = Meshed
6	Protection for primary feeders	Protected or Not Protected	11-12	00 = None protected 01 = First feeder protected 10 = Second feeder protected 11 = Both feeders protected
7	Protection for secondary feeders	Protected or Not Protected	13	0 = Not protected 1 = Protected
8	Network Routing Scheme	Connection or No Connection between two nodes	$(n^2-n)/2$ where n is the number of nodes	Per pair of nodes: 0 = No connection 1 = Connection present

The number of MV substations can either be one, two or four. Based on the number of MV substations, the supply area is divided into equally sized sub-areas with the MV substation located in the centre of each sub-area. Each MV substation supplies loads located in the corresponding sub-area only, there are no electrical connections between different substations or sub-areas. The number of secondary feeders per MV substation can take a value up to 31.

If a MV substation is supplied via a single primary feeder, a fault in the primary feeder leads to an immediate cessation of the supply to all consumers connected to that MV substation. A second primary feeder (as well as related protection systems) adds redundancy to the system and increases quality. In that case, a fault in one of the primary feeder no longer leads to an interruption as then, the faulted primary feeder is automatically isolated and supply is maintained via the remaining healthy primary feeder (assuming that it has sufficient capacity).

To identify the possible routing of the feeders, first a Delaunay triangulation of the MV/LV transformers and the MV substations is applied. A Delaunay triangulation of a point set is a collection of edges satisfying an "empty circle" property. For each edge one can find a circle containing the edge's endpoints but not containing any other point.[1] These edges form suitable feeder paths for connecting the transformer stations to the substation (Peco and Gomez 2000). Based on the identified feeder paths, an initial routing of the network can be performed using either the Dijkstra or the Travelling Salesman algorithm.[2] Starting from a given feeder of the MV substation, the Dijkstra algorithm connects all the loads assigned to that feeder such that the total length of the feeder is minimised. This is done for each MV substation and each feeder. The Travelling Salesman algorithm on the other hand constructs networks by determining the shortest closed loop that joins a number of load points. The starting and terminating point are both feeders of the same substation.

Secondary feeders can be radial or meshed. If the feeder is meshed, loads connected by that feeder can be supplied via two or more possible routes. In case of an outage in the standard feeder route, supply can be restored via an alternative route. Firstly, the faulted part of the feeder is isolated and then switching actions are performed such that an alternative feeder route is created from the MV substation to the interrupted load. Once isolated, the faulted components of the feeder can be repaired with supply to consumers already being restored.[3] This reduces the

[1] For a detailed discussion of Delaunay triangulation, see for example Lee and Schachter (1980).

[2] For a detailed description of the Dijkstra and Travelling Salesman algorithms, see for example Johnsonbaugh (1999).

[3] Repair may either comprise physical repair of the component or replacing it by a new healthy one.

average duration of interruptions compared to a radial feeder where supply can only be restored once the faulted component has been repaired.

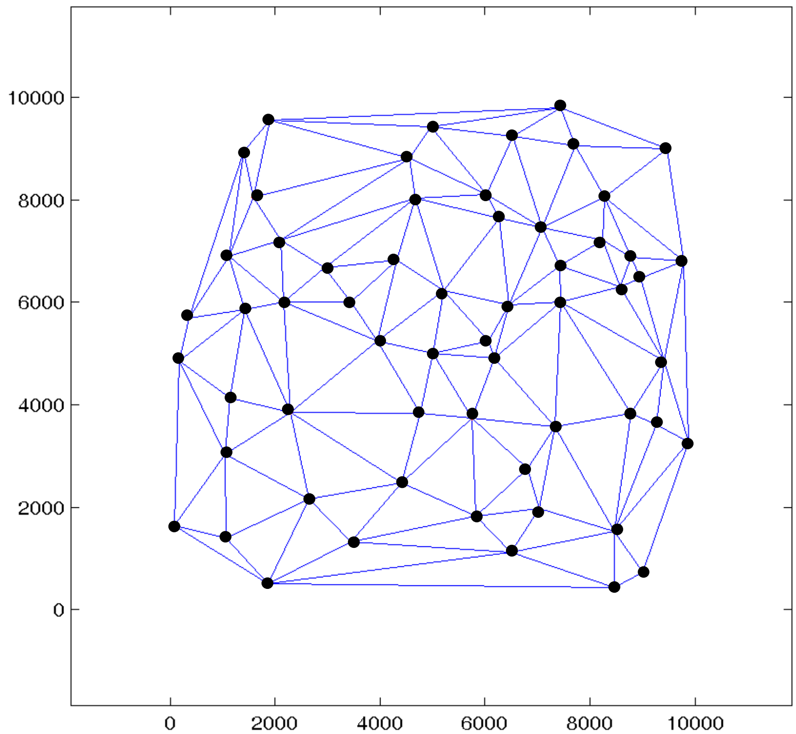


Figure 3. Delauny triangulation of the supply area studied in section 6.4 See also Figure 6-4.

The capacity of each feeder is selected from a list of available feeder types. This selection depends on two factors. Firstly, each feeder should have a minimal capacity such that the system can serve the peak load under normal circumstances i.e. in a situation without any faults. In the case of a meshed network, when a failure occurs, it may be that certain feeders are loaded beyond their normal loading as a result of rerouted power flows. If such circumstances occur, then the feeder capacity needs to be increased subsequently. Feeders may furthermore be protected or not. Additional feeder protection limits the impact of a fault to the respective protection zone.

There are different possibilities to construct the network and each alternative has its own cost and quality performance. Generally, adding more redundancy to the network increases quality but also come at additional costs. For example, feeding a MV substation by two primary feeders leads to an increase in quality as a failure in one of the feeders no longer leads to an interruption. Similarly, increasing the number of secondary feeders leads to relatively shorter feeders and therefore less interrupted consumers. Similarly, adding protection reduces the impact of the interruption while designing the network in a meshed way provides the possibility to reroute power in case of interruptions and thus reduces the duration of interruptions. Not each quality improving measure may be effective from the social point of view. By considering the possible options to construct the network on the basis of different quality choices, the best performing alternative can be identified and used as the benchmark.

1.2.3 Genetic Diversification

Selection of parents for the construction of a new generation is based on a mix of elitist class and tournament selection.[4] Firstly, alternatives are sorted by their level of sotex and a selection is made of the best performers or so-called elite. For example, the elite can be defined as alternatives belonging to the first ten percent of alternatives ranked in order of lowest sotex. This selection method makes sure that alternatives with relatively high performance are

[4] See also Brown (2003, p. 311) for a description of these parental selection methods.

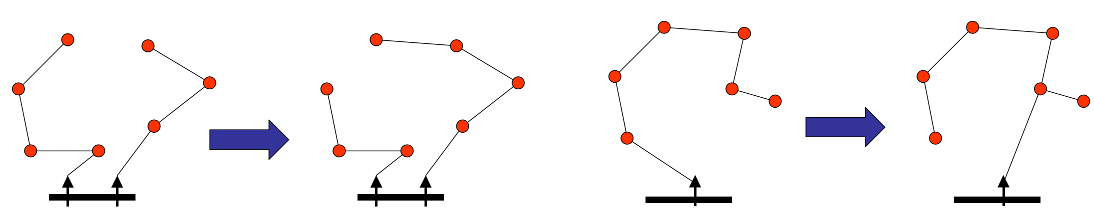
maintained as parents. The elitist method however has the disadvantage that genetic diversity is reduced over time. To counteract this potential problem, a second set of parents is selected through the tournament selection method. Here, a random selection of two alternatives is made and the parent with 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 one alternative may be selected as parent more than once. For example, an elite alternative is not excluded from participation in the tournament and thus may be selected under both the elitist class and tournament. Furthermore, a given network may be selected multiple times under the tournament.

For creating a new generation of network alternatives, a genetic crossover is applied. Each combination of two parents produces two children. The child's chromosome is determined by a random selection between the genetic material of its two parents. The child thus inherits the combined characteristics of its parents. An example of the procedure used to create children is shown in the below Table.

Table 2. Example of genetic crossover to produce two children.

Genetic Information	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
Routing Scheme	Dijkstra	Travel	Dijkstra	Dijkstra
Basic 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

Once the genetic crossover has been applied, a second round of genetic diversification starts namely mutation. Mutation consists of a slight change in one of the characteristics of a given child and occurs with a predefined (small) probability. The importance of mutation lies in the fact that it provides for a constant supply a fresh network alternatives thus increasing genetic diversity. In this case, branch replacement techniques are applied to rearrange the network's routing scheme. This is limited to the routing of secondary feeders; the primary feeders are not modified. Two types of branch replacements techniques are used. Techniques of type I modify the feeding point of a load. Changes of type II modify two segments at the same time. Annex V contains an overview of the algorithms used for conducting the branch replacements.



(a) Branch replacement of type I.

(b) Branch replacement of type II.

Figure 4: Example of type I and type II branch replacement techniques.

1.2.4 Reliability Analysis[5]

The information contained in the chromosome of the network alternative can be used to analyse the performance of that network alternative. This analysis consists of two main parts. Firstly, a reliability analysis of the network is conducted and from this, interruption costs experienced by consumers can be obtained. Secondly, the costs of the network itself are determined on the basis of the number and price of the network assets as well the costs of losses. Summing up interruption costs and network costs provides the measure of total social costs or sotex and this is the main performance indicator for each network alternative.

The reliability analysis provides information about the frequency and interruption experienced by each consumer. From this total interruption costs can be derived being the as the sum of interruption costs experienced by each customer. For an individual consumer *i*, annual interruption costs *ic* can be defined as follow:

$$ic_i = ENS_i \cdot IC_i$$

And total interruption costs can be derived from:

$$ic = \sum_i ENS_i \cdot IC_i$$

Here, *ENS* is the annual amount of energy not supplied and *IC* is the interruption costs incurred per kWh of *ENS*. The annual *ENS* per consumer in turn can be approximated by:

$$ENS_i = f_i \cdot d_i \cdot \hat{D}_i \cdot LF_i$$

The parameters $\hat{D}$ and *LF* are input data that denote respectively the peak load and the load factor for that consumer. The frequency *f* and duration *d* of interruptions per consumer are the output of the reliability analysis. For calculating these indicators, use has been made of the computer program Distrel, which 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. A given network component is thought to be in either 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 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:

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

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

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

Once failed, the component will not reside in the DOWN-state but will be brought back to the UP-state by conducting repair (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. If $t_{d,i}$ is the time that the component k resides in the DOWN-state, then its repair rate can be defined as:

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

The failure and repair rates will generally not be constant but 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's lifetime. In the intermediate period, which is the largest part of the component's 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 rate may vary over time but is assumed constant in the analysis of reliability (Klaassen et al. 1988).

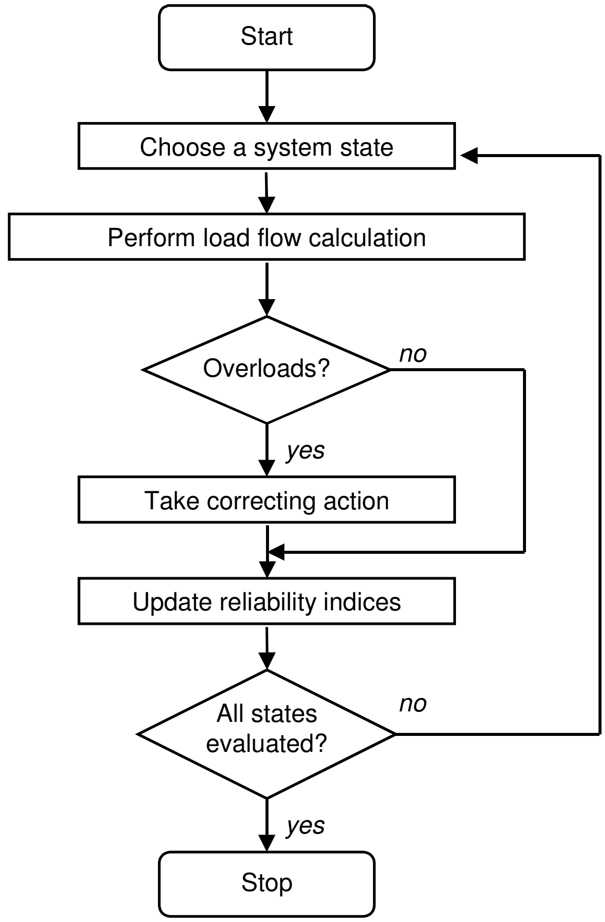


Figure 5. Basic steps involved in conducting a reliability analysis under Distrel

The failure and repair characteristic of a component represent the probabilities of moving from one state to the other. By considering all network components simultaneously, a system state can be defined as a given combination of the states of all network components. Each system state thus consists of components being either in the DOWN or UP state and this may or may not involve interruptions for consumers. The total number of system states is then equal to 2^L where L is the total number of network components. The probability P for a certain system state to occur can be derived by solving the following set of equations (Meeuwsen 1999a):

$$P(l) \cdot \sum_{m \in N} \tau_{lm} = \sum_{m \in N} P(m) \cdot \tau_{ml}, \quad l = 1,2,3,...L$$

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

$$D(l) = \frac{1}{\sum_{m} \tau_{lm}}$$

And the frequency of being in that state is:

$$F(l) = \frac{P(l)}{D(l)}$$

From this information, the interruption frequency and duration indices for each consumer can be reconstructed. The steps involved in carrying out this analysis are shown in Figure 6. First, a certain system state – which is defined as a combination of the states of all individual components - is selected and an evaluation is performed 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. By observing all possible states, the interruption frequency and duration for each load point can be determined.

As may be clear, when the number of components is increasing, the number of system states grows exponentially and consequently, the computation time required for the reliability analysis may become very long. To reduce computation time, only first order states are considered i.e. in a given system state, only one component is assumed to fail at any given moment. By excluding states with multiple component faults, the number of system states to be analysed can be reduced substantially. This is furthermore not likely to have significant impact on the accuracy, as the probability of two or more components failing at the same time is relatively low.

1.2.5 Cost Analysis

The performance of the network is measured by the sum of interruption and network costs. Network costs can be divided into investment costs and the costs of losses. Investment costs comprise the costs 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 configuration and is contained in the chromosome. 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 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 $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$ 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 as this is a more reliable estimate of feeder length.

The prices and volume of assets determine the total investment costs (*capex*) that will need to be recovered during the lifetime of the assets. Capex can be divided into two parts namely depreciation and return. Depreciation costs recover the initial purchase costs of the asset while return is associated with the capital costs of the asset. The costs of capital consists of both the costs of debt (interest) as the costs of equity i.e. payments to shareholders. 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 class *a* can be given by (Willis 1997, p. 209):

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

Where *ror* stands for 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 costs of network losses. Due to the inherent resistance of connections, there will be ohmic losses in the network. The costs of these losses can be calculated by multiplying the total losses in kWh by the purchase price per kWh. The ohmic losses (in kWh) for each connection *c* can be approximated by (Willis 1997, p. 32):

$$losses_c = \hat{I}_c^{\,2} \cdot R_c \cdot 8760 \cdot LF_c^{\,2}$$

Where $\hat{I}$ stands for the peak current through the connection in normal operating conditions, *R* is the resistance of the connection, and *LF* is the load factor. Assuming a constant price per kWh, total network costs can then be found by:

$$nc = \sum_a capex_a + p_L \cdot \sum_c losses_c$$

Where p_L is the price per kWh of electricity paid for losses. The annual social costs of the network can then be defined as follows:

$$sotex = ic + nc$$

1.3 Evaluation of the NST

1.3.1Experiences with Network Models

The idea of using a model to construct artificial networks that can be used for reference purposes is not a new one. Network models for electricity distribution are, for example, used by regulators in Sweden, Chile, and Spain. These models are now briefly discussed.

The Swedish regulator employs a network model known as the Network Performance Assessment Model (NPAM).[7] The NPAM constructs a 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 the group are subsequently connected to this transformer. This process starts by first connecting the consumer that is closest to the transformer and then, each subsequent consumer is connected to the transformer or to an already connected consumer, whichever is closest. This process is

[7] 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.

repeated for all groups until all consumers within a group have been connected to a transformer. The same principle is then used to connect the different groups to a transformer positioned in the electricity gravity centre of the next voltage level. Eventually 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. Firstly, a calculation is performed of network costs. These consist of opex, capex, and network losses. Opex is estimated as the sum of administration, operation, and maintenance. Administrative costs are assumed to be proportional to the number of clients and cover the costs of meter depreciation, meter reading, invoicing and processing. Other operational and maintenance costs are assumed to be 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 using functions that depend on the density of the fictive network and are valued at a standard price.

The second step in calculating the network performance consists of calculating the costs of quality. This is done by considering the interruption costs incurred by consumers on the basis of reliability level actually experienced by consumers. The costs of quality are thus not derived from the quality performance of the fictive network, but on the actual quality level that consumers experience. The reason for this is, according to (Gammelgard and Larsson 2003), that it is anticipated that incentives for an appropriate reliability level are provided outside the model. In determining quality costs, a distinction is made between consumers based on the density of the network. The principle followed is that interruptions are more expensive to 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 costs for the network is calculated. The network's total performance is then defined as the sum of the network costs and interruption costs. This provides 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 actual demand and expected load growth. Starting from the existing grid configuration and assets, an optimisation of maintenance, operations, and management of the firm is performed (Rudnick and Raineri 1997). During this process, the model takes into account fixed costs of administration, invoicing, user service expenses and variable costs, which include network losses, investments, operational 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. The ideal firm is constructed for each firm separately based on the types of zones corresponding to the operating conditions of that firm (Rudnick and Donoso 2000).

Both the regulator and the firms perform optimisation studies. The cost of the ideal firm is defined as a weighted average of the regulator's estimation of ideal costs and that of the firms' where the weights are set at respectively 2/3 and 1/3. The results of these studies form the basis for determining the firm's income. The optimisation studies are however not public and the technical details of the calculation of the model firm are not disclosed due to the highly detailed analysis. The fact that different studies are conducted and that these studies tend to generate different results indicates that there is no common optimisation methodology but rather that different methodologies are being employed. For example, Rudnick and Raineri (1997) report differences of almost 100 percent between the regulator's and the firm's own estimation of optimised costs. Furthermore, as far as known, quality is not directly considered in the optimisation process.

Under the Spanish regulatory framework, use if made of a network model that is known as BULNES. The outcome of BULNES is the optimal network costs for each distribution firm and this information is then used to determine the relative costs of distribution and allocate income amongst the different firms (Sumicsid 2003). 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 different firms rather than determine the absolute level of income. The model's main output is the optimal network costs for each firm and this is calculated by reconstructing the network for this 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 costs for this optimised network are then derived based on assumptions regarding the price of the assets as well as a unit price for preventive maintenance costs, corrective maintenance costs, and opex. Furthermore, adjustments in prices are made to reflect operating differences between firms e.g. ice, salt, precipitation, altitude, and rights of way. Interruption costs incurred by consumers are not considered by BULNES. Rather, reliability enters the model in the form of the costs of carrying out corrective maintenance based on the expected number of interruptions and associated repair costs.

Another network model of Spanish origin is proposed by Peco and Gomez (2000). This model is similar to the BULNES model but with the notable difference that it considers quality explicitly. The model creates 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 no equipment failures. The network is always radial and is optimised with respect to costs of investments and losses, subject to operational constrains of feeder capacity and voltage drop limits. The optimisation procedure takes place using heuristic algorithms that designs a radial network from sources to consumers from scratch, minimising both the investment and costs of network losses. In doing so, possible constraints imposed by the geographical location (e.g. right-of-way) of nodes are also taken into account.

Once the initial optimal network has been obtained, a second optimisation procedure is applied where the costs of interruptions are minimised through designing feeder reinforcements, installing additional feeder sections that allow alternative supply of the loads, and determining optimal investment in switching and protective devices. During this process, network reinforcements are applied until the total of network and interruption costs cannot be reduced anymore i.e. the least cost network in the social sense has been obtained.

1.3.2 NST vs. Traditional Models

There are some important differences between the NST and the network models as discussed above. The output of traditional models is a single network that is the result of an optimisation process. In contrast, the output of the NST is a series of network alternatives out of which one or more best performing networks may be identified. Thus, the NST does not only indicate the best (optimal) network alternative, but also provides information on what other options could have been chosen to construct a network for a given supply area and how well these other options perform. This provides additional information that the regulator could use at his own advantage. The problem of considering only a single optimal network is that this reduces the robustness of the analysis. In the literature, a number of algorithms for optimisation of electricity distribution networks have been presented. These algorithms have important differences and are based on different assumptions regarding the network topology.[8] For example, certain algorithms only consider networks that have a radial design thus automatically exclude meshed networks. It may however well be that under the prevailing circumstances, a

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

meshed network would have been a better option. The choice of optimisation algorithm however a priori constraints the outcome of the analysis to radial networks only. Under the NST on the other hand, as much as possible variation in the basic characteristics of the network is allowed thus increasing the probability of arriving at the true optimal network. For reasons of reducing computation time, there is a natural limit to this flexibility. However, the basic observation remains that the outcome of the simulation analysis is not restricted a priori by the choice for one particular optimisation algorithm.

Another and perhaps more important feature of the NST is that it considers costs and quality in a fully integrated fashion. Network alternatives are evaluated both in terms of their cost and quality performance. Traditional models as discussed above 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 defines network performance on the basis of actual interruptions experienced by consumers. The model by Peco and Gomez (2000) comes closest to 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 cost optimisation. This is an important limitation, as the quality optimisation will be constrained by the outcome of the first stage. For example, a certain network may initially be expensive when evaluated from the cost side only but, given that it also leads to high quality, may well proof to reflect a better price-quality trade-off than other types of networks. This network would however not be considered in the second-stage analysis as it would be discarded already in the first stage. The NST on the other hand considers price and quality performance simultaneously. The performance of the network is defined in terms of social costs and on this basis, subsequent generations are constructed. This allows consideration for all types of networks as long as the overall performance as measured in total social costs is satisfactorily.

Table 3. Summary of differences between traditional models and the NST.

Aspect	Traditional Models	NST
Scope of the analysis	Limited to a certain class of networks	Flexibility in the choice of network characteristics
Consideration for quality	Implicit or in second stage	Fully integrated price-quality analysis

1.4 Case Study

1.4.1Input Data

The NST has been applied to a fictive supply area of 10x10 km consisting of 58 consumers (represented by MV/LV transformer stations) serving clusters of residential and commercial consumers. As the case deals with the distribution network only, industrial consumers are excluded from the analysis. Residential consumers and commercial consumers are respectively supplied by 250 kVA and 400 kVA transformers under the assumption of a peak load of 5 kVA and 40 kVA per respective consumer type. In total, the distribution network serves 2140 residential and 190 commercial consumers which results in a non-coincidental peak load of around 15 MVA. In reality, not all consumers will demand their peak load at the same moment. To capture this effect, the non-coincident peak is multiplied by a coincidence factor of 0.8, which brings the coincident peak load to approximately 12 MVA. Furthermore, a power factor (cos φ) of 0.95 is assumed which results in an active coincidental peak of 11.4 MW. Throughout the analysis, a load factor of 0.65 is assumed.

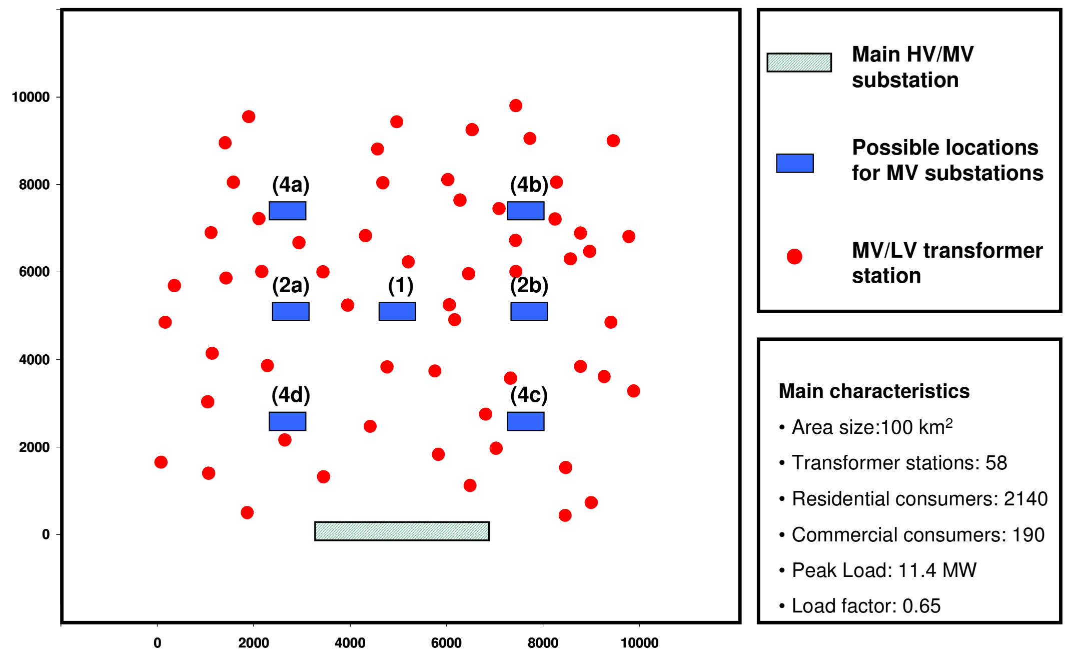


Figure 6. Overview of supply area. Distances are in metres.

A simplified overview of the supply area is provided in Figure 6. The location of the MV/LV transformers is fixed. Each transformer is fed via a MV substation, which in turn is fed by the main HV/MV substation. The location of the main HV/MV substation is fixed at 5000 metres below the centre of the supply area. The location of the MV substations depends on their number (respectively one, two or four), which is a decision variable in the analysis. The network is assumed to consist of underground cables only. An assumption is made of one joint per two kilometres of cable. 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 have been obtained from Ajodhia (1999) and inflated to 2005 levels. A rate-of-return of 10 percent and a lifetime of 30 years is assumed for all assets. The following table shows the prices for the various components in the network as well as for 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 / disconnector
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 and repair rates assumed for cables and joints.

The switching time is relevant in the case of a meshed network and reflects the average time taken to restore power through rerouting the feeder. All other components (e.g. breakers, rail sections and protection systems) are assumed to be 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 an the value of non-delivered energy as applied by the Norwegian regulator NVE (Trengereid 2003). A distinction is made between residential and commercial consumers. The cost per kWh of non-supplied electricity is shown in Table 6.

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

Consumer Type	Interruption costs per kWh non-supplied
Residential	0.40 EUR / kWh
Commercial	4.67 EUR / kWh

1.4.2 Simulation Results

The total calculation time for the case study is about one hour on a PC with a Pentium 1500 MHz processor. The results are shown in Figure 7 where the annual sotex for each network alternative is plotted as a function of quality (measured by SAIDI). An approximation of the sotex curve is also provided in the Figure by enveloping all network alternatives with least sotex for a given quality level. In line with expectations, starting from a perfect quality level (SAIDI = 0), sotex levels first decrease and then increase again once the optimal level is exceeded. The sotex curve should however be interpreted with care as its shape is biased by the parental selection process. Due to the fact that network alternatives that score better have a higher probability of being considered in a next generation, the sotex curve may in reality well be less steep than shown in the Figure.

As can be observed, the best performing network alternative has a SAIDI performance of 3.2 hours per year and this results in an annual level of sotex around 431,320 EUR per year. Figure 8 shows a schematic representation of the four best performing network alternatives. As can be observed, there are only marginal differences in the routing of these networks. The main characteristics namely a single MV substation, a single primary feeder and a radial design apply to all networks. In terms of sotex, the difference between the four networks is very small; for example, the difference between the first and forth best performing alternative is only 1,460 EUR/year. It is likely that uncertainties in input data (i.e. prices and failure data) as well as in modelling assumptions offset such small differences. In particular, due to the stochastic nature of the analysis, the optimal network i.e. the best performing network alternative will in principle be (slightly) different for each analysis performed with the NST.

Taking these factors into account, it does not seem justified to treat the best performing network as the truly optimal one. Rather, one should analyse the features of the best performing network alternative(s) and use this as the basis to determine what, from the social point of view, should be the characteristics of an optimal network for the given supply area. To investigate this point further, it is helpful to consider the type of networks clustered around the best performing alternative. A general classification of network alternatives can be made along two dimensions namely (1) whether the network consists of mainly radial or meshed feeders, and (2) whether a single or double primary feeder is being used.

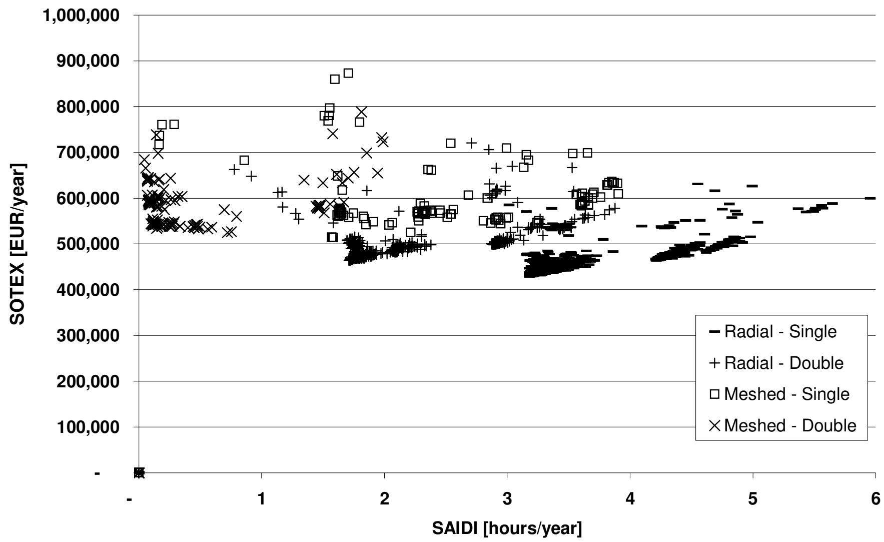
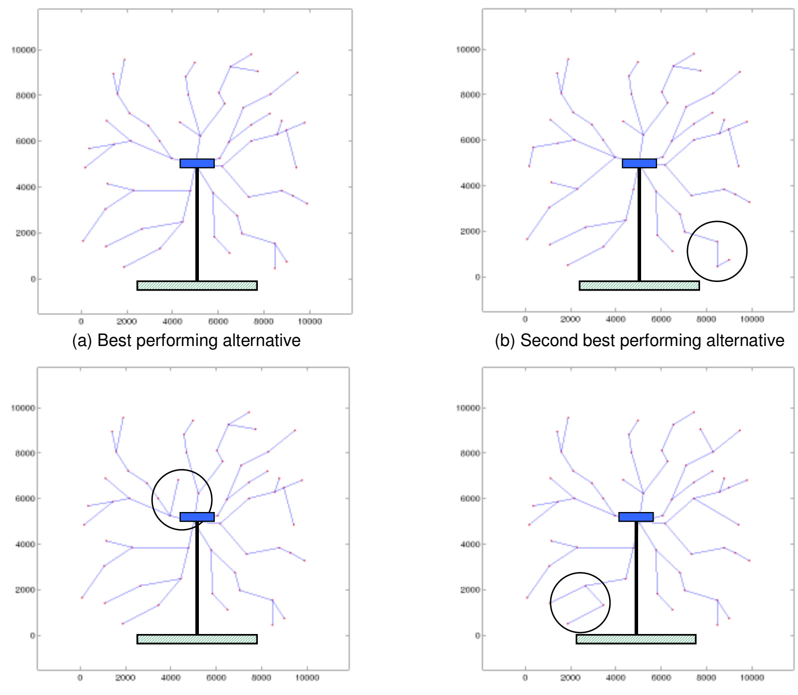


Figure 7. Results of the simulation analysis.

The average performance of four main classes of network alternative is presented in Figure 9. Radial networks, as can be seen, have an average quality performance that is lower than that for meshed networks. This is reflected in a relatively higher portion of interruption costs. The increase in reliability performance when moving from radial to meshed networks is caused by the reduction in average restoration time. Under meshed networks, there is a possibility to reroute power in case of interruptions and this is reflected in the decrease in the duration of an interruption. At the same time, meshed networks are also more expensive. This is driven by two factors. Firstly, a meshed design implies that on average, more connections need to be installed compared to a radial network. Secondly, connections in meshed networks generally require a higher capacity in order to allow the possibility of rerouting in case of a fault. If a certain feeder is rerouted, there will be generally an increase in the loading of the different feeder segments. This leads to a higher required feeder capacity and consequently higher costs.

The difference between radial and meshed networks in term of network costs is, on average, around 150,000 EUR/year. On the other hand, the decrease in interruption costs when moving from a radial to a meshed design is only in the order of 26,000 EUR/year. Thus, on average, it is uneconomic to use a meshed design, as the extra costs do not outweigh the decrease in interruption costs. Although there may be individual meshed networks that perform better than certain radial ones, radial networks provide a better price-quality trade-off in general. A similar comparison 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 feeder no longer result in an interruption. If one primary feeder fails, the electricity supply can still be maintained through the second feeder.[9] However, the associated decrease in interruption costs (approximately 40,000 EUR/year) is not sufficient to cover the additional costs of the second primary feeder (approximately 105,000 EUR/year). This suggests that in this particular case, a single primary feeder is most economic as this represents a better trade-off between costs and quality.

[9] Adding subsequent feeding cables would lead to a further improvement in reliability. Here however, only first order faults are considered i.e. simultaneous faults of two or more network components are not considered.



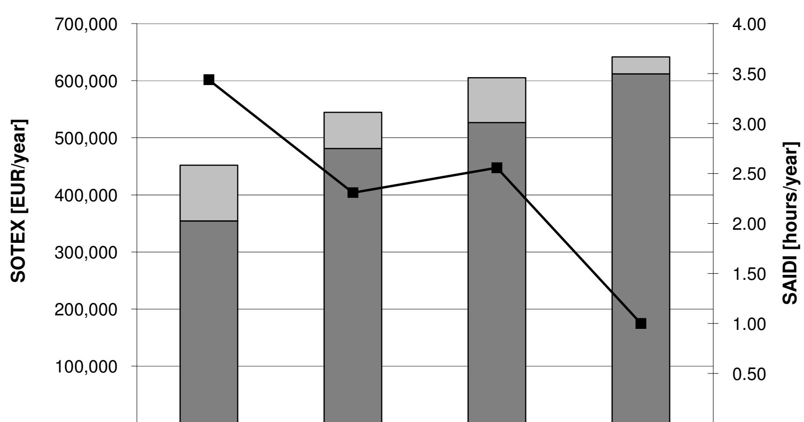
(a) Best performing alternative

(b) Second best performing alternative

(c) This best performing alternative

(d) Fourth best performing alternative

Figure 8. Schematic overview and main characteristics of the four best performing network alternatives.



	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 9 Summary of results for four classes of network alternatives.

In summary, for the given Greenfield supply area, a radial network consisting of a single primary feeder is generally preferred. These networks provide the best trade-off between quality and costs and, as can be seen from Figure 7, are positioned around a SAIDI level of 3.2 hours per year and have a sotex around 432,000 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 would propose a meshed design and possibly double primary feeders, the regulator could argue that – even though this would lead to a higher quality level – the firm's proposal is too expensive from the social point of view. On the other hand, if the firm proposed a network of similar characteristics as what is perceived as optimal by the regulator but with significantly higher costs, the regulator could request the firm to explain this difference.

As the analysis reveals however, the difference between the best performing and second-best alternatives is relatively small and probably falls within margin of error that is present in the input data as well as assumptions within the model itself. Therefore, the results of the analysis should be interpreted with care and its limitations recognised. For example, the NST's results should not be used to discuss specific routing details of the network. Such discussions would also not fit within the context of price-cap regulation and tends to lead to micro-management by the regulator. Rather, the discretion on the technical design of the network should be left to the firm as long as it complies with the price and quality targets as set by the regulator on the basis of the information revealed by the NST.

Scenario Analysis

The outcome of the NST is driven by a number of assumptions regarding the input data and more specifically, regarding the price and failure parameters of network components. 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 scenarios have been identified where the input parameters have been respectively increased and decreased by a factor two. The input factors that have been considered are prices of network components, the failure rate of cables and joints, the repair rate of cables and joints, and the interruption costs per kWh. The key results as compared to the base scenario are shown in Table 6-7 and a graphical representation of the impact on the price-quality trade-off is provided in Figures 6-10 and 6-11. The main results are now discussed.

As can be seen, a decrease in the price of network components leads to an increase in the optimal quality level. With prices reduced, it becomes economic to install an additional primary feeder. This leads to an increase in reliability as faults in the supply of the MV substation no longer result in interruptions. A decrease in prices thus leads to an increase in the optimal quality level. This observation can also be considered from a more general point of view. If the firm is able to operate in a more efficient manner, the costs required to increase quality are lower and consequently, it becomes economic to install additional redundancy in the network. In the converse case, if network prices increase, then it becomes more expensive to provide a higher quality level. An increase in component prices thus leaves consumers worse off as these now face higher prices as well as a decrease in quality.

In this particular case, an increase in network prices however has limited impact on the optimal quality level. The explanation for this is that the scope for cost reduction is limited as initially, the level of redundancy in the network is already low. Possible cost saving measures that could be taken is to remove the protection of the feeders. This however has substantial impact on quality while the cost savings are relatively limited. As may be observed, a doubling of component prices does not justify savings on protection as the resulting increase in interruption costs exceeds the associated decrease in network costs.

Scenario	Base Case	Equipment Price		Failure Rate		Repair Rate		Interruption Costs	
		Cheap	Expensive	High Reliability	Low Reliability	High Reliability	Low 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 network alternatives under different scenarios.

Increasing the failure and repair rates of network components leads to respectively more and longer interruptions and therefore higher interruption costs at given network costs. At some point, it becomes economic to install 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 for all consumers. If the reliability of the primary feeder is increased, then the impact of faults in this feeder increases accordingly. Subsequently, adding a second primary feeder leads to a substantial improvement in quality as a fault in a single feeder no longer causes interruptions. In this particular case, the net savings are high enough to justify the investment in the additional primary feeder. Overall however, consumers are still worse off as the optimal quality level is lower (due to less reliable network components) and network costs increase due to the additional primary feeder. This is in line with expectations as the use of less reliable network components (for the same price) makes the provision of quality more expensive (which implies a lower quality level). Conversely, as may also be observed, the use of more reliable network components – represented by a decrease in the failure and repair rates – lead to an increase in the optimal quality level while network costs remain more or less constant. As quality is already quite high then, it does not seem to make sense to add any more redundancy to the network, as the components are already highly reliable.[10] Consumers thus benefit in the sense that they are provided with a higher quality for the same costs.

An increase in interruption costs implies that consumer demand for quality increases and this is reflected in a higher optimal quality level. As consumer value quality more, quality improvement measures become more economic. In this case, adding the second primary feeder leads to a decrease in interruption costs that offsets the costs of this feeder. The higher price that consumers need to pay as a consequence of this seems to be justified given the prevailing quality demands. On the other hand, if interruption costs decrease, this leads to a lower optimal quality level as well as a (small) decrease in network costs. The lower sotex however implies that consumers are better off if their quality demand is lower. As demand for quality decreases, it is not necessary to improve the network's quality and therefore, costs can be saved. Here, similar as in the case of an increase in network prices, further reducing quality has no net benefit. Given that quality remains more or less the same as in the base case, consumers now incur less interruption costs for the given level of quality thus leading to a net improvement in sotex levels.

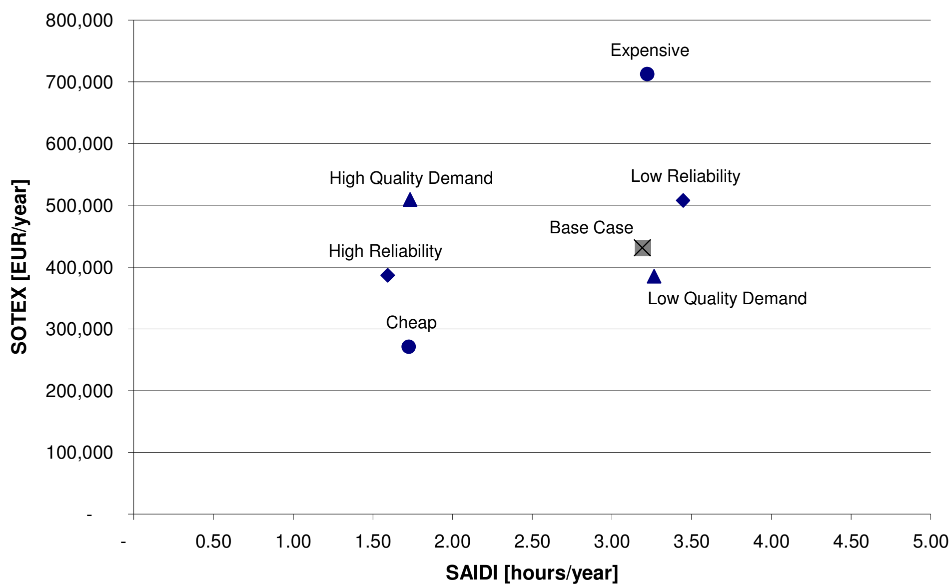
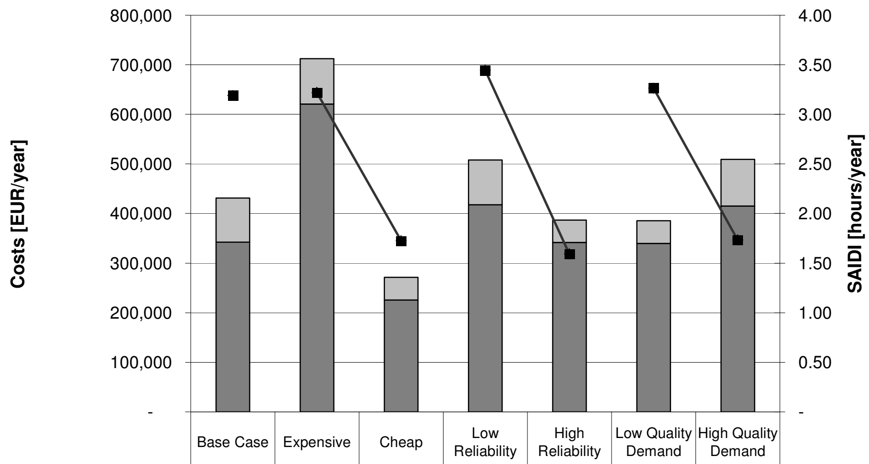


Figure 10. Graphical representation of the optimal price-quality trade-off under different scenarios.

[10] To explain this point, consider the following hypothetical case. If there is a single primary with perfect reliability (i.e. a failure rate of zero) then for quality it would not make any sense to add an additional primary feeder as the probability of the first feeder failing is zero anyhow. The added redundancy would thus have no function but would still come at high costs.



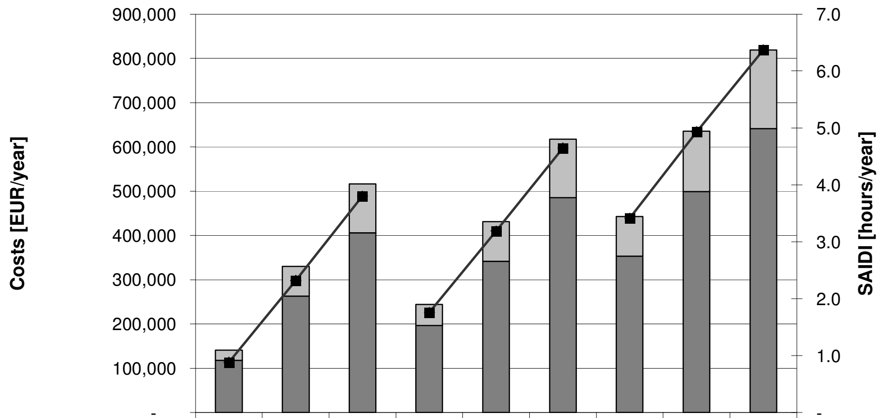
	Base Case	Expensive	Cheap	Low Reliability	High Reliability	Low Quality Demand	High Quality Demand
Interruption Costs	89,217	91,527	45,509	90,423	45,006	45,569	94,128
Network Costs	342,108	621,016	225,731	417,769	341,583	339,650	415,290
SAIDI	3.19	3.22	1.73	3.45	1.59	3.26	1.73

Figure 11. Differences in optimal price-quality trade-offs under different scenarios.

Apart from the impact of changing parameters on the model's outcome, it is also interesting to look at the impact of changing the structural characteristics of the supply area itself. Two factors have been considered namely the location of the main HV/MV substation and the density of demand. To observe the impact of demand density on the model's outcome, the supply area has been respectively contracted and expanded. Two cases have been considered namely a "dense" network and a "sparse" network where the size of the supply area has been respectively contracted to half and expanded to twice the original size. With respect to the location of the HV/MV substation, the distance of this substation to the centre of the supply area has been adjusted. In the initial case, the HV/MV substation is located 5,000 metres below the centre of the supply area. For the purpose of the analysis, this distance has been adjusted to respectively 10,000 and zero metres. These two cases are respectively denoted as "close" and "far". Only the vertical position of the substation has been adjusted; the horizontal position has been maintained at the centre of the supply area.

Changing demand conditions has no impact of the basic characteristics of the network; in all cases the best performing alternative is a radial network with a single primary feeder. Changing demand and distances however doe have impact on the trade-off between cost and quality. Figure 12 shows the optimal price-quality trade-off under different demand and HV/MV substation distance scenarios. As can be seen, moving the HV/MV substation further away from the supply area leads to higher network costs as well as higher interruption costs. At the one hand, longer distances imply longer cables and therefore higher cable costs. At the other hand, the probability of a failure increases with the length of the cable and therefore results in a decrease in quality. These effects are clearly visible in the above Figure. In this case, network costs tend to increase faster than interruption costs thus making investments in additional quality uneconomic. In particular, if the location of the HV/MV substation is further away from the supply area, the cost of adding an additional secondary feeder also increases. The improvement in quality of an additional secondary feeder does not offset these extra costs thus making the second feeder uneconomic.

The other effect that has been analysed is demand density. Demand density can be defined as the average distance between loads and the centre of the supply area. As may be observed, decreasing demand density results in higher network costs as well higher interruption costs. This implies that the optimal quality level for sparse networks is lower. Sparse networks are more expensive due to the relatively longer distances that feeders need to cover. At the same time, longer feeders lead to a decrease in quality as the probability of a feeder being exposed to a fault is also higher. A supply area with high load density is thus preferable as this leads to shorter feeders and consequently fewer costs and lower probability of an interruption.



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

1.5 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 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 information regarding the preferred network characteristics for the given supply area. Also, 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 quality demands across the network. The resulting optimal network reflects a trade-off between price and quality for the network as a whole but at the same time also considers spatial variations in quality demand by consumers. Furthermore, the problem of the time lag between cost and quality is – for investments at least - in principle solved as the disclosed level of investment in principle leads to an optimal level of quality.

In the spirit of price-cap regulation, it is not desirable for the regulator to intervene in the investment planning process of the firm. Rather than getting involved in the details of the firm's operations, price-cap regulation aims to provide socially desirable outcomes by the means of incentives. Clearly, replicating the full investment planning process would not be in line with this line of thinking. The NST is in line with this thinking and provides regulators with an instrument to obtain information about the effectiveness of a given investment proposal without the need to perform detailed technical assessments and with the use of relatively little data. The information obtained through the analysis can then feed into the process of determining an appropriate investment level or more specifically, determining the allowances for the RAB.

The limitations of the NST should however also be recognised. The NST is only a model and therefore an imperfect representation of reality. The outcomes of the analysis are driven by the assumptions made in the modelling process. The disadvantage of a simulation approach is that there is a risk of arriving at a local rather than global optimum. Fewer assumptions increase the probability of identifying the true optimal network but at the same time also lead to longer computation times. Thus, there is a trade-off between realism and practicality of the analysis. In the face of modelling restrictions, it is not likely that the true optimal network will be an exact duplicate of the one identified by the NST as such. Furthermore, there are uncertainties in parameters as well as in the input data that may adversely influence the NST's outcome. Recognising these limitations, it is therefore perhaps more appropriate to consider the NST as a tool that reveals information about a suitable investment range and the desirable network properties rather than exact prescription of what should be the optimal network for a given supply area.