Department of Electrical Engineering

Geographical Perspectives on the Development of Power Distribution Systems in Sparsely Populated Areas

Eero Saarijärvi

Aalto University

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Geographical Perspectives on the Development of Power Distribution Systems in Sparsely Populated Areas

Eero Saarijärvi

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Aalto University
School of Electrical Engineering
Department of Electrical Engineering

Supervising professor
Matti Lehtonen

Thesis advisor
Matti Lehtonen

Preliminary examiners
Peter Schegner, TU Dresden, Germany
Petr Toman, Brno University of Technology, Czech Republic

Opponents
Kimmo Kauhaniemi, University of Vaasa, Finland
Peter Schegner, TU Dresden, Germany

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Abstract

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Abstract

It has been proposed that the present power distribution overhead lines should be replaced by underground cables, to address the concerns related to major disturbances caused by snow loads and storms. However, in an objective comparison of different network development strategies, the special characteristics of each of the line types and the terrain must be considered when determining optimal network topologies. In sparsely populated areas the need for cost-effective solutions tailored to best fit the specific terrain and operational environment is emphasized. In this thesis, a method capable of providing a network topology planning algorithm with line type specific characteristics of the operational environment, including an accurate dynamic topographic model involving variable costs, was developed. The work included case studies, the initial data of which was provided by Finnish network utilities from a variety of environments. Applying the developed methodology using a terrain model, also a contribution of this thesis, to the case studies provided general perspectives on the factors affecting the network topologies and the relative merits of different development strategies. The results were compared with the literature, which enabled further assessment of the validity of the methodology and parameterization used in this thesis. The results of the case studies showed that the optimal penetration of sectionalization is greatly affected by the load density. However, the quantity, quality and valuation of the interruptions affect the basic level of the penetration. Then again, optimally placing reserve connections was found to be a much more complex task, being partly affected by not only the geographical distribution of the loads but also by the characteristics of the terrain. While comparing fully backed-up against cost-optimally backed-up network topologies, the potential for utilizing lightweight structures was observed to have a considerable impact. Further, the characteristics of the terrain were found to affect not only cabled networks, but also the topologies of cost-optimal overhead line networks. The developed method for finding the cost-optimal network topology by using an accurate geographic model of the operational environment in terms of life cycle cost surfaces was found to be an efficient means for comparing different circumstances and network topologies and their mutual interactions. A close connection between the network data available in network information systems and the various geographic information sources was also recognized. Further, the means to effectively utilize this connection in the different processes of network planning and operation is presented.

Keywords cost surface, distribution network, geographic information, life cycle cost, medium voltage, network topology, sparsely populated area, topography

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Tiivistelmä

Nykyisiä pääosin avojohtorakenteisiin perustuvia sähköjakeluverkkoja on ehdotettu korvattavaksi maakaapeleilla, jolloin erityisesti myrskyjen ja lumikuormien aiheuttamista suurhäiriöistä voitaisiin pitkälti päästä eroon. Kuitenkin, erilaisten vaihtoehtoisten kehittämisstrategioiden objektiivisessa vertailussa tulee huomioida myös kuhunkin johtorakenteeseen liittyvät erityispiirteet suhteessa kullekin optimaaliseen verkkotopologiaan ja maastollisiin olosuhteisiin. Haja-asutusalueilla kustannustehokkaiden kulloisiinkin maastollisiin erityisolosuhteisiin kohdennettujen ratkaisujen merkitys on erityisen suuri, johtuen heikosta asiakaspohjasta. Työssä kehitettiin menetelmä, jossa eri johtolajien toimintaympäristön mukaan määräytyvät erityispiirteet voitiin mallintaa verkkotopologian suunnittelualgoritmille huomioiden alueen tarkka topografia dynaamisesti muuttuvat kustannukset mukaan lukien. Työhön sisältyi case-tutkimus, jonka lähtöaineisto muodostui todellisista suomalaisista jakeluverkoista ja vaihtelevista olosuhteista. Edellä mainittua menetelmää ja niin ikään työssä rakennettua maastomallia ja siihen liittyvää parametrisointia käyttäen pystyttiin havainnoimaan erilaisia verkkojen topologiaan ja keskinäiseen paremmuuteen vaikuttavia tekijöitä yleisellä tasolla. Tuloksia verrattiin aikaisemmin kirjallisuudessa esitettyyn tietoon ja tämän pohjalta pystyttiin osaltaan arvioimaan kehitetyn menetelmän ja käytetyn parametrisoinnin kelpoisuutta. Case-tutkimuksen tuloksista havaittiin muun muassa, että erotinten ja maastokatkaisijoiden optimaalinen penetraatio verkossa määräytyy pitkälti kuormitustiheyden mukaan, mutta toisaalta keskeytysten määrä, laatu ja arvostus suoraan vaikuttavat tämän lähtötasoon. Sen sijaan varayhteyksien rakentamisen havaittiin olevan huomattavasti kompleksisempi asia, johon liittyy kuormien alueellisen jakautumisen lisäksi maastollisia näkökohtia. Vertaamalla täysin varasyötettyjä verkkoja optimaalisesti varasyötettyihin verkkoihin havaittiin merkittäviä eroja eri verkkoalueissa suhteessa potentiaaliin käyttää kevyitä johtorakenteita. Edelleen, maastollisten olosuhteiden havaittiin vaikuttavan, ei pelkästään kaapeloituihin, vaan osaltaan myös avojohtorakentein toteutettuihin kustannusoptimaalisiin verkkoihin. Kehitetty menetelmä kustannustehokkaimman verkkotopologian määrittämiseksi tarkkaa maastomallia ja näistä muodostettuja elinkaari-kustannuspintoja käyttäen osoittautui tehokkaaksi tavaksi vertailla eri olosuhteita ja verkkorakenteita ja näiden keskinäisiä vuorovaikutuksia.
Työssä tunnistettiin myös tiivis yhteys verkkotietojärjestelmien sisältämän verkkodatan ja eri paikkatietoaineistojen välillä. Edelleen työssä esitettiin tapoja erilaisten paikkatietojen hyödyntämiseksi verkkosuunnittelun ja käytön eri prosesseissa.

Avainsanat elinkaarikustannus, haja-asutusalue, jakeluverkko, keskijännite, kustannuspinta, paikkatieto, topografia, verkkotopologia

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"*–Siinä se on.*
–Ja tuon mokoman röttelön takia on rähjätty."[1]

Eero Saarijärvi
16 December 2013

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[1] V. Linna, "Tuntematon sotilas," Helsinki: WSOY, 1954.

Contribution of the author

The author has developed the methodology used in the study and made all the analyses himself. The results and conclusions are sole work of the author.

Table of contents

Nomenclature

ABBREVIATIONS

A	ampere
AC	alternating current
AHXAMK-W	abbreviation for a medium voltage cable
Al	aluminum
AMR	automatic meter reading
CB	circuit breaker
CC	covered conductor (overhead line)
CHP	combined heat and power
CIC	customer interruption cost
CLC	CORINE Land Cover
Cu	copper
DC	direct current
DG	distributed generation
DSO	distribution system operator
EF	earth fault
EMA	Energy Market Authority
EU	European Union
EV	electrical vehicle
Fe	iron (steel alloys in conductors)
GI	geographic information
GIS	geographic information system (not to be confused with Gas Insulated Substation)
GPR	ground penetrating radar
GSF	Geological Survey of Finland (Geologian tutkimuskeskus)
HDD	horizontal directional drilling
HV	high voltage
INSPIRE	Infrastructure for Spatial Information in the European Community
IRR	internal rate of return
KAPELI	abbreviation for a development project of a light-weight cable network
km	kilometer
kV	kilovolt
kVA	kilovolt ampere
kvar	kilovolt ampere, reactive
kW	kilowatt
LCC	life cycle cost
LT	line type
LV	low voltage
m	meter
MV	medium voltage
NIS	network information system
NLS	National Land Survey of Finland (Maanmittauslaitos)
NPA	network performance assessment
NPAM	network performance assessment model
NPV	net present value
NTOA	network topology optimization algorithm
NW	network

OE	operational environment
OHL	bare conductor overhead line
PAS	abbreviation for a covered conductor type
PSS	primary substation
Raven	abbreviation for a bare overhead line conductor type, 54 Al / 9 Fe
RMS	root mean square
SCADA	supervisory control and data acquisition
Sparrow	abbreviation for a bare overhead line conductor type, 34 Al / 6 Fe
SSS	secondary substation
TDB	topographic database
TSO	transmission system operator
UGC	underground cable
UWC	underwater cable
VAT	value added tax
VOH	abbreviation for a project, network topology optimization algorithm
WGS84	abbreviation for a geodetic system (world geodetic system) and corresponding ellipsoid
XLPE	cross-linked polyethylene

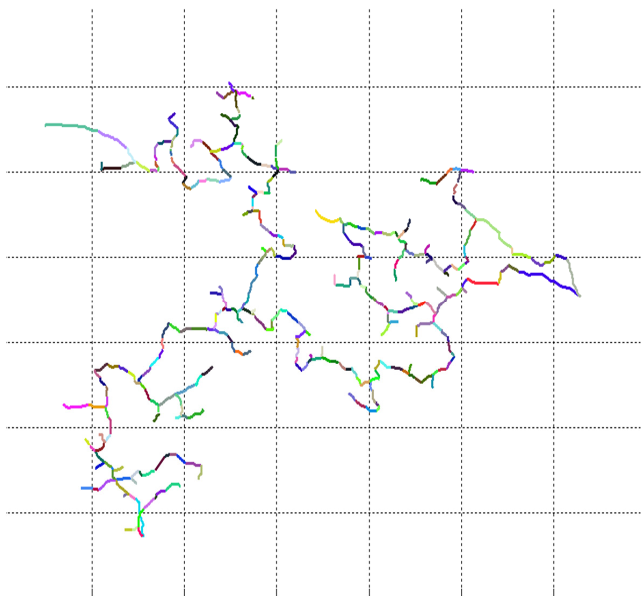
SYMBOLS

a	interruption cost parameter (power)
a_{re}	interruption cost parameter for reclosings (power)
b	interruption cost parameter (energy)
C	total cost over review period
C_{bas}	basic line cost including power losses
C_f	cost per fault
C_F	interruption cost over review period
c_h	price of the energy of the losses
C_I	investment cost
C_{inst}	installation cost
C_L	cost of losses over review period
C_{maj}	major interruption cost
C_{msw}	cost per manual switching
C_O	operational and maintenance cost over review period
C_R	residual value and demolition cost
C_{rc}	the cost per distance unit (for cost surface)
C_{re}	cost per reclosing
C_{rep}	cost of time spent in repairing
C_{rsw}	cost per remote switching
C_{rw}	right of way cost
d_{seg}	length of line segment
N_1	starting node
N_2	end node
p	interest rate
P	power, load
p_h	power losses per length
P_h	power losses
Q	reactive power
q_h	reactive power losses per length
r	line resistance per length
R	resistance
S	apparent power
t	review period
T_{dc}	data collection period
T_h	utilization period of losses

T_r	repair time
U	main voltage
x	line reactance per length
X	reactance
K	capitalization factor
λ	fault frequency
λ_{re}	reclosing frequency
ρ	load growth per annum
Ψ	auxiliary variable (for calculating K)

Chapter 1

Getting off the Ground



This chapter sets the framework for this thesis; it formulates the research problem, positions the scope of the work and introduces the main contributions.

1.1 Organization of the thesis

1.1.1 Formulating the research problem and framing the study

Extensive underground cabling is often proposed for mitigating concerns about insufficient reliability and service security in the present overhead line networks. However, there are different views on the cost drivers affecting the development of overhead line and underground cable networks. A direct comparison, where certain feeder sections are replaced one by one with different line types, would not unveil all the potential of different network topologies, considering the burdens and possibilities of the regionally specific geographical environments. The geographical distribution of the demand, customer mix, and reachability in terms of costliness of each of the load nodes affected by the geographical characteristics of the cross-terrain are weighty drivers in network planning, differently affecting each of the alternative line types.

Achieving optimal network design requires governing the complex and interrelated processes in the distribution system and its operational environment, i.e., continuous balancing between optimal degree of automation, sectionalization, reserve connections, routing of the lines subject to geographical drivers and constraints, selection of the most suitable line types and conductor sizes, and configuration of the network; not forgetting the technical constraints and economic and safety regulations. As a network is basically a system of inter-connected components, all parts more or less affect each other and any changes in one part of the network affect the rest. Thus, considering certain alternatives, e.g., on a feeder level basis, would not be a sufficient approach, but rather studies should be conducted on a broader network area basis.

This study presents analytical methods which are capable of dealing with the above challenges. The study has two main goals:

1. To develop processes and tools for rural distribution network planning, considering an accurate dynamic full life cycle cost oriented geographical model of the operational environment.
2. Through case studies, to apply the above for a variety of alternative strategies for varying environments, in terms of geography, geographical distribution of load points and load densities from Finnish utilities, in order to quantify the feasibility of different future network development strategies.

The different strategies which are compared against each other in the case studies are bare conductor overhead lines combined with underground cabling, covered conductor overhead lines combined with underground cabling, and underground cabling alone. For each of the studied alternative strategies, the aim is to find the optimal network layout which best suits that particular geographical environment (topography and geographical distribution of the demand). The geographic model of the operational environment considers parameters such as, spatially varying fault rates, repair times and installation costs. All studied strategies are subject to cost-benefit evaluation when considering the reserve connections and sectionalization; however, an additional strategy of cabling combined with full backup is also examined.

This thesis focuses on the medium voltage distribution network. The sub-transmission network and the low voltage distribution networks are parts of the power system directly interfacing with the medium voltage distribution network. However, in this thesis only the medium voltage distribution network sections are concerned. The network areas of the case studies constitute real load point data from several Finnish utilities.

1.1.2 Perspective of the study

At least four stakeholders are involved in electricity distribution: customer, owner, community and distribution system operator (DSO), each of which has a different view with regard to the optimal development strategies. The customer basically requires electricity of high quality and availability at a reasonable price. The owner invests in the business in order to get a favorable and secure return on investment. The community has its aim in maximizing the socio-economic welfare, which, in turn, requires power distribution systems to be reliable and cost-effective. Consequently, the distribution system operators are subject to regulation put in force by the authorities. Network utilities aim to operate within the framework set by the regulation so that the needs of the customer and the owner are best met.

The effect of changing the viewpoint has been studied earlier [Haa12] [Alv11]. For example, consider the mutual equality of different customer groups, e.g., an urban and a rural network customer, having the same network tariff. Definitely there are differences in the economic feasibility between these network areas of different load densities. Without regulatory obligations, consider the incentives for a distribution system operator to distribute their services to remote parts in a rural area providing likely risky and at best only moderate or even overall negative economic return on investment. In the end, distribution system operators operate in regional monopolies, meaning that an efficient regulation model is needed in order to ensure sufficient incentives to provide an acceptable level of reliable service for all the customers, especially, in an era when more and more of the originally municipally owned network assets are steered by new owners, which possibly are more aggressively seeking the highest allowed revenues. In general, when considering the profitability of the business and the overall characteristics of the legislative framework of the operational environment from the view point of the distribution system operator, the mechanisms of the specific regulation model in force are of great significance and cannot be neglected in studies followed through from those grounds. In this thesis, the feasibility of the different network development strategies is evaluated from the view point of society, i.e., the study aims to consider all the costs in terms of the cost for the public economy. In the long term, this is where the regulation is also believed to be aiming [Hon09].

1.1.3 Author's contribution with regard to the previous work

The methodology of this study builds on an earlier work referred to as the network topology optimization algorithm (NTOA) developed at the Department of Electrical Engineering of Aalto University. However, the progress of this dissertation has required substantial development of the NTOA, to which the author has contributed. The application for providing the NTOA with an accurate cost-dynamic geographic model of the operational environment, working consistently with the NTOA, is the sole creation of the author of this thesis. In brief, the new methodology introduced in this thesis can concretely be referred to as the main process of the combined algorithm designed for running these two separate algorithms as a whole, aiming towards the mutual main objective of minimizing life cycle cost by providing the means to consider the inter-relations of the network topology and the geographical data.

1.1.4 Criteria for studied network areas

With regard to the case studies, in order to achieve the full benefit from an NTOA, there are certain criteria when selecting suitable network areas. As discussed earlier, the studied region must be sufficiently broad so that the topological inter-relations between the different parts of the network area are considered. Typically, a region enclosed by primary substations is potentially suitable as well as areas having outer boundaries against neighboring distribution system operators (considering possible cross-border reserve connections). Natural geographical constraints, such as peninsulas, often provide suitable outer boundaries for a network area. The configuration and topology of the existing network in general are not necessarily suitable criteria, as these are outcomes from previous development strategies, which historically may have been quite different.

1.2 Scientific contribution

1.2.1 General

This study assesses the importance of the cost drivers in distribution network planning related to geographical data, in particular topographical data, with a focus on sparsely populated areas. The topographic database used as a basis for the above contains the most accurate geographic data consistently available over the entire breadth of the country [Nls12]. Moreover, a practical and automated implementation of utilizing such information is carried out and explained in this thesis. Optimal topologies are studied for different network development strategies (individually generated optimal networks for the different development strategies), taking into account the environmental variables related to topography.

One of the main contributions is based on the case studies of the Finnish rural distribution networks. However, through selecting site specific relevant geographic data and building up the parameterization accordingly, the same processes can be applied to a wide variety of networks in environments of any kind. Also, considering the main processes where the accurate geographic data is brought into use of a feeder optimization algorithm [Saa13], it is irrelevant, whether or not the feeder optimization algorithm itself is similar to the specific NTOA used in this study, uses a genetic algorithms approach, ant colonies or any other type of algorithm in the generation of the optimal network.

The contribution of this thesis can be divided into three main components. First (1.) of these is the new methodology in the topology optimization process, where full life cycle cost driven cost surfaces are used in the internodal parameter computation. Second (2.) is parameterization, which is an objective, realistic and comprehensive numeric presentation of the operational environment to be utilized in finding the most feasible network structures. The third (3.) main component of the contribution is the case studies, which in the end answers the questions regarding the feasibility of the different proposed network development strategies in the case of different geographical and network operational environments.

1.2.2 Life cycle cost driven cost-surfaces: a novel approach (1.)

This study uses a novel methodology to integrate accurate geographic data as part of the network feeder optimization algorithm [Saa13]. Earlier, there have been approaches, where, e.g., the geographically related fixed costs have been considered through static cost surfaces. In this study, however, the full cost objective of network planning, based on detailed geographical information, is exploited comprehensively. This is done through an iterative process, where a specific network topology affects the computation of the individual node-to-node connection specific cost surfaces, and vice versa. In this manner, the variable costs (e.g., power losses and interruption costs) also affect the node-to-node parameterization. Chapter 5 concentrates on giving a detailed explanation of the above.

1.2.3 Parameterization: building a numeric model of the operational environment (2.)

A lot of emphasis has been laid on acquiring a realistic parameterization of the operational environment (OE), in order to be able to conduct the case studies and related comparisons objectively without pre-judgments. The use of topographic data makes a good starting point for this, as many of the important parameters are often categorized as being topographically referenced. However, the set of used parameters has been gathered from a group of relevant sources. This, in turn, makes the evaluation of the equitability of the different acquired data important, in order to contribute to the societally important discussion regarding the strategic development of rural power distribution systems. The operational environment is, in addition to the model being mainly built on the topographic data, viewed with regard to other geographical aspects, e.g., forestry and geotechnical, in order to provide the topographic model with additional terrain types.

Further, the utilization of network specific observations regarding the operation, maintenance and construction of the network, in order to acquire spatially specific fault rates, repair times and fixed costs, is introduced. The separate processes of distribution network development are then viewed as a whole, resulting in a consistent proposal for utilizing the whole range of the produced information in the different processes of distribution network planning. In order for the study to be reproducible, the concluded parameterization is built up and documented carefully in Chapter 6 and Chapter 7.

1.2.4 Case studies: strategic development of distribution networks (3.)

Meritorious scientific work has previously been conducted in the field of strategic development of Finnish rural power systems. However, many authors have reported the difficulty in dealing with the complex inter-relations, where all strategic choices affect each other. As a response to this, an analytic approach, which aims in objectively dealing with the above mentioned challenges, has been introduced in this study and applied to a representative group of real network cases from Finnish rural utilities.

Several different development strategies are applied to each of the studied network areas. For each development strategy an optimal network structure, considering the full objective of life cycle cost minimization, is generated. Aspects taken into account in the generation of optimal networks are, e.g., node-to-node connection specific parameterization in accordance to the main objective of network optimal routing through the internodally individual cost surfaces, selection of the most feasible line types, reserve connections driven by the main objective and sectionalization of the network driven by the main objective.

With regard to societal impact, the results of the case studies are the main contribution of this thesis. The cases represent a wide variety of sparsely inhabited areas from the Finnish utilities, making good grounds for general observations. Further, the applicability and potential for generalizing the results for the neighboring countries is examined.

Special emphasis in the case studies and specifically in the cabling strategies has been laid on the evaluation of the feasibility of lightweight cables. The commonly used cable types of the Finnish utilities are optimized for urban environments. Following this observation, a lightweight cable optimized for the needs of the rural environments was developed in a research project to which this thesis is related and an extensive test series was conducted in order to ascertain the technical feasibility of the new cable design [Hyv13]. This thesis and the case studies conducted, then again, make grounds to find the operational and geographic environments where such lightweight cables are economically feasible. The results from the case studies are presented in Appendixes 1-5 and in Chapter 8, starting from page 109.

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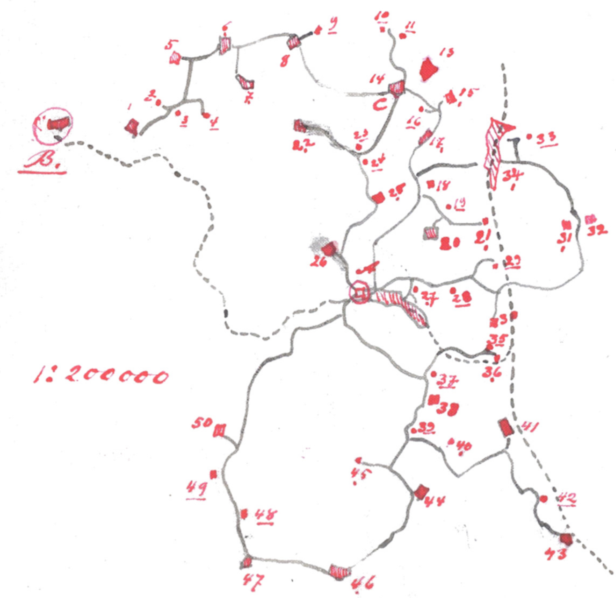
Chapter 2

Literature Review



This chapter reviews the literature and aims to further position this dissertation in relation to the previous work in this field. An overall broad look first scans the literature in terms of the related problems. Finally, the most relevant considerations of the earlier works and their relation to this thesis are outlined.

Figure: V.J. Soima, 1913 [Soi13], a schematic for rural power distribution network

2.1 General

Pointing to what was discussed earlier in the previous chapter concerning the goal of this study, the aim is to develop new methodologies for rural area distribution network automated planning, to apply and verify these methodologies through Finnish case studies and to gain generalized results concerning the strategic development of distribution systems. In this literature review, both of these subjects are discussed separately, starting with the literature relevant to automated network planning algorithms followed by literature concerning the strategic development of rural power distribution networks.

2.2 Network planning algorithms

The introduced new methodology integrates a network topology optimization algorithm (NTOA) with a node-to-node router that provides the NTOA with an accurate full life cycle cost oriented geographic model of the operational environment. The following sections of the literature review related to the methodology of this thesis start with the above mentioned two underlying separate, yet strongly inter-connected, subjects. First, the literature regarding node-to-node routers is introduced and reviewed. Then, different NTOAs, which are plentiful, are reviewed and summarized. Some, but not many, papers are available in the literature where the combination of these two network planning tasks is dealt with. These are reviewed the last.

2.2.1 Point-to-point routing

In practice, a realistic limit for the number of nodes an NTOA is capable of processing within a realistic time is hundreds rather than thousands of nodes. When considering the optimal structures of rural distribution networks at the medium voltage level the reach of a credible study area might be, e.g., 50 km wide. If the desired accuracy of the spatial geographic data is for example 5 m, this would result in the total number of nodes being 100 million. Such a quantity of nodes to be dealt with directly is certainly out of question for any of the network planning algorithms presented in the literature. However, narrowing the scope of the study to the sub-problem of individual cases of point-to-point routings, the overall complexity of the task is dramatically reduced.

Point-to-point routing can, with regard to the aims of this study, be referred to as finding the least (i.e., shortest) cost path in a given graph, where the graph is a numeric presentation of the space of available routing options. Many different algorithms related to the finding of the shortest path, or minimum spanning tree, have been presented in the literature [Dij59] [Flo62] [Pri57] [Kru56] [For56]. In this study, the Dijkstra algorithm [Dij59] is utilized, being applied to the costs of connecting the raster cells of the cost surface in search of a least-cost path from a starting node to an ending node. Despite not being a very recent work, Dijkstra algorithm is still commonly used in various applications in many fields of science, either directly or in a modified form. For example, rather recent papers aim to improve the overall performance using heuristics and are being applied to distribution network problems [Hu09], and to optimize fault isolation and supply restoration [Sud04]. Some have also used the Dijkstra algorithm for the generation of an initial network in their network planning algorithms [Nar97].

The basic concept of using terrain based information (generally, geographic information) for finding optimal routing for power lines has been introduced in the literature [Wes97] [Raj98]. Often the geographically feasible area is divided into cost regions, upon which the least-cost-routing is selected. This indeed is essentially the very same concept as presented in this thesis in terms of the cost surfaces. As the geographic characteristics are first interpreted as costs, the routing can be done simply by searching for the least cost route. Sometimes the point-to-point routing has been proposed to be adjusted manually by the network planners [Luc01]. However, if the aim is to find all routings for a network of, e.g., 300 nodes, with a total of 44850 internodal routings considered, an automated computer based approach would, in practice, be the only feasible option. Manually adjusting the routing would, though, be a viable option during the terrain planning processes concerning certain projected network construction sites.

In general, the routing of distribution or transmission feeders is a continuous task, compromising between the shortest path and avoiding costly obstacles. In its simplest form, the Euclidean path guarantees the shortest path between two given points. However, when the inequalities in the properties of the cross-terrain are added, the complexity of the task is significantly increased. The most evident factors affecting routing are the installation costs of an underground cable and fault rates for overhead lines. Further, in addition to the direct cost of moving from a cell to its neighboring cell, the cost due to curves in the routing has also been included in certain studies [Mon05]. For overhead lines, each turn might require more costly special structures, which in turn adds to the total costs. Not only the curves on the horizontal plane, but also the costs due to inclination (slope) in the routing have been discussed as an important cost driver in the literature [Shu12]. In the context of Finnish rural area distribution networks, the slope might indeed have some impact at a very detailed level, though it is often considered meaningless [Kor00] and can be considered to be able to be dealt with on a spatial level during the terrain planning process. In the approach [Saa13] presented in this thesis, the variable costs can also be considered. Reliability, which can be properly considered only as variable cost, is one of the most important cost drivers in the strategic planning of distribution networks [Kiv08].

2.2.2 Distribution network topology planning algorithms

Table 2.1 summarizes some of the key characteristics of the reviewed articles concerning network topology planning algorithms. Using a straightforward categorization, such as the one used here, might undervalue or even neglect many of the special characteristics undoubtedly underlying each of the individual publications. For example, the scope of the study is here mainly categorized in terms of a numeric example where provided. The aim is by no means to claim that certain proposed methods or approaches could not be adjusted or modified to suit other types of environments as well. Here, the aim is, if possible, to address the primary interests of the different authors and research groups and to get an overall view of what has been done in the field of network planning algorithms, and to discover which kinds of overall approaches have been used in the past. The articles considering geographical aspects are reviewed in the next subchapter.

Table 2.1. Reviewed papers, concerning network topology planning algorithms. Empty fields imply that a clear indication of belonging to any of the groups was not available.

	Algorithm type	Scope[1]	Reliability cost[2]	Backup[3]	Geography
[Asa03]	tabu search		no		
[Bou02]	dynamic programming	rural	yes	radial	yes
[Car00]	evolutionary algorithm				
[Car01]	evolutionary algorithm				
[Cos12]	multi-objective reactive tabu		yes	res. conn. + switches	
[Dia01]	dynamic programming	rural	no		
[Dia02]	evolutionary algorithm	urban	no	heuristic	
[Dia03]	evolutionary algorithm	rural	no		
[Fer99]	evolutionary algorithm		no		
[Gom04]	ant colonies	urban		radial	
[Hu09]	Dijkstra and heuristics				
[Jia04]	Kruskal algorithm		no	optimal	
[Jon96]	simulated annealing		yes	radial	
[Kha97]	review paper				
[Kho09]	review paper				
[Lin98]	genetic algorithm		no	radial	
[Luo09]		urban	no		yes
[Mig98]	evolutionary algorithm	urban and rural	yes	radial	
[Mig02]	branch exchange	rural	yes	radial	
[Mor00]	exhaustive, reconfiguring existing NW		no	radial	
[Nah08]	simulated annealing	rural	yes	radial	no
[Naj09]	genetic algorithm	urban	no	radial	
[Nar94]	branch exchange		no	radial	
[Nar97]	Dijkstra, Ford-Fulkerson, tabu search	urban	no	full	yes
[Par04]	simulated annealing		no	radial	
[Pep97]	branch exchange		no	radial	
[Ram91]	mixed integer linear programming		no		
[Ram98]	genetic algorithm		no	radial	
[Ram99]	fuzzy sets, tabu search			radial	
[Ram04]	fuzzy sets		yes	optimal	
[Ram06]	fuzzy sets, tabu search		yes		
[Sal94]	mixed integer linear programming		no	radial	
[Sam12]	direct approach		yes	radial	
[Sam12b]	direct method		yes	radial	yes
[Shu12]	mixed integer linear programming		no		yes
[Sin12]	bacterial foraging		no	radial	
[Sko02]	genetic algorithm	urban	no	heuristic	yes
[Sko05]	dynamic programming	urban	yes	heuristic	

[Tan96]	mixed integer linear programming	urban	yes	radial	
[Wan04]	genetic tabu hybrid	urban	yes	heuristic	yes
[Vaz04]	mixed integer linear programming		no		
[Yeh95]	artificial intelligence	urban	no		yes
[Yeh96]	genetic algorithm and heuristics	urban	no		yes
[Zhi09]	evolutionary algorithm		no		yes

[1] urban or rural
[2] some papers do consider outages, e.g., in terms of contingency technical constraints, but here the aim is to find those cases, where the outages are considered in terms of interruption costs
[3] radial = no backups, full = full backup, heuristic = pre-determined, optimal = cost driven (optimized)

As illustrated in Table 2.1, numerous different approaches have been introduced in the literature considering network topology optimization, including many which have got their inspiration from natural phenomenon, some that use branch exchange methods and others that implement dynamic programming. In dynamic programming [Bou02] [Dia01] [Sko05] the space of possible solutions is split into smaller pieces and the final solution is obtained by combining the solutions of the separate sub-spaces, while mixed integer linear programming [Jia04] [Ram91] [Sal94] [Shu12] [Tan96] [Vaz04], often combined with branch and bound techniques, requires linear or perhaps more often a linearized objective. Different approaches using evolutionary algorithms [Car00] [Car01] [Dia02] [Dia03] [Fer99] [Mig98] [Zhi09] and genetic algorithms [Lin98] [Naj09] [Ram98] [Sko02] [Wan04], a sub-category of evolutionary algorithms, aim to imitate natural evolution. There, different solution candidates are tested using a so called fitness function in order to sort out the candidates, to save the potential ones and to eliminate the less promising ones from the population. One of the main challenges often brought up with evolutionary and genetic algorithms is the actual coding of the problem for the algorithm. Ant colony algorithms [Gom04], then again, have got their original inspiration of an observation that an ant colony tends to find and use the shortest path between food source and nest. Basically this is thought to be consequence of the fact that as the heaps of individual ants randomly follow the different available routes, the ones that are the shortest are passed through the most often in a given time. As each ant leaves a pheromone trail behind, which then functions as a guide in selecting the right track, this gradually leads to the shortest paths having the strongest trail and, consequently, following this positive feedback the tracks with the strongest pheromone trail quickly become even more often travelled. In bacterial foraging techniques [Sin12] and in simulated annealing [Jon96] [Nah08] [Par04] the algorithms respectively imitate the behavior of, e.g., E coli bacteria and the metallurgic characteristics of iron, as it is heated and slowly cooled down finally leading to minimum potential energy state. Simulated annealing has the reputation of efficiently dealing with problems having plenty of local minima as well as with non-linear problems.

However, in the end, many of the problems and tradeoffs remain the same regardless of the chosen approach. Computational complexity rapidly increases as the number of nodes in the studied network increases. This, in turn, sets practical boundaries for the size of networks in terms of the number of nodes being able to be processed. Getting trapped in local optimums, which however would not be globally optimum, is often seen as one of the major challenges in optimization algorithms applied to complex and often non-linear systems. The only means to actually guarantee an all-inclusive optimum solution would be an exhaustive search [Yeh96], which considering the typical extent of the solution space is impossible to implement. Thus, in practice, there are no means to guarantee the quality of a solution of any realistically sized network in terms of whether the solution is actually a local or the global optimum solution.

Another aspect, where the need for compromises is evident, is in the overall consideration of the accuracy of the model of the operational environment. For example, in the case of Finnish rural distribution systems, the significance of geographical aspects in network planning is indisputable. For example fault rates and installation costs strongly drive the planning processes and can only be considered realistic if certain geographical aspects of the network area are considered. For the planning of urban feeder systems, many other aspects might be much weightier, partly explaining the differences seen in the spectrum of approaches in the literature.

The review time span in distribution network planning is typically decades. Predicting reliably this far into the future is impossible. However, long term network plans are needed and further, these need something to be built on. Information, processed into these plans, is gathered from, e.g., city planning and governmental forecasts. Dealing with time spans of this magnitude, there are a lot of uncertainties related to all forecasts and considering the development scenarios without involving these might lead to getting too strongly tied to certain individual possible but not only alternative scenarios. Merely, the future should be seen as a set of alternative scenarios for the future [Cel01] or as upper and lower limits produced by sensitivity analyses. In general, the literature contains several instances where network planning under uncertainty has been the focus [Car00] [Cel01] [Sko05] [Ram99] [Ram04] [Ram06].

As seen in Table 2.1, there are several approaches when it comes to the objective of the planning algorithms and, generally, in the degree and extent of heuristically pre-determining certain choices in generating the optimal network topology. Related to this, in cities a network with full backup might be a justified alternative and instead of strictly narrowing the aim to minimizing the life cycle costs, the minimization of fault duration and frequency indexes might be a relevant goal. However, in rural areas, where the load densities are much lower resulting in a lower revenue base for carrying the investments, the life cycle costs have the greatest impact on feasible network topology, resulting in cost-optimally considered topologies of trunk lines having backup and radial parts being left without. Network planning being overall a complex task, drawing a line between these two can hardly be easy and undisputable. However, in this study the latter approach is clearly more relevant due to the focus on distribution networks in sparsely populated areas. Viewing the papers, many have to some extent considered reliability as part of the objective (refer to the reliability-column in Table 2.1). However, regarding the cost-oriented consideration of optimizing the backup, the number of relevant reference works is greatly reduced. Treated separately, reserve connections [Ram04] and sectionalization [Cel99] [Cos12] have drawn some attention, yet the research problem of this study requires that these two are treated together, and this is rarely found in literature. The NTOA used in this study does consider the reserve connections, sectionalization and the selection of line types and conductor sizes based on the overall most economic option, while subjecting each step to technical constraints [Mil08] [Mil09] [Mil11] [Mil12] [Mil13]. In line with the aim to drop each of the reviewed algorithms into some bin, the NTOA being utilized in this study can be categorized as a branch-exchange algorithm, the type of which has quite often been applied [Mig02] [Nar94] [Pep97].

Verifying the simulation model and results might, in the end, be the most difficult task. As the space of potential solutions is too wide to allow exhaustively going through all the possible solutions, there can be no guarantee whether or not a proposed solution actually is a globally optimum solution. More importantly, network simulation results are impossible to be tested and verified in real environments, as this would require actual networks to be built and observed over entire service lifetimes of, e.g., 40 years. The literature presents verification through comparisons against other algorithms [Kha09]. Sometimes verification has been obtained simply by comparing the simulated results to the ones put together by experienced network planners [Asa03]. Even the sound appearance of the numerical examples, provided as demonstrations for a proposed method, have been used for verification purposes [Nar97]. As proper and credible verification is very difficult in reality, and probably leaves room for discussion at best, many papers do not consider any kind of verification, but usually provide some numeric example and leave the rest to the reader.

2.2.3 Network planning algorithms with geographic considerations

The use of geographical information has been at least mentioned in the context of network planning several times (refer to the geography-column in Table 2.1). However, many of these instances cannot be directly paralleled with this work. To start with, as in Table 2.1, the different approaches can be put into categories according to whether their main scope is rural or urban. In this thesis the scope is rural. However, if the focus were on urban networks, different aspects would probably be worth considering. In urban environments the routing of the power lines is basically tied with the routing of the street grid and, further, there are typically limitations for the placing of primary and secondary substations. In such cases, considering the street sections might be a sufficient level of detail for the geographic modeling [Nar97] [Wan04] [Yeh95].

Then again, in rural sparsely built environments all distances are much longer. Having more space between the load nodes inevitably leads to having more options concerning the routing and, in general, a greater number of geographical details. Only considering the road sections would miss, not only, a lot of the potential for more flexible routing, but also possible challenges related to the actual geographic environment. One of the pioneering works regarding rural area automated network planning presented an approach where the optimal network topologies were considered by including geographic constraints as input nodes for the network planning algorithm [Bou01] [Bou02]. As discussed earlier, any of the earlier presented network topology optimization algorithms are capable of only dealing with a rather limited number of nodes, likely only hundreds of nodes. Consequently, using this approach would result in an unsatisfactorily poor accuracy of the geographic data able to be considered. Thus, a more efficient approach must be obtained in order to cope with the large quantities of details of the geographic data.

An approach, partly capable of responding to the above challenges was recently presented. The overall problem was considered piecewise starting from the individual connections between the separate nodes [Shu12]. Static cost surfaces were applied enabling consideration of the fixed costs, i.e., investment costs related to each of the node-to-node connections. The very same approach is essentially used in the methodology presented in this thesis [Saa13]. Processing the geographic details separate from the main process of optimizing the network topology basically removes all the limitations considering the resolution of the separately processed node-to-node connections. However, using static cost surfaces enables, as explained, consideration of only the fixed costs. Thus, an approach that goes further than using static cost surfaces is required. The approach used in this thesis considers reliability in addition to the installation costs by introducing the topology parameters, enabling the generation of individually computed life cycle cost surfaces for each of the internodal connections [Saa13].

2.3 Strategic development of rural power distribution systems

Considering only the medium voltage level, the distribution network infrastructure in Finland consists of approximately 150 thousand kilometers of feeders which, in terms of total length, are dominated by overhead lines in the rural environments. Low voltage lines and other parts of the infrastructure, e.g., primary and secondary substations, add to this. As this infrastructure has a replacement value of billions of euro and at the same time this infrastructure is rapidly ageing, the socio-economic attention towards the major strategic decisions is guaranteed. Meritorious research has been carried out at several institutes in this field of research.

To start with, the selection of view point greatly affects the outcome of any studies concerning distribution network strategic planning. As distribution utilities operate as natural monopolies, which results in a lack of actual competitors, the authorities, which represent the societal view, use regulation to ensure the incentives of distribution system operators to develop and maintain the network assets in an efficient manner [Hon09]. As electricity distribution networks already reach almost everywhere, the majority of present network planning can be seen as Brownfield rather than Greenfield planning. Brownfield planning has to deal with the existing network infrastructure in terms of remaining service lifetimes, which makes the starting point of the planning somewhat different to Greenfield cases, which are not encumbered with such a burden. This in turn, might require intensified incentives during the transition periods when making major strategic changes, e.g., such as changing from an overhead line network system to a fully cabled underground distribution system. However, in the long term the aim of the regulation and the goal of socio-economic welfare should meet [Haa12] [Hon09]. The differences, with regard to the objectives of the different parties related to power distribution, have been solidly presented in [Haa12], along with an approach introduced in [Alv11]. Many have considered the objectives of meeting the specific regulation model in force [Låg12] [Las07], rather than directly maximizing the socio-economic welfare [Las07b].

Regarding the actual implementation of the regulation in different countries, various approaches have been used. Whichever regulation model is in force, its main purpose is to provide the distribution system operators operating as monopolies with incentives for efficient operation and asset management of the network. In a rate of return model, such as is used in Finland [Hyv08], the allowed rate of return is calculated for each distribution system operator using certain indices from their performance and economy. In Norway the regulation is implemented using a revenue cap model [Hon04]. In Sweden the Network Performance Assessment Model (NPAM) was developed for regulatory purposes [Lar05] [Hyv08] [Hon04] [Wal08]. NPAM, which uses reference networks generated with an algorithm, is actually a very interesting approach when considering the main contributions of this thesis. The reference network used for the calculation of the Network Reliability Assessment (NPA) in NPAM is a radial network for which certain cost adjustments are made according to component redundancy and reliability cost [Ber08]. An interesting nuance is that the reference network often used in NPAM is also an underground network [Hon04]. This could be seen as a consequence of the political atmosphere, which strongly changed towards favoring underground cabling after the storm events of 2005 [Sta05]. Benchmarking against other similar DSOs has been studied in many countries as a means to evaluate the performance of the utilities [Hyv08]. This might function well in countries where there are enough cases from similar circumstances, but might be problematic in countries like Finland, where there are only a few considerably large urban networks.

When it comes to network planning, the most common way of dealing with the multi-objective task of minimizing the network costs and maximizing the reliability is to make all of the objectives comparable. If reliability can be put into present worth, directly comparable with the actual network investment and operational costs, the multi-objective optimization task is simplified to a single-attribute minimization task where the total cost is to be minimized. The reliability is often considered in terms of customer interruption costs, which is quantified with certain parameters based, e.g., on customer surveys [Sil05] or on the gross domestic product of the country [Mok97]. The use of customer interruption cost (CIC), in terms of a linear or linearized model with two parameters, one for outage power (€/kW) and another for the non-delivered energy (€/kWh), is the basic concept which is used in many studies [Låg12] [Las07] [Las07b] [Kiv04] [Kiv08] [Ver05] including this thesis. Another approach for considering network reliability is the use of strategic targets, e.g., aiming towards certain levels of the commonly used reliability indices, i.e., system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) [Pyl09], which, as brought up, might be a sufficient goal for urban networks having a strong customer base that is rather insensitive to minor changes in the total cost of the network.

Whichever the goal, the strategic means often brought up and studied in literature in the context of efforts for improving the reliability of the power distribution networks include network automation, sectionalization, the use of covered conductor overhead lines instead of bare conductor overhead lines, placing overhead lines next to roads, and underground cabling [Bri98] [Haa09] [Las07] [Las07b] [Låg12] [Låg07] [Pop05].

As for quantifying the reliability, fault rates often come up first as they make the foundation for all analyses [Ber02] [For50]. For cable networks, the fault rates used in these kinds of studies, while actual relevant observations for corresponding environments are lacking due to the relative newness of rural cabling, must be quantified and approximated using earlier observed data, e.g., from city and urban networks, and applied to the environments of sparsely populated areas. Estimations for the values of fault rates based on a rather broad international fault statistics base have been proposed [Ble89], providing a rather good baseline for all studies, despite the fact that some researchers have reported quite significantly differing lower values [Far93]. While comparing values from different sources, it is important to keep track of certain affecting factors, e.g., the applied voltage level in the different distribution systems and what causes are included or excluded while computing the actual fault rates. For instance, if the figures only relate to spontaneous structural failures excluding the faults related to external causes, i.e., faults caused by, e.g., excavation sites, which have been recognized to be one of the main reasons for failures in cable networks [Leh10], the standpoint for the analysis is quite significantly different. Considering overhead line networks, specifically in Finland, wind and storm, snow and ice, lightning and mechanical failures are known to be causing the majority of the faults in the distribution networks [Leh10]. While the discussion in this thesis slightly leans towards the local Finnish environment, very similar results concerning fault rates for overhead line networks have been reported from Sweden, where heavy snowfall and wind were found to be resulting in the highest risks related to failures in distribution networks [Wal12]. With an even broader international scope, weather has been recognized as one of the major factors affecting fault rates [Bol01] [Zho06], often combined with other characteristics of the environment [Wan02] (i.e., terrain types: open space vs. forests etc.). Thus, the results and findings of the case studies have a wider geographical significance but only strictly apply to the local Finnish environments.

One of the aspects related to reliability are major interruptions. The main problem with major interruptions is the large quantity of faults within a very short period of time. This, in turn, leads to an immediate lack of sufficient operational resources. Many papers conclude that underground cabling might be the only means to gain complete immunity against major interruptions, though in terms of cost-benefit analysis, full cabling is not seen feasible [Las07] [Las07b]. In addition, there are some cases where improvements can be achieved, e.g., by investing in intensified forest maintenance along the feeder corridors [Mar09]. One of the grounds for estimating the expected costs due to extremely wide and severe outages could be the reports made after such occasions, e.g., reports from the storm in Sweden in 2005 [Sta05]. When considering the degree and severity of a major disturbance, there is a major difference between the upper and lower ends of the scale. The above mentioned 2005 occasion could be seen as representing the upper end. Approaches categorizing major interruptions with regard to their severity have been specifically applied to Finnish environments [Par06]. Similar risk analysis approaches, with risk analysis here basically referring to probabilities of certain incidents multiplied by the magnitude of the consequences if realized, considering the Nordic areas (i.e., Finland, Sweden, Denmark and Norway) as a whole, but applied to the transmission system level [Doo06], but also specifically suited for the distribution systems in Sweden [Wal09], have been reported.

As mentioned above, different line types have different impact, e.g., on the immunity against major interruptions. In general, overhead lines are more prone to faults when compared to underground cabling. Some researchers propose that an overall optimal network is a mixture of different line types [Kum06] [Las07]. Then again, some studies have found it problematic to combine overhead lines and cables [Låg07], as, e.g., part of the reliability improvement investments is in such cases not fully exploited. Fully cabled network in the case of a rural power distribution is often found economically infeasible [Las07] [Las07b] [Mar09]. The present customer interruption cost parameters have been found to be 4-5 times too low to be able to change this balance [Las07b]. However, a question left open was the consideration of major disturbances and their future weight in the regulatory regime [Las07b].

However, the feasibility of all choices in distribution network planning might end up looking somewhat different when changing the viewpoint. It has been shown that the most feasible alternative for the owner of the assets includes plenty of cabling, as it results in high cash flow. For society the most feasible alternative is investing in sectionalization and placing overhead lines next to roads and a customer that prefers the lowest possible distribution fees, may best be satisfied with a maintenance oriented approach [Haa12]. If full cabling of all present overhead lines was to be implemented, the distribution fees have been estimated to rise by 30 to 50 percent, depending on the scheduling of the investments [Las07].

Technologies related to underground cabling, e.g., cable manufacturing and cable installation techniques such as ploughing, are predicted to be developing as more experiences are gained both domestically and in neighboring countries, e.g., in Sweden [Las07]. As mentioned above, an optimal network in Finnish rural environments might, in the end, be a combination of different technologies including different line types. Cabling used selectively in favorable environments is not an option to be directly neglected. Indeed, the lightweight cable recently developed in Finland and tested at Aalto University [Hyv13] could be seen as one of these kinds of expected progresses in the field of underground cabling technologies. This lightweight cable has been particularly optimized for low loaded rural networks, although opposing approaches have also been presented. One of the proposed applications is to set up strong cable trunk line sections feeding areas otherwise dominantly made of overhead lines. Such trunk lines can be valuable feeding points during major disturbances, providing more options for restoration and reconfiguration by the means of secured feed points [Loh05].

Sectionalization is one of the means to improve the reliability of distribution networks. In this study, three types of sectionalization equipment are considered: manually (on site) operated disconnectors, remotely (from network control center) operated disconnectors and relay-controlled reclosers. Reclosers are traditionally placed in main branching points of the network to separate long rural overhead feeders from other more densely loaded parts of the network. By this means the faults occurring on the rural parts do not interrupt the upstream customers, at least in terms of reclosing sequences and sustained interruptions. Voltage sags, however, might be an issue, which only changes in the point of common coupling can affect. During contingencies disconnectors are maneuvered in order to reconfigure the network and to restore supply to as much of the load as possible during the repair time. In literature, sectionalization has been found to be a feasible target for network reliability improvement investments [Mar09], especially in the case of overhead line networks [Låg07] [Låg12].

The geographical characteristics of network areas have gained less attention in the literature regarding distribution network strategic development. There are some recent papers, where, e.g., the European wide Corine land cover (CLC) data [Eea00] has been used in a study regarding network reliability [Las10]. Many other studies use parameters that are strongly spatially variable, but do not consider them as such and rather use global average parameters for all cases. When it comes to the suitability of the CLC data, it is known to be fragmentary and there are also some issues with the data not being up-to-date [Las10]. However, one of the mentioned incentives to use this CLC data is its free availability [Las10]. Even so, as the tendency has been to open data bases previously subject to fees for open access, this cannot be seen as such an important matter in the future. For instance, considering Europe, the member states of the European Community are obliged to take action regarding the legislation of the geographical information with an overall aim of creating a European wide infrastructure for spatial information (INSPIRE) [Eur07]. The Finnish law enacted following this directive guarantees access to the before mentioned infrastructure free of charge [Suo12]§12. In this study, these spatial differences are considered comprehensively. The topographic data used in this study is acquired from the Finnish Topographic Database (TDB) [Nls12], which is the most accurate and up-to-date topographic data consistently available over the entire country and is subject to the before mentioned law.

While the earlier discussion focused on the strategic development from the local specific operational environment of Finnish rural areas, the strategic development of rural medium voltage networks has raised concerns elsewhere too. What was discussed earlier concerning the selection of the view point and its relation to the different countries with differences in operational environments must be borne in mind. However, the strategic means to increase the reliability of distribution systems are largely the same as presented earlier for the Finnish case, e.g., the experiences and practices reported from Sweden, including the earlier mentioned converting of overhead lines to underground or overhead cables, sectionalizing the network and increasing the automation [Ben09] [Hil05] or, as another example, the experiences from the United Kingdom [Bri98]. Then again, one of the main differences in comparison to Finland might be in that in Sweden the 2005 events [Sta05] greatly increased the underground cable installations in a rather short period of time. In Sweden a law enacted soon after these events [Wal10] has consequently lowered the research interest towards line types other than the ones having the best immunity against major disturbances. Research interests have, then again, partly been directed, e.g., towards allocating the resources in aims to achieve what is required through these legislative actions [Hil05] [Wal12].

Considering the strong tendency towards cabled networks with expedited scheduling of the renovations in Sweden, some early results from the field might be available from those experiences. These are extremely valuable inputs for the verification of the effect of the listed strategic means by actually measuring the impact in terms of improvements in the reliability. In Sweden, a decrease of 40 percent in SAIDI values has been reported by converting overhead lines to underground cables [Ben09]. Further, in search of the similarities with the neighboring countries, the goals enclosed with the reports concerning the development of a so called universal rural cable system [Efr97] [Efr00] must be paralleled with the goals often brought up also in Finland concerning the expected developments in cable technologies as a whole. The overall concerns regarding reliability are without doubt universal in network planning, e.g., based on the review concerning the network planning algorithms earlier. Further, as discussed, different countries may use different implementations for the regulation. However, ultimately a universal concern is to provide the utilities with sufficient incentives to aim towards reliable networks with reasonable network fees [Edf05]. The strategic goals in network planning the same, but there are slight shades of difference in the approaches to achieve them. Nevertheless, the geographic environment is an aspect which has gained less attention and which does make differences between areas and countries. This is where this study aims to provide a fresh perspective.

While several of the above aspects of rural distribution network strategic planning were presented separately, recall what was said about network planning in general. Distribution networks are systems of inter-connected components and the development of distribution networks is a continuous balancing act with many variables. For example, reliability cannot be properly dealt with without considering the characteristics of the different line types, or the potential of investments in sectionalization, etc.

Chapter 3

General View on Power Distribution

Electricity distribution networks tie up a significant amount of capital in projects that have long payback times. The challenges that are faced due to overall changing operational environment, e.g., demands for improved reliability while being subjected to objectives of overall operational effectiveness, have resulted in critical considerations concerning the feasibility of conventional practices. Chapter 3 broadly discusses and provides views to the future operational environment of electricity distribution.

3.1 General view of the sparsely populated areas of Finland

Distribution networks in the sparsely populated areas of Finland consist of relatively long feeders supplying low loads. Certain centers of growth, essentially referring to the largest cities, are expanding, whereas the population in the rural areas is decreasing in many cases. This, in turn, has in some cases led to a situation where the load growth in terms of electricity consumption is very slow [Lak08] [Hyv08] or even negative. In certain regions, e.g., within a reasonable range from the above mentioned centers of growth, recreational dwelling might play an important role in bringing new customers to distribution utilities.

The use of electricity in rural areas is often dominated by heating of houses. Electric storage heating and water boilers for hot water supply utilizing time-of-use pricing and direct electric heating are common. Also, newer technologies such as heat pumps, both air heat and ground heat sourced, are growing in popularity. Similar trends have been observed in neighboring countries as well, e.g., in Sweden.

The Finnish climate, especially the winter and snow, provide challenges for many operations related to power distribution networks. In winter, snow causes frequent problems with overhead lines when trees lean against the lines, especially during and after heavy snowfall. Regularly performed maintenance routines also become more demanding in cold temperatures, e.g., finding and repairing faults in underground cable networks might be challenging. Crown snow load is a special condition that may be a problem especially in cold areas with significant altitude changes. This phenomenon is known to cause problems in, e.g., the Kainuu region, whereas it might not be that much of an issue in the southern parts of the country.

When considering the above mentioned challenges for distribution network operation, there are many significant differences between the different parts of the country: coastal regions differ from the inland areas, the terrain is typically hillier in the eastern parts of the country whereas the western coast is known for flat landscapes and in general the climate gradually becomes colder when moving up North. If a major storm, similar in scale to the 2005 Gudrun-storm in Sweden [Sta05], strikes Finland the Baltic Sea might be the most probable direction of approach. Less severe major storms are rather more frequent and gain a lot of public attention, e.g., the storm faced during the winter of 2011/12, as large numbers of customers experienced long interruptions following the difficult weather conditions around New Year.

Placing the power lines suitably helps in lessening the impact of storms and weather in general. This has, indeed, been studied quite often as a strategic means for the development of rural power distribution networks, as discussed in the literature review. In general, there are quite many aspects to be considered, when forecasting, e.g., the consequences of extreme weather on the power distribution systems. For example, strong winds from an unexpected direction (trees tend to get stronger facing the prevailing winds) combined with ground having no frost might result in severe consequences. Spatially considering, the characteristics of the terrain and vegetation will affect the resulting physical damage, e.g., comparing two of the most common species of coniferous trees in Finland: spruces have roots that run rather close to the surface, resulting in a proneness to fall down with strong wind loads, whereas pines have a strong vertical main root, better supporting the trunk against strong winds. Deciduous trees, mainly birches and alders, are often associated with problems in relation to snow loads.

Characteristics of the soil in Finland are typically challenging for underground installations. The most common soil type, moraine, is demanding for any groundwork, such as the installation of underground cables. The overall characteristics of the terrain and soil are indicated by considering the land use over the past. Most probably, geotechnically speaking, the most feasible areas have been utilized as cultivated land, meaning fields and meadows. Related to what was earlier discussed concerning winter, the ground frost resulting from the freezing and, consequently, bulking of the soil, might be an issue, especially with certain highly ground frost sensitive soil types, when considering the reliability of all underground structures with less than 2 meters depth of installation.

The deregulation of electricity markets was put in force in Finland with a law enacted in 1995. The law includes an obligation to differentiate the selling of electrical energy from the selling of electricity distribution services [Suo95][§28]. Distribution utilities do operate as monopolies within the geographically bounded distribution areas they have jurisdiction over. Conformity to the laws for the operations of electricity distribution companies is monitored and regulated by the Energy Market Authority (EMA). As discussed in the literature review, regulation in Finland is implemented using a rate of return model. There, a distribution system operator is allowed to collect a profit, which is determined by the regulation model. The actual profit of the company at the end of each regulation period is compared with the profit allowed by a periodically revised regulation model. According to the assessment, the network fees for the following regulation period are adjusted accordingly.

3.2 Expected changes in operational environment

In Finland, automatic meter reading (AMR) is widely used. Distribution utilities are obliged to have provided their customers with hourly based automatic meter reading by the end of 2013 [Suo09]. Considering the low voltage networks, automatic meter reading provides, e.g., a means for fault detection. Automatic meter reading also enables more precise load prediction, which can be based on hourly measured data. Also, the meters are typically equipped with contact assemblies making it possible to remotely control certain loads. This would seem to be a useful feature for certain smart grid applications, e.g., customer demand control of certain loads or demand response. Further, as the customer energy billing can be done on hourly based tariffs there can be seen a potential for different applications for enhanced demand side management (DSM). The data collected with the automatic meter reading can, in the future, provide means for analyses related to reliability [Las10].

The anticipated climatic change is, in general, expected to be causing more harm than benefit to the network business. It is expected that occasions of extreme weather will become more frequent. This, again, results in more incidents related to the different weather phenomena, especially in the case of overhead line networks. Lightning, snow loads, and stronger winds are predicted to be the main contributors of the increased numbers of problems [Mar06]. Further, the risk of major disturbances is expected to rise. These changes seem to be favoring underground cables networks over overhead line structures.

In view of the long service lifetime of the power distribution networks, it might be worth considering the possible market penetration of electrical vehicles. In particular, cable networks are known for their inflexibility. With high penetration of electrical vehicles, there might be consequences both for the sufficiency of available power transfer capacity and for power quality [Küt13] [Küt13b]. The load growth due to the charging of electrical vehicles might be considerable when compared to the electrical loads in rural networks today. Maximum power demand along with the consumed energy in the networks may increase significantly, especially if the charging of the electrical vehicles is not controlled by any means [Qia11][Las09][Las12]. This is often considered as a problem, but actually it might end up being a means to strengthen the turnover base in distribution networks of sparsely populated areas, partly mitigating the challenges related to financing the network services with the often considerably weak customer base, particularly, if the increased energy consumption comes with only a moderately increasing peak demands. Related to this, often, in the context of electrical vehicles, the rather considerable energy storage capacity is seen as a potential for different smart grid applications, e.g., demand side response in terms of controlled or delayed charging patterns, vehicle to grid applications, referring to feeding the energy from the vehicle battery back to network, e.g., during contingencies, or using the vehicle batteries to secure power supply for certain critical loads (uninterrupted power supply, UPS). Many of the above are thought to be motivated with incentives related to operational or investment costs. It might be possible to, e.g., avoid costly investments in increasing the network capacity or it might be possible to optimize the purchase of the electrical energy from the retail market. At present, the high cost of the batteries is still hindering many of these applications. One aspect to consider is also who gains in these arrangements. Intelligent charging could be seen to be based on incentives from the view point of the transmission system operator, distribution system operator, energy retailer or the end customer who drives the electrical vehicle.

As all renewable energy resources are expected to be favored for the power production in the future, the distributed generation (DG) of electrical energy might also become more general. For example, small wind turbines, small scale combined heat and power (CHP) units and photovoltaic generation might be more often placed in parallel with the consumer nodes in the distribution networks (i.e., prosumer nodes), e.g., making partly independent Microgrids [Mil12]. In cases where there are dispersed generation points in the distribution network, the protection schemes might need to be reconsidered [Kum04] [Kum05]. In addition, voltage levels and transition situations may need special attention [Mäk04] and, further, uncertainties related to the production of the distributed resources in general might be worth considering [Cel01]. On the positive side, need for investments in reserve connections may be less and the power losses of the network are lowered [Mil12]. However, there remain some open questions regarding the overall socio-economic feasibility of the high penetration of Microgrids. The economy of scale still applies to the production costs of electrical energy and the line beyond which the distributed generation combined with possibly partially islanded operation of certain parts of the power system, tightly related to the Microgrids, becomes more feasible option compared to conventional approaches has to be examined further.

In Finland, the regulator considers the customer interruption costs as one of the attributes affecting the assessment of the performance of the utility. Referring to what was discussed earlier regarding political intervention it might be that in the future these aspects gain more weight. On top of the customer interruption cost as an input in the assessment of the performance of the distribution system operator, there are additional obligations to compensate customers with part of the yearly fees in case of sustained interruptions of over 12 hours [Suo95][§27]. At present, the maximum for the recompense, gradually increasing with the duration of the interruption, is 700 euro, but there are clear indications that this maximum will in close future be raised to 2000 euro [Tem11].

3.3 Line types as the main building material of the strategies

By far, the most common medium voltage line type in Finland is the *bare conductor overhead line*. The planning philosophy at the time the now aging networks were planned and constructed was merely the minimization of the network length subject to technical constraints, e.g., voltage drop and thermal limits, with the aim of saving material costs. The concept of life cycle costing, also including broader concerns regarding reliability, is of later origin. Overhead lines were thus often routed through forests, which has resulted in many problems (noting that complete tree clearance is not usually considered feasible for medium voltage lines), e.g., with snow loads and vulnerability to massive destruction in the case of extraordinary weather conditions. A risk of devastative major storms with extensive destruction added to the more frequent and many times realized smaller scale major storms result in significant costs for the society and the distribution utilities. Some of these risks may be reduced by, e.g., placing the lines along roadsides where possible. Indeed the service security referring to the major destructions and the reliability in general is primarily the reason for the political anxiety concerning the strategic choices of future power distribution in rural areas.

When compared to bare conductor overhead lines, the *covered conductor overhead lines* have significantly fewer faults. There, conductors are covered with cross-linked polyethylene (XLPE) insulation. Considering the total length of the networks in operation, covered conductor overhead lines are not nearly as common in Finland as bare conductor overhead lines. However, in Finland roughly 50 percent, and in Sweden almost 100 percent, of all new overhead line installations are with covered conductors. Considering the challenges related to the operation of networks with covered conductors, regular patrolling of the lines in order to spot possible problems, such as leaning trees of fallen conductors, is required. Covered conductor overhead lines are often placed next to roads, which helps in carrying out this task. Covered conductor overhead lines require less clearance between and around the phase conductors, and hence the feeder corridor is typically narrower (3.5 m for CC against 8 m for OHL [Sen92]). Following this, acquiring the right of way especially for parallel covered conductor overhead lines, e.g., near primary substations, might be easier and less expensive than for multiple parallel bare conductor overhead lines.

Traditionally, *underground cables* have mainly been used in the distribution networks of cities and urban areas. The biggest advantage for underground cables is immunity against major destructions. Further, cables are aesthetically less disturbing, e.g., in densely built areas. On the other side, cables are often considered costly and inflexible and, although, being less prone to faults, repair times are longer than those with overhead structures and repairing is more costly. Considering a totally new system, i.e., extensive rural cable network, technical issues, e.g., related to high earth capacitances, and accurate and fast fault locating [Pro09] need to be considered. A significant portion of overall investment cost related to underground cable networks is due to earthwork, strongly varying with the specific geotechnical characteristics of the installation site.

Comparing *cable network* with *overhead line network*, the latter option has significantly weaker capacitive coupling to ground and between the phase conductors, resulting in lower levels of earth fault and capacitive charging currents. Concerning *networks of all line types* in Finland, the medium voltage systems nearly always have either an ungrounded neutral or a resonant earthed neutral, mainly due to poor conditions for grounding. A system with resonant earthed neutral requires fewer reclosing sequences to clear earth faults than a similar system with an ungrounded neutral, as part of the faults with lowered current spontaneously extinguish prior to the relay operation, resulting in no interruption to the customer.

3.3.1 Overview of some alternative line types

In addition to the above mentioned, there are some other possible future alternatives. A few of them are overviewed here, but are not further concerned in this thesis. When bypassing, e.g., rock exposures in fully cabled network systems, overhead cables may well be an option worth considering. Further, if the laborious process of acquiring the right of way for the feeder corridors is seen as one of the aspects strongly affecting the terrain planning processes, an overhead cable being the option requiring the minimum space, might be having an advantage. Overall, the issues related to obtaining the space for the power distribution systems might gain more weight in areas, where the different needs of a multitude of different users of the public space and landscape are present, e.g. in the proximities of cities, in recreational areas having sensitive landscapes, and in protected areas and national parks. In general, with strategic choices made under uncertainty, e.g., related to load growth, an overhead line being less costly to upgrade might provide an option with smaller risks. Detection of incidents, such as trees fallen onto overhead cables, faces similar problems as covered conductor overhead lines. Proper protection against lightning overvoltages also needs to be considered carefully.

1000 volt systems developed as a substitute for medium voltage lines in certain cases benefit from being classified as low voltage [Eur06]. One of the major advantages with the 1000 volt system is the utilization of the low cost low voltage equipment used for 0.4 kV service level systems. With a 1000 volt system maximum cable length subject to voltage drop constraints, is improved up to six times in comparison to an equivalent 0.4 kV system. Further, 1000 volt systems benefit via making separate protection zones in the network, which is a means to improve the overall reliability of the network [Las07b] [Loh05]. On the other side, additional costs include the needed connection unit and the special transformers, and the additional power losses of the transformers, which provide the additional voltage level. Typically, 1000 V systems are radial spurs feeding only a few customers [Loh05] using cables installed in the road structures (lower priority private roads) by cable ploughing. It is considerably easier to acquire the right of way for a low voltage cable installation than for a medium voltage overhead line. Quite often, 1000 V cases are feasible for load ranges of 10 – 50 kW and 1 – 5 km distances [Lak08] [Loh05].

3.4 Network sectionalization and reserve connections

Sectionalizing the network provides a powerful means to improve the reliability of the distribution network. Sectionalization in itself does not affect the expected number of faults. In fact, in terms of adding fault prone components to the network, it might even increase this number. However, sectionalization provides the means to reconfigure the network during contingencies in order to restore the supply to as much of the load as possible within the operating time of the switches and to isolate the faulted sections, with as few loads as possible, from the network during the repair. More details concerning the optimal placement of the switches and reserve connections in the NTOA being utilized in this study can be obtained from [Mil12b].

3.4.1 Circuit breakers and reclosers

In all distribution systems, the core of the protection lies within the circuit breakers at the primary substations. Circuit breakers are primarily controlled by the means of local automation, referring to the different relays observing the status of the network at all times. Several different relays are used and configured for the detection of, e.g., earth faults, specifically designed for isolated or resonant earthed neutral systems, and short circuit faults. The problem with having circuit breaker protection only at the primary substations is that if the circuit breaker is opened and then closed after a set delay, e.g., in order to clear a temporary fault, all the customers connected to the same feeder will experience an interruption.

Reclosers are circuit breakers that have the capability to break short circuit currents and have the relaying built in. Reclosers can also be placed along the outgoing feeders in places where the benefit gained through improved reliability, in terms of what was earlier discussed about the number of interrupted customers and the related interruption costs, is maximized. The short circuit currents due to faults occurring further in the network are less than that of the faults occurring near the busbar of the feeding primary substation. This, in turn, might lower the requirements set for the performance of these reclosers, often mounted in poles.

Reclosers clear the short circuit faults and, if used, reclosers placed in optimal places in the network help in reducing the interruption costs. Voltage sags, however, are another power quality aspect, on which reclosers and circuit breakers have less means to affect. The duration of the sags can, though, be affected by configuring the relay tripping delays accordingly, within the limits set by the selectivity of the protection.

3.4.2 Disconnectors

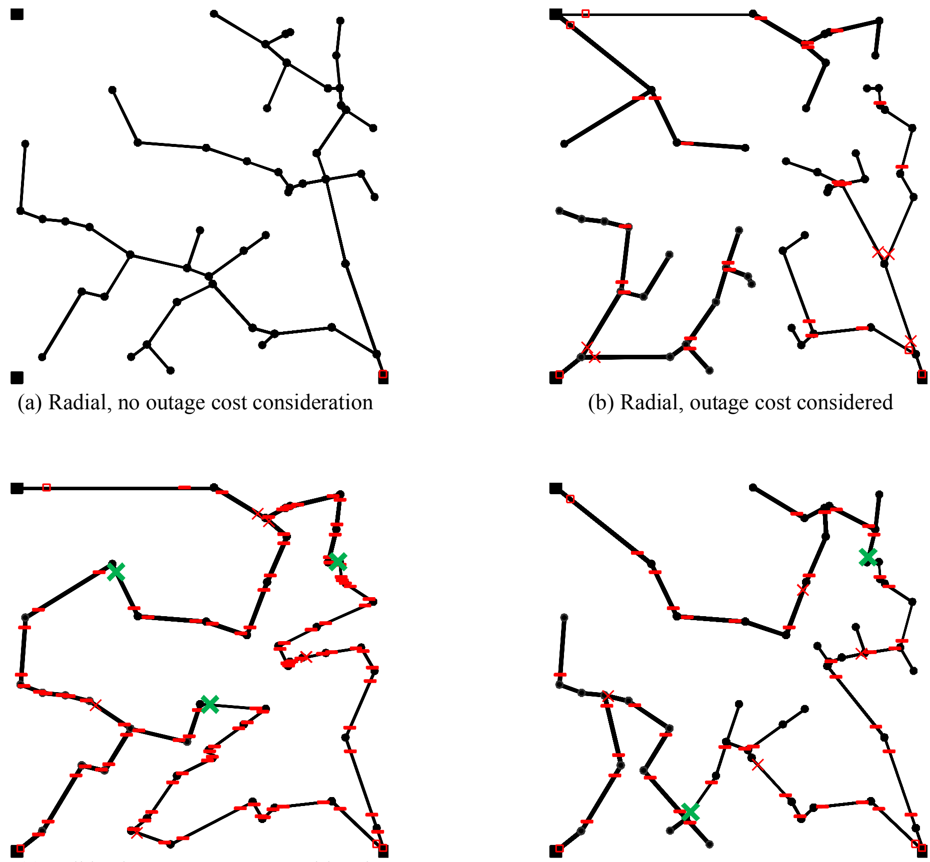
Disconnectors (sometimes also referred to as sectionalizers or switches) do not have the capability to break short circuit currents. Thus, they can typically only be operated once the circuit breaker has opened the faulted circuit. Disconnectors are often load-making (and sometimes load-breaking), meaning they can be closed onto the load without an additional circuit breaker operation, e.g., after reconnection of the repaired line section.

One of the other major differences in comparison to circuit breakers, which, as discussed, are primarily operated using relays, is that disconnectors are often operated either manually on site or remotely from the network control center. Whether the disconnector is manual or remote operated, in turn, affects the switching times. The switching of a remote controlled disconnector might take a few minutes, whereas with manual operation of a disconnector the switching time varies, e.g., according to the distances the service personnel have to travel to access the switch. Automatic switches are disconnectors configured to be operated under the SCADA (supervisory control and data acquisition) system automatically, without the need for the network control center personnel to take action.

Disconnectors are primarily used for reconfiguring the network when needed. During contingencies caused, e.g., by line faults, they are used for fault isolation and supply restoration as discussed earlier. Similar reconfiguring of the network is also used during normal maintenance works, e.g., changing the poles, however, customers are informed of these kinds of interruptions in advance in order to minimize the inconvenience. Automatic switches, together with a strongly backed-up network topology, and possibly even meshed configuration during normal operation, might in the future be one of the means in order to achieve the functionalities of smart grids, e.g., referring to self-healing networks.

3.4.3 Reserve connections

When considering the means of sectionalization in order to enhance the reliability of the distribution networks, reserve connections are closely related to the reliability improvement investments on sectionalization. In a radial network topology without reserve connections, it is only possible to restore supply to certain customers and the customers downstream from the nearest upstream disconnector from the fault will have to be interrupted for the entire duration of the repair (unless, e.g., movable reserve cables or reserve power supply units are used for restoration of the supply). By means of reserve connections, the supply can be restored to a larger portion of the customers. Figure 3.1 presents different fundamental network topologies, considering reserve connections and sectionalization.



(a) Radial, no outage cost consideration

(b) Radial, outage cost considered

(c) Full backup, outage cost considered

(d) Optimal backup, outage cost considered

Symbols: primary substation (■), secondary substation (•), circuit breaker or recloser (□), remote operated disconnector (x) and manual disconnector (-). Green symbols stand for normally open switches.

Figure 3.1. Different basic network topologies: (a) radial network without concerning reliability (which results in no motivation for reserve connections nor for sectionalization), (b) radial network with reliability costs included in the objective, (c) fully backed-up network and (d) a life cycle cost optimal network having cost-optimal backup (reserve connections and switches).

In this thesis, the terms full backup (Figure 3.1c) and cost-optimal backup (Figure 3.1d) are often used. Full backup, by definition, means that each of the load nodes has a backup against all possible individual line faults, i.e., it has two possible feeding directions, and also that each of these nodes is equipped with either manual or remote switches or reclosers on both sides. Only requiring the above ensures that supply for all load nodes can be restored by the means of reconfiguring the network against all possible line faults. This, indeed, means that having full reserve connections alone is not sufficient to meet the requirements of full backup. Further, in some cases it may be considered, that the primary substations serving as feeding points for the load nodes are not completely secure, meaning they have a certain level of availability (less than 100 %). In the NTOA utilized in this study, a reserve supply can be forced to be arranged from a neighboring primary substation, instead of a neighboring feeder from the same primary substation. This may be relevant in certain rural networks, where the primary substations are sometimes supplied by radial 110 kV non-backed-up lines (instead of the *N*-1 approach, which would provide security from any individual component failure). Further, with primary substations with a single busbar system and with primary substations with a single main transformer, backup from neighboring primary substation is needed, e.g., during maintenance work of these components.

Using optimal backup (Figure 3.1d) simply means that each of the reserve connections, enclosed with the cost-optimal sectionalization, is considered in terms of its impact on the overall network cost over the review period. A purely radial network topology might consider interruption costs, Figure 3.1b (however, in the literature this is often not the case, rather, radial networks without reliability considerations are often proposed, Figure 3.1a), but optimally placed reserve connections are not considered as a means for finding an overall optimal network topology. Purely radial networks cannot be seen as feasible in reality, as reserve connections (sometimes referred to as tie-lines in the literature) are commonly used in present rural networks. Tendency to emphasize the reliability aspects in strategic planning seems to be increasingly favoring the use of optimized backup in rural distribution networks.

3.5 Finding a balance with heuristics and policies

The case studies, observations from which are one of the main contributions of this thesis, is carried out using the algorithm developed as the other main contribution. For such an algorithm, the given parameterization, again considered as one of the main contributions of this thesis, is the exclusive means to describe all the characteristics of the operational environment. Quite often a situation arises where the planner using such an algorithm suggests the avoidance of certain alternatives or operation models intuitively based on engineering rationalization. Consider, e.g., the installation of underground cables in mires, which are being forcefully prepared for the purposes of forestry. In these kinds of situations, the user, eventually having the best professional knowledge when considering the realistic characteristics of the actual operational environment, might want to set heuristic obstructions for certain alternatives. Algorithms, as support tools for distribution network planning, may provide their unbribable opinion, yet the interpretation of the results requires good expertise from the user. Using any heuristic should always be a subject to a careful consideration, as the objectivity of the results from an algorithm is one of their major pros and can often challenge pre-held assumptions and simplistic generalizations.

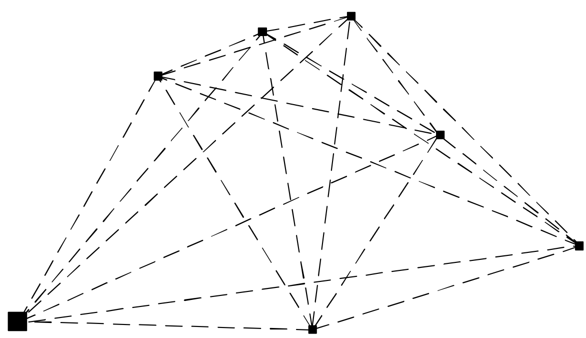
Referring to what was discussed above, concerning the actual characteristics of the operational environment, in practice, there are often, e.g., many company policies and legislative issues limiting the variety of the actual technical alternatives being available in each situation. For example, referring to what was earlier discussed concerning the differentiation of the operations in the electricity business; these separated operations might often operate under a common company brand, which might be considered as an important asset and, in terms of the company strategy, should be positively evocative. These kinds of lines of thought might bring up questions concerning what was originally the aim with the differentiation of these businesses and how well has this goal been achieved.

Political interventions might, in a very short time, strongly shake up the operational environment of the electricity distribution business. Often this is referred to as the risks related to the regulation. In Sweden, these kinds of politically raised compulsions have led to changes in the legislation directing the operations of the distribution utilities. There it is enacted in a law, that interruptions longer than 24 hours might lead to further consequences. It is not known how severe these consequences would be in practice [Wal11][66]. However, this can be seen as a very clear indication from the government to motivate the utilities to strongly consider the use of line types immune against major disturbances. If this kind of law is passed, the strategic planning processes are, indeed, simplified quite significantly, as certain line types are in practice excluded from the portfolio of the regulatory-economically feasible alternatives.

Electricity distribution networks are a critical and vital infrastructure for modern societies. Political decisions made to secure the reliable energy supply might, however, sometimes be missing objective consideration of the contradictorily affecting attributes. More reliable networks typically cost more and, in the end, customer is the payer of all the extra costs. If any major changes of the course are made, these should be justified based on an analytic and objective consideration, being aware of the different aspects and being able to tell what, is the role of each of the affecting factors.

Chapter 4

Introduction to Research Methodology



This chapter discusses the techno-economic basis for network planning in general. The underlying reasons for applying dedicated computer applications instead of a manual approach for the case studies in the thesis, are presented.

4.1 Feasibility analysis in network planning

In general, finding a single solution being able to optimize multiple conflicting objectives simultaneously, e.g., minimizing costs along with maximizing reliability, in studies concerning complex systems is usually not possible, but rather the solutions can be considered as compromises considering different views. Originally in economics, but also in the field of power systems engineering [Cos12], these kinds of problematics have been approached using, e.g., the concept known as Pareto optimality. Pareto optimality, broadly, refers to situations or solutions, where all the changes concerning any of the attributes lead to reducing the benefits in terms of some other attribute. In this thesis the aim is to quantify and combine all the multiple conflicting objectives into a single objective, being the total cost considered over the review period.

4.1.1 Socio-economic objective in network planning

The aim in network planning is to find a technically acceptable economical solution. Usually there are different competing technical alternatives, e.g., cable network or overhead line network, among which the task is to find the most feasible alternative. Generally, using different technologies, having individual characteristics, results in different optimal network topologies and in differences in where to stand with the characteristics of the terrain and geography. This, as discussed earlier concerning the formulation of the research problem of this thesis, makes a direct comparison of the different alternative technologies misleading. In equitable comparison an optimal network structure for each of the alternative strategies must be considered. Generally, concerning the formulation of the objective, quite similar approaches with the one used in this thesis, has been proposed in many studies [Hon09] [Hyv08] [Lak08] [Las07] [Las07b]. The optimization task from the socio-economic view point can be presented as Equation (1),

$$\min\{C\} = \min\{C_I + C_L + C_O + C_F + C_R\} \tag{1}$$

where

C	is total cost (over review period),
C_I	is investment cost,
C_L	is cost of losses,
C_O	covers operational and maintenance costs,
C_F	covers interruption costs (including CIC, repairing etc.) and
C_R	covers the residual value and demolition expenses.

The total cost over review period (C) is minimized while considering the technical, legislative and regulatory constraints. These constraints include, e.g., the allowed voltage drop, thermal load capacity, short circuit withstand, demands for reliability of supply and service security, fault detection and procedures during contingencies and electrical safety regulation.

4.1.2 Approaches for evaluating economic feasibility

As discussed earlier in this thesis, and in literature, the view point, e.g., whether it is the socio-economic, the regulatory-economic or the customers view point, strongly affects, not only the formulation of the objective, but also the resulting feasibility of different strategies [Haa12] [Alv11]. Given the societal view point, considering certain adjustments used in the calculations, e.g., customer interruption cost reducing the benefits of the customer, the benefits of all alternative strategies are considered equal. From the perspective of an individual distribution system operator the benefits of an investment would strongly depend on the regulation. In general, there are different approaches for evaluating the economical feasibility of certain project. The ones being used most commonly are net present value (NPV), equivalent annuity, payback period and internal rate of return (IRR).

Regardless the approach considered as best suiting each situation, the basic concept of time value of money is applied by applying the interest rate to the installments occurring at different times during the review period. Net present value method does this by summing the overall costs and profits, using relevant discounting factors, to get the net present value projected to an equivalent worth at the first year of the review period. The equivalent annuity method is closely related to the net present value method, except that instead of total an equivalent sum over the review period, the cost over the review period is divided into yearly annuities. Annuities are often used when comparing projects with different service lifetimes. In industry, feasibility of investments with a relatively short service lifetime is often evaluated using the payback period method. There, the costs and benefits are compared and the payback time is considered the time the savings pay back the investments. Similarly, for internal rate of return, the variable attribute is the interest rate which equalizes the profits and costs given the other attributes.

The economical studies involved in the network planning concern an additional highly important attribute to the above mentioned interest rate p and review period t, namely the load growth ρ. The profits produced by certain network are tied with the loading of the network and also certain variable cost components are either linearly or quadratically proportional to the loading of the network. Consequently, the economic feasibility cannot be accurately measured without having the timely progression of the demand being modeled sufficiently. The capitalization factor K [Lak08] to be used for the net present value of the different cost components is,

$$\kappa = \psi \frac{\psi^t - 1}{\psi - 1}, \tag{2}$$

where, for yearly installments being quadratic relative to the demand (e.g., line losses)

$$\psi = \frac{(1+\rho)^2}{1+p} \tag{3}$$

and for yearly installments being linearly relative to the demand (e.g., customer interruption costs)

$$\psi = \frac{(1+\rho)}{1+p}, \tag{4}$$

where

K is the capitalization factor (a),
Ψ is an intermediate variable,
t is the review period (a),
ρ is the load growth (1/a) and
p is the interest rate (1/a).

The above Equations (2)-(4), derived using the properties of geometric series, are used to convert the yearly occurring installments to the present values based on the installments of the first year of the review period. For installments remaining constant for each year over the entire review period, e.g., for the no-load power losses of the transformers, the relevant capitalization factor can be acquired using a zero rate of load growth. If, e.g., the load growth is expected to be changing over the review period, according equations, applied, e.g., separately for each of the years, must be used. In the NTOA, used in this study, the load growth can have separately individual values for each of the load nodes and for each year over the review period, enabling the consideration of spatially relevant development scenarios for each geographic location.

Considering the review period, related to the service lifetime of the components [Zha07], there are different perspectives. Technically considering, each of the components of the network has its expected time of service, e.g., the wooden poles impregnated using certain chemicals combined with certain stresses due to environmental conditions, e.g., moisture and sunlight, are expected to withstand 30… 45 years of operation. However, internationally considering there are cases, where network components, e.g., insulators near the sea might have drastically shorter service lifetimes, i.e., only 5 years [San89]. Thus, strongly depending on the characteristics of the operational environment, there might possibly be a need to consider the different service lifetimes of different competing strategies, e.g., by using annuities instead of net present values. Apart from the technical service lifetime, an economic service lifetime of, e.g., certain overhead line conductor might relate with unexpected changes in load growth, resulting in economically feasible upgrading earlier than what would be technically necessitated. In areas with stable and well predictable development, the network installations typically serve close to what is technically feasible, whereas in areas of rapid and unexpected changes in the load growth, the economic service lifetime is often shorter. Table 4.1 lists some typical values for the ranges of technically feasible service lifetimes.

Table 4.1. Technical service lifetimes of certain network components [Ene05]

Component service lifetime (a)	
Pole-mounted secondary substation	25…40
Pad-mounted substation	30…40
Transformer (MV / LV)	30…40
Overhead line, MV	30…45
Disconnector, light	25…30
Remote operated disconnector station	25…30
Underground cable, MV	30…45

4.2 Choosing an approach: an optimization algorithm

Distribution network topology planning being an overall complex multi-objective optimization task and, further, as the aim of this study is to include a large amount of detailed geographic data in this process, a manual approach cannot be seen as an overall feasible option. To put it straight, the vast number of recognized inter-relations of the different related aspects, e.g., placing the feeder corridor affecting, e.g., the line lengths, spatially varying fault frequencies and construction costs and, on the other side, on the benefits gained through improved reliability, are the main reasons that motivated using an automated routine, an NTOA, in this study. With this approach the benefits of the considerable computing resources provided with present commercially available hardware, are efficiently utilized. Further, once the automated routines are set, also the sensitivity analyses, enclosed with studies with uncertainties concerning the initial data and parameterization, are made with fewer efforts.

The above mentioned aspects related to the problematics of the distribution network planning are next demonstrated with a brief study on a small example network. Figure 4.1 illustrates a proposed topology for a simple made-up 7 node cable network. It is obvious that the candidate network presented by the solid lines in this example is not the shortest in terms of total length. However, if this were to present a network topology resulting from a more comprehensive study, than that of only minimizing the total length of the network, where it is considered that the cable installations in rocky areas are costly and prone to faults, the longer routing following fields might be justified in terms of total costs and reliability.

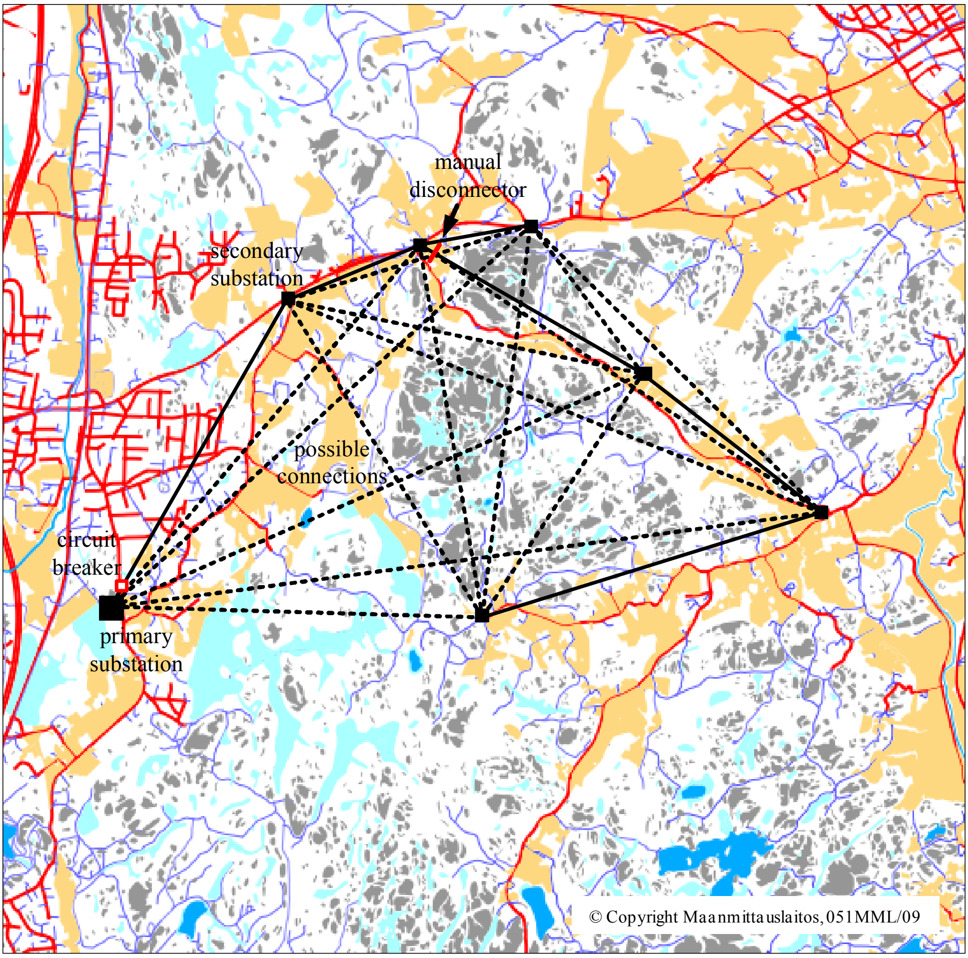


Figure 4.1. Simple 7 node example network representing all possible node-to-node connections (dashed lines), a candidate radial network (solid lines) and sectionalization for that particular candidate network (one manual disconnector and the default circuit breaker at the primary substation)

Dashed lines in Figure 4.1 represent all the possible connections in this network. Each of the connections is involved with vast number of details of geographic data, which can be concretely referred to with the visual presentation of such geographic information being the map image on the background. If, e.g., the accuracy of the geographic information is 5 m and the internodal distance is 3 km, a circular area enclosing the internodal connection with a scaling factor of 1.5 would include a number of geographic information elements of

$$\frac{\pi(1.5 \cdot 3\,\text{km}/2)^2}{(5\,\text{m})^2} = 0.64 \cdot 10^6 ,$$

which would provide a number of possible routings connecting the two nodes being much greater.

Generally considering the number of internodal connections, then again, in a network of N nodes all the possible internodal connections can be presented in an N x N matrix, which has N^2 elements. However, ignoring the diagonal elements (connection of a node with itself) and considering the direction of the path irrelevant (the cost for the path from node N_1 to node N_2 equals to the cost for the path from node N_2 to node N_1), the number of needed elements for fully describing the connections reduces to $(N^2 - N) / 2$, which in this 7 node case is 21 connections. This number is not to be confused with the number of alternative topologies and the vast number of alternative configurations related to each of the topologies, also considering possible reserve connections and the disconnectors (three alternatives for each location, in this case 11 locations, ignoring the default circuit breakers for each of the outgoing feeders), for the network of N nodes – that number is much greater. It is worth noting that the candidate network is presented only as topological schematic and the actual internodal routing would follow the least-cost path (usually longer than the Euclidean distance). This figure is meant for emphasizing the need for an approach, where the topography and topology must be considered together using the main objective of network planning, the full life cycle cost including also the interruption costs and other variable costs.

Now, all the possible topologies of a network under study (typically up to 350 nodes), also considering possibly more than one alternative line types individually for each of the internodal connections, the reserve connections, three alternative types of sectionalization devices and the topographically optimal routing, with regard to that particular combination of network topology and configuration, must be considered in terms of overall optimal solution. The optimal network is simply the one which, in the end, gives the lowest overall life cycle cost. The problem with realistically sized networks is that there are too many alternatives to be able to consider them all systematically. Evidently, a more efficient way than a purely exhaustive method, which approach has sometimes been applied to the significantly smaller scale problem of only reconfiguring an existing network [Mor00], must be used to find a near-optimal or practically most feasible network.

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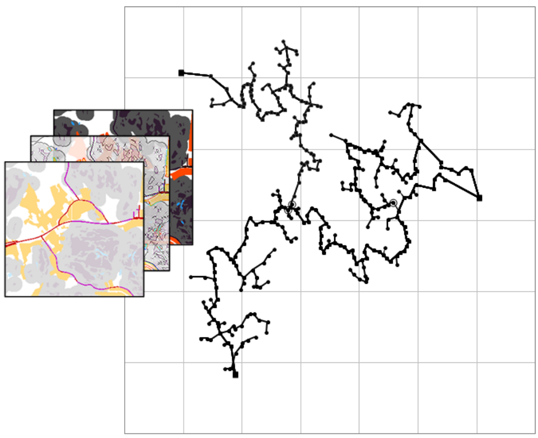
Chapter 5

Providing a Network Topology Planning Algorithm with Geographic Information



This chapter introduces the algorithms that form the core of the methodology presented in this thesis, building on the theoretical considerations from Chapter 4.

5.1 The VOH algorithm

A schematic of the main routines of the NTOA, also referred to as VOH following its Finnish acronym, used in this study is shown in Appendix 6. In this NTOA the optimization starts with the generation of a radial network. Different branch exchange functions, among others, are then used to produce a network including also the reserve connections. The sectionalization meaning the disconnectors (manual and remote operable) and reclosers are considered as well as the open points and the optimal configuration for the normal operation. The reserve connections, sectionalization equipment and open points are all considered with regard to the complete main objective of minimization of the life cycle cost as given in Equation (1), including the fixed costs as well as the variable costs. There are means for overruling this least-cost driven selection of, e.g., the backup or the sectionalization. A network can, e.g., be forced to have full backup or full switching (meaning disconnector at all possible locations). However, it is worth emphasizing the basic case where none of these user set heuristics are in force that all decisions are always simply aiming towards an objective of minimizing the life cycle cost of the entire network. Some of these basic scenarios using different planning preferences were shown earlier in Chapter 3 on page 45 while discussing the sectionalization and the reserve connections.

5.2 Providing VOH with accurate geographical model

5.2.1 The concept of life cycle cost driven cost surfaces

In the following novel approach [Saa13], the individual node-to-node specific life cycle cost (LCC) surfaces are used in the computation of the internodal specific parameters for the entire network and are to be used in the network topology optimization process of the NTOA. According to the literature review, there were no indications of any similar approach, being capable of dealing with the variable costs, i.e., reliability and power flow related cost components, being introduced before.

The individual cost surfaces are computed using the node-to-node connection specific topological parameters, first derived from an initial network. In this approach the cost surfaces vary depending on the specific configuration of the network. Special emphasis is put on making this initial network as objective as possible, which in turn reduces the need for further iterations. This chapter focuses solely on presenting the methodology later used for the case studies.

5.2.2 Formulation of the objective

Quote[2] from [Saa13] starts (ends on page 66): “Equation (1) is the main objective function, which presents the total life cycle cost of the network and is to be minimized over the review period. The function (5) is used for the computation of the raster cost surfaces, i.e. for the cost per unit distance values C_{rc} valid inside each of the geographically referenced raster cells,

$$C_{rc} = C_{bas} + C_{rw} + C_{inst} + C_{maj} + \lambda \cdot \left(C_f + C_{msw} + C_{rsw} + T_r \cdot C_{rep}\right) + \lambda_{re} \cdot C_{re} \tag{5}$$

where

C_{rc}	is the cost per distance unit (€/m),
C_{bas}	is basic fixed line cost incl. power losses (€/m),
C_{rw}	is right of way cost (€/m),
C_{inst}	is installation cost (€/m),
C_{maj}	is major interruption cost (€/m),
λ	is fault frequency (1/100km/a),
C_f	is cost per fault (€),
C_{msw}	is cost per manual switching (€),
C_{rsw}	is cost per remote switching (€),
T_r	is repair time (h),
C_{rep}	is cost of time spent in repairing (€/h),
λ_{re}	is reclosing frequency (1/100km/a) and
C_{re}	is cost per reclosing (€).

Static parameters related to geographical data include C_{rw}, C_{maj}, C_{inst}, T_r, λ and λ_{re}. Variable topology and node-to-node connection specific parameters include C_f, C_{re}, C_{msw}, C_{rsw}, C_{bas} and C_{rep}.

Cost surfaces are basically matrices, where each element contains the cost per unit distance (C_{rc}) valid inside a geographically referenced raster cell. Vertices of the graph are defined to be the center points of each of these cells. Now the cost of moving from the vertex i to another vertex j can be calculated simply by integrating the cost per distance with regard to distance x following the segment of a line connecting the vertices i and j, refer to Equation (6):

$$C_E(i,j) = C_E(E) = \int_0^d C_{rc}(x)dx \tag{6}$$

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where

C_E is the cost of an edge (€),
E is an edge connecting vertices i and j and
d is distance between vertices i and j (m).

A graph is generated by allowing certain connections (edges) between the vertices. All the possible connections of an n elements wide and m elements high cost surface can be presented in an (n x m) x (n x m) matrix, where the diagonal refers to connections of an element with itself (trivial case). The lower triangular matrix is the upper triangular matrix mirrored in respect to the diagonal, because the connections are considered direction independent (cost for connection from i to j equals cost of connection from j to i). Each of the raster cells has 8 direct neighbors (except for the borders) and 16 second neighbors, etc. When not only the first neighbors are allowed, the routing direction will not be limited to multiples of 45 degrees. This results in a more complex graph having more connections and longer computation time, but makes it possible to find routes of lower cost and also routes that are more realistic.

The optimization task is to find the node-to-node (N_1-to-N_2) least-cost-path through the graph generated from the cost surface by allowing the most desirable connections (Equation (6)), i.e., min(C_{path}), where the cost of the path (C_{path}) is defined by the following Equation (7),

$$C_{path}(N_1, N_2) = \sum_{E \in path} C_E = \sum_{E \in path} \int_0^d C_{rc}(x)dx \tag{7}$$

where

$path$ is a list of edges making a connection between nodes N_1 and N_2,
C_E is the cost of an edge and
C_{path} is the total cost over the path from N_1 to N_2.

The optimum path is found by applying the Dijkstra algorithm [Dij59] to the costs of connecting the raster cells (Equation (6)).

5.2.3 Main process of the algorithm

Figure 5.1 presents the main process of the developed method. The process starts with the generation of an initial network using a Network Topology Optimization Algorithm (NTOA). Topology in this paper refers to the connections between the substations (nodes), sectionalization of the network (switch disconnectors and reclosers) and the normally open points of the network. In literature, *routing* is sometimes used as a synonym to *topology*. However, in this thesis routing refers to the geographically oriented detailed path between a given pair of nodes (i.e. substations). The initial network topology is generated based on default parameters for permanent fault and reclosing frequencies, repair times, standard fixed line costs (assuming average installation conditions) and a scale factor to approximate the actual distance between connected nodes based on their Euclidean point to point distances. The initial network is then used to calculate the topology related and node-to-node connection specific variable parameters mentioned above, which are used in the calculation of the cost surfaces. These should be readily available from the NTOA, especially if it computes network interruption costs in terms of the various cost components (per fault, reclosing, manual switching, and remote switching) due to faults or reclosings on each line section of the network [Mil12b].

Static geographical data is brought into the cost surface cost function as well. Several sources of geographical data (layers $GI_1 \ldots GI_n$) can be used simultaneously, as illustrated in Figure 5.1. Different layers can be used in order to obtain a better and more accurate model of the environment. For example, soil map data and ground elevation data (which can be used to calculate inclination) could be used to adjust the installation cost of underground cables, different forest types (referring to forest maps) could be used to more accurately acquire location specific fault rates for overhead lines, land owner data could be used to minimize the number of land owners involved in the terrain planning process, etc. The different layers are considered in the cost function. To demonstrate this, an approach utilizing geographical and network information applied in a statistical model is proposed in Chapter 6 starting from page 78. In the example process presented in this thesis, the cost function only considers a single layer, which is formed from topographic data.

The cost surfaces are calculated individually for each of the node-to-node connections using Equation (5), making it possible to consider all the cost components in the primary objective cost function presented in Equation (1), including outage costs, the cost of losses and the other variable costs.

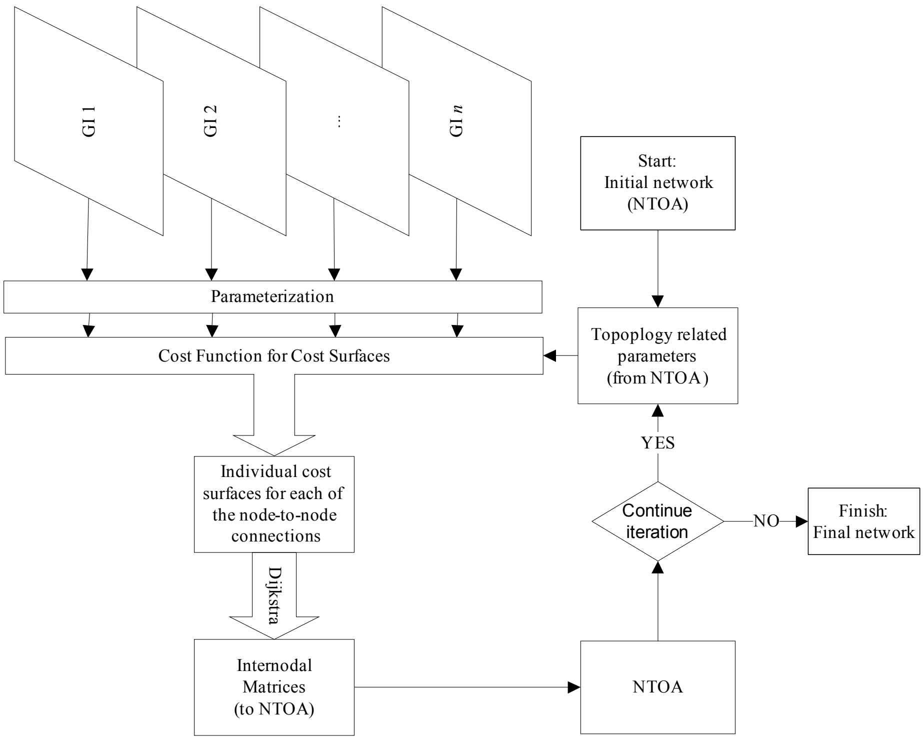


Figure 5.1. Main process

Figure 5.2 shows the computation of the cost surfaces and their use in the internodal parameter computation in more detail. Once the cost surfaces have been calculated (Figure 5.2c), the Dijkstra algorithm [Dij59] is used to find the least-cost-path (Figure 5.2f) between the nodes, i.e. through the cost surfaces, considering the full objective cost function of Equation (1) and all its cost components.

The least-cost-path found by Dijkstra is again used for the generation of the node-to-node specific parameters computed as distance-weighted averages (Figure 5.2g). As is illustrated in Figure 5.2d-g, the internodal parameters are computed using only the static geographic data and following the network-optimal path. The variable topology parameters are only used as cost drivers in the search for the network-optimal path for each of the individual internodal connections, but are not included in the internodal parameters once the least-cost-path is found. The NTOA will generate new variable topology parameters in the next iteration, where the network plan will be generated with the benefit of the geographically influenced internodal parameters, rather than the default parameters used for the initial network.

This process is repeated separately for each of the node-to-node connections until all the internodal matrices (k x k matrices, where k refers to the number of nodes) are filled with node-to-node specific internodal parameters: internodal distances, internodal fault frequencies, internodal fixed cost corrections, internodal reclosing frequencies and internodal repair times. Each of the individual $(N^2 - N)/2$ connections has an individual set of these six parameters, which are used in the NTOA in order to find the optimal network topology in order to best satisfy the main objective function (1).

In reality, at least with the NTOA developed at the Aalto University [Mil12] [Mil12b] [Mil09] [Mil13], the number of proximate nodes to which a node can be connected is heuristically limited. NTOAs typically use a series of routines that force the network out of locally optimum but globally sub-optimum solutions. Remote connections might be needed in such routines, but for this purpose the default parameters are sufficient. Limiting the reach of possible connections to a fixed number of closest nodes makes the process much faster. However, this number is a user setting, which can be set to any preferred value.

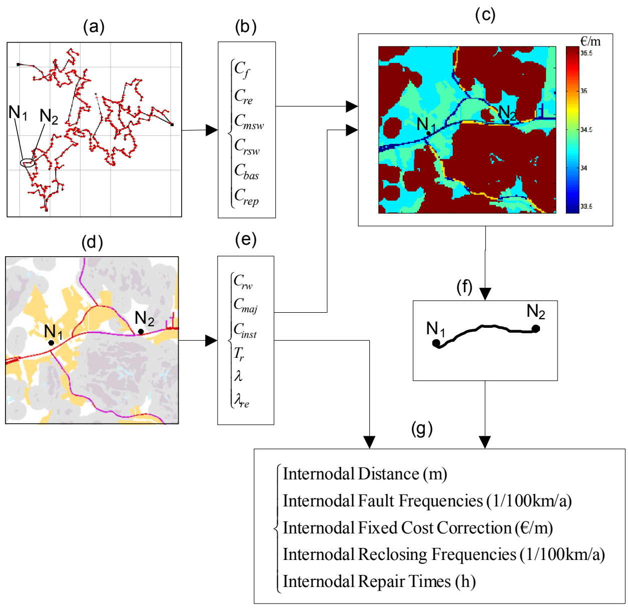


Figure 5.2. Combining topological parameters (b) from an initial radial network (a) with geographic parameters (e) from static topographic data (d) inside the cost surface cost function, the least-cost-path (f) through the graph generated of the cost surface (c) and the node-to-node connection specific internodal parameters (g) calculated using the least-cost-path.

In order to lessen the need for further iterations, the initial network, which is used to acquire the topology related parameters, must be such that it treats all the connections in the network equally but does consider their topological location and, thus, significance in the network overall. In rural areas the networks are typically only partly backed-up, meaning that faults might result in interruptions for certain customers that last the switching and repair time. To take this into account, a radial initial network without any backups is justified. In urban networks, where the situation is opposite to this, a fully backed-up network better suits the purpose. It must be remembered that even if the initial network is radial without any backup or fully backed-up, the resulting final network can still be radial, cost-optimally backed-up or fully backed-up.

Figure 5.3 presents examples of rural cost surfaces with two different line types, covered conductor overhead line (Figure 5.3a) and underground cable (Figure 5.3b), for a single node-to-node connection. These example figures aim to illustrate the effect of the different cost components and drivers associated with different line types and network loads.

As can be seen, with covered conductor overhead line (Figure 5.3a) the roadsides are shown clearly in the cost surfaces as low cost corridors. This is a consequence of the lower fault rates there, whereas with cables (Figure 5.3b) the fixed costs are more dominant and roads do not have any influence. For cables the rock exposures and their proximities, which mean high installation cost, are shown very clearly. In the end, all this is affected by the specific parameterization set by the user.

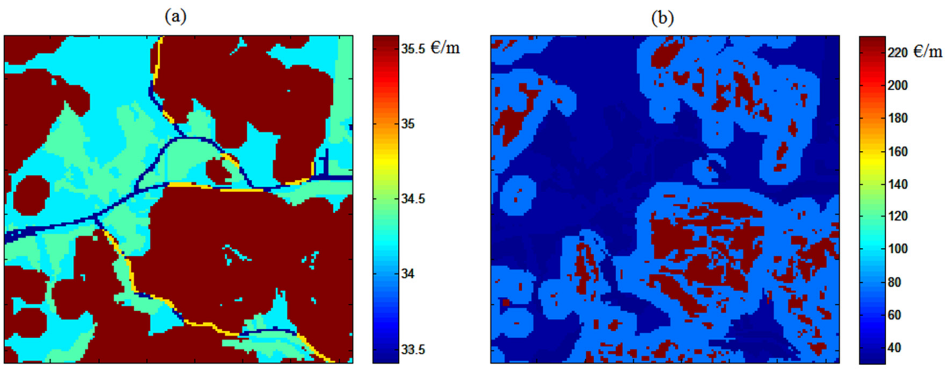
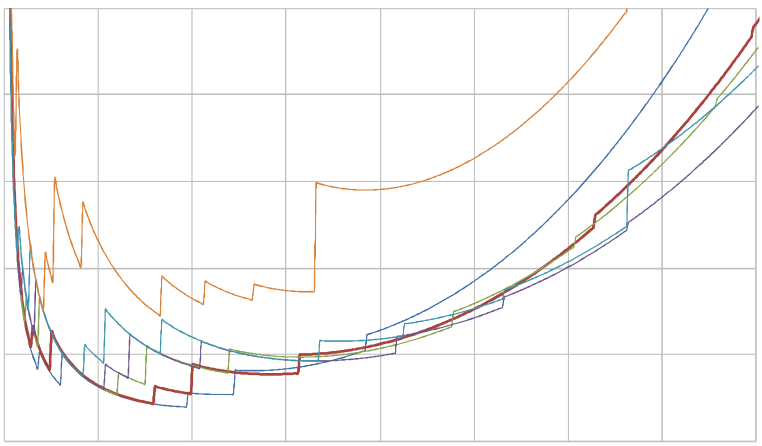


Figure 5.3. Examples of cost surfaces for a single node-to-node connection based on the full life cycle cost (€/m), (a) CC and (b) UGC" (Quote ends, started on page 61)

Chapter 6

Into the Parameterization



Parameterization is the only means to describe an operational environment for computer based applications. Chapter 6 broadly discusses the acquisition of objective and realistic parameterization, without which the simulation results would lack credibility. The processing of geographical information and network information on a spatially referenced basis for use in the different processes of network planning is introduced.

6.1 Acquiring the permission for using land

The laborious process of negotiating the permissions for feeder corridors with the land owners is one of the major concerns in medium voltage network terrain planning processes. Earlier these aspects have been touched, e.g., when considering the feasibility of 1000 volt or overhead cable systems over the 20 kV overhead line installations. Further, related to the right of way for feeder corridors an existing feeder corridor can be considered as an asset, which should be considered in the parameterization, e.g., in terms of minimizing the number of involved land owners, in order to save in the working hours of the terrain planners.

In this thesis, the direct cost of right of way compensation, usually based on area, is considered. The cost of right of way is usually determined by the sum value method [Maa03]. In the sum value method various cost components are included, e.g., for soil on an area basis and for timber (or harvest in the case of fields) based on the actual value of the asset, considering also possible expenses of works carried out, e.g., soil preparation. Once all the components are summed together, certain heuristically determined adjustments are typically made. In general, credible assessment of property (forest mensuration) requires expertise from this field.

6.2 Setting and getting the targets concerning service quality

There are several measures for power quality, of which at least some can be affected by network planning. Problems related to power quality include slow voltage variations, supply interruptions, voltage sags, flicker, voltage unbalance, voltage distortion, swells and transient overvoltages and mains frequency deviations [Sfs10]. The distribution system operator is responsible, but usually not alone, for supply interruptions, voltage dips, harmonics and transients [Ren11]. Other stakeholders, generation, transmission system operator and customers, also have their responsibilities concerning good power quality.

In this thesis, only the *supply interruptions* are considered. At least the following costs are related to interruptions and their mitigation: customer interruption cost (CIC), sectionalization and reinforcement of the network, repairing and stand-by expenses of the repairing personnel.

Interruption costs strongly depend on the load of the network zone being affected: the number of customers and the consumed power, but also on the customer mix being interrupted. Construction costs on their behalf are highly dependent on the length of the network and making a network more secure by the means of backup connections leads to longer networks. In a cost-optimal case, not all line sections can be backed up, but some laterals only have one possible feeding direction. Thus, in sparsely inhabited rural areas, where loads are low and distances long, network customers of a cost-optimal topology need to withstand a certain number of interruptions of longer duration, possibly including the repair time, than those in completely backed-up networks. Cost-optimal topology (e.g. the degree of backup) is, then again, directly affected by the valuing of the supply interruptions.

Following a supply interruption in a network, the customers affected are to be limited to as few as possible. The stepwise process of restoring the supply is modeled by switching and repair time parameters: recloser or circuit breaker operation time, remote controlled disconnector operating time, manual disconnector operating time and, finally, depending on the network topology, certain customers might have to wait for the full repairing time. Repairing time may, in the case of radial non-backed-up line sections, be shortened by using a mobile reserve cable or mobile reserve power unit. Repairing time is expected to vary depending on the terrain type, being affected by the time for locating the fault and possibly due to varying accessibility to fault locations.

6.2.1 Distribution network faults

By definition, faults are incidents when a component or system is not capable of operating as planned. Interruptions are incidents when a customer of the distribution network does not receive the service, i.e., voltage, from the distribution system operator as planned, e.g., in terms of temporary or sustained interruptions. Customer interruptions often result from a fault in the network system.

Faults in the medium voltage networks are often considered to be responsible for the majority of all supply interruptions. As discussed earlier, the impact of each individual fault can be affected by, e.g., the sectionalization and reserve connections. These, however, do not directly reduce the number of fault incidents in a distribution network, but merely reduce the time of interruption once a fault occurs. As discussed earlier the placing of the distribution feeders can significantly affect the number of expected line faults over a certain review time. In short, reducing faults, inevitably, reduces interruptions.

To better understand the scope of this subject and the potential of different means for reducing faults in distribution networks, it might be a good idea to grasp the subject from the typical reasons known to cause faults in distribution systems. The main causes for permanent or sustained (not cleared by reclosings) faults on power lines in Finnish distribution networks are wind and storm, snow and ice, lightning, other weather related reasons, animals, mechanical failures, faulty operations on behalf of the network operator, and faults caused by a third party. For overhead lines the most important categories are wind and storm, snow and ice, lightning and mechanical failures [Leh10]. Figure 6.1

presents the yearly distribution of fault incidents, both sustained and reclosings, of a power distribution network in the Kainuu region. The medium voltage network consists mainly of bare conductor overhead lines. The winter peak (snow and ice) between November - February can be easily observed, as well as the peak during mid summer (lightning). Bringing back what was discussed in the literature review, very similar results, i.e., heavy snowfall and wind, being one of the main contributors of the faults, have been reported from Sweden [Wal12]. For underground cables the main reasons, covering roughly two thirds of all faults, are causes related to third parties and mechanical failures [Leh10].

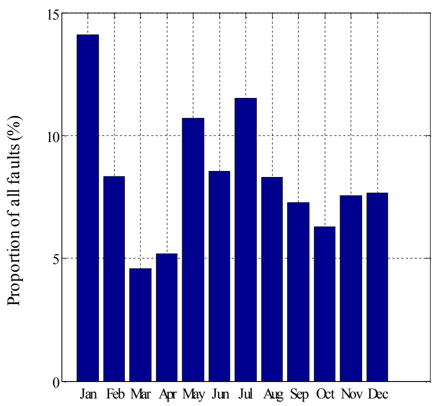


Figure 6.1. Temporal distribution of faults in a distribution network in Kainuu region during 2004-2012

Considering a new system, i.e. rural underground cable networks, the lack of available relevant data from that specific environment might raise some questions regarding the parameterization. In present cable networks faults caused by a third party are incidents typically occurring at, e.g., water pipe or telecom excavation work sites. Mechanical failures most often occur at cable joints and terminals. Spontaneous faults on a solid cable section without any external reason are rare.

When considering rural underground cable networks, it might be expected that third parties might, as well, cause a large share of all faults. For example, one matter that is often brought up, in the context of utilizing the presumably favorable soil in fields for installing underground cables, is the possible risk posed to the subsurface drainage systems. Further, new installation and renovation of existing drainage systems might later, in turn, pose a risk to the underground cable installations.

Continuing with potential risks to underground cable systems, ground frost might become an issue, especially if cable burial is performed at lowest possible cost using methods such as cable ploughing, without proper bedding of the cable. Ground frost moves rocks and boulders in the ground, harmfully affecting cable installations.

For short interruptions occurring in overhead line network systems, the main causes are often similar to those for permanent faults: lightning, wind and storm, ice and snow, animals, mechanical causes and faults caused a by third party. Reclosings are not considered technically expedient in cable networks.

6.2.2 On interdependency with regard to reliability

Knowing the mechanisms that lead to faults in the distribution networks might provide understanding about the probabilistic properties of faults. If the cause of a single fault is not connected to another fault, meaning independent faults, the required operational manpower resources are likely to be completely different from the case where a fault imposes a higher risk of facing another fault somewhere else in the same network.

Major disturbances, which are considered a significant problem for overhead line networks, are a typical example of common cause failures, where a large number of faults have a strong dependency. If a distribution network faces a major disturbance, the total number of faults in a relatively short period of time is the main problem, not necessarily the number of faults in itself (except for a total destruction). If the same number of faults were distributed equally through the year, there would be fewer problems with, e.g., the sufficiency of available repairing resources. Considering faults as individual incidents using a single value for fault rates might not always be sufficient for modeling the impact of faults in a network. Attention must also be paid to their distribution over time. For example, stepwise distributions considering the occasions of adverse weather with higher failure rates, better suiting the reality, have been proposed in the literature [Bol01]. Figure 6.2 presents a real timely distribution of faults in terms of faults per day for the Kainuu region. As can be seen, if the limit for major disturbances is set to, e.g., 40 faults per day, there is roughly one day per year (10 days, 9 years) during which this limit is reached. Setting this limit beyond the point where serious problems begin, clearly involves considering the overall extent of the distribution operators network area and the available operational resources for managing a multitude of simultaneous contingencies.

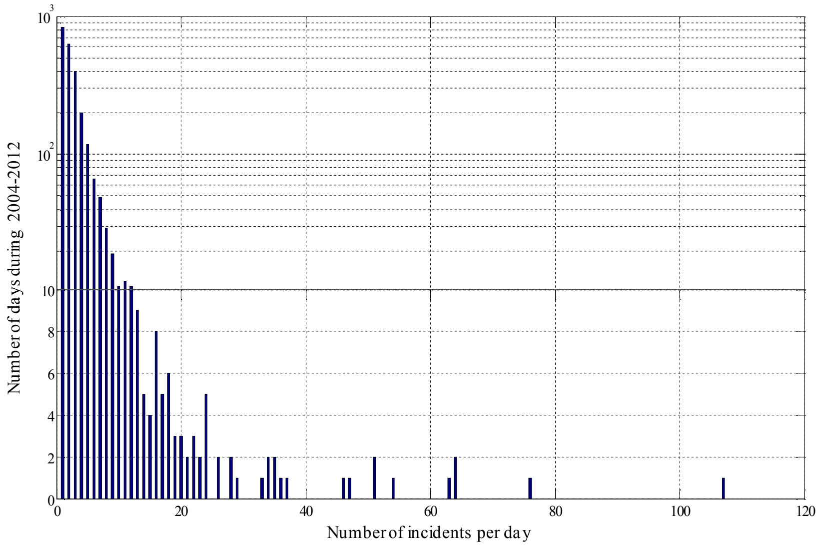


Figure 6.2. Temporal distribution of faults: faults per day in Kainuu region during 2004-2012. Note the logarithmic scale above 10 days on the Y-axis.

A typical and evident dependent cause for network faults is related to weather and usually these kinds of aspects link back to overhead line networks. Perhaps a weaker link between individual incidents could be found for faults in a cable network. Rural underground cables might have increased fault rates on a certain yearly concentration of earthwork related, e.g., to field underwater management restoration work, or during certain months of the year when incidents caused by the ground frost might possibly concentrate. Overhead cables might seem rather fault tolerant, but consider a strong and wide thunderstorm front sweeping over a network area. Certainly, considering the laborious and time consuming repair work of cable compared to overhead line faults, there might be some aspects to be prepared for.

6.3 Operating costs of the distribution networks

Overall, operational and maintenance costs consist of the costs for operating the network, inspections of the network, maintenance and technical servicing of the network, clearing the feeder corridors, and operation and communication system upkeep [Loh05]. Losses, which are the main contributor of the operational costs considered in this thesis, mainly consist of resistive losses in the conductors and transformer losses. Possible arrangements for capacitive reactive current compensation, i.e., reactors, might also result in additional energy losses.

The resistive line losses in the conductors consist of losses caused by the resistive component I_r and reactive component I_q of the load current. Losses due to resistive current depend on the magnitude and profile of the load. More precisely, losses due to the loading of the network can be accurately assessed by integrating the loss power over the entire duration of the review period. However, here simply the utilization time of the peak hourly losses is used to make an approximation. Reactive current losses depend highly, e.g., on the used line type, but also on the consumption of reactive power by the network loads. Especially in extensive cable networks, distributed compensation reactors might be an economically feasible option. The dissipated active power p_h and reactive power q_h per length unit are as given in Equations (8) and (9),

$$p_h = 3r\left(I_r^2 + I_q^2\right) \tag{8}$$

and

$$q_h = 3x\left(I_r^2 + I_q^2\right), \tag{9}$$

where

p_h	is the active power dissipated in the line resistance per length (W/m),
q_h	is the reactive power consumed by the line reactance per length (var/m),
r	is the line resistance per length (Ω/m),
x	is the line reactance per length (Ω/m),
I_r	is the resistive component of current (A) and
I_q	is the reactive component of current (A).

Considering the scope of this study, the energy losses of the secondary transformers do not affect the mutual order of the feasibility of the different network development strategies. Line losses, though, strongly affect the selection of the most economically feasible conductor size for each internodal connection.

6.3.1 Reactive power and earth faults in extensive cable networks

Figure 6.3 illustrates the generation and consumption of reactive power in a simple medium voltage feeder. When considering the balance $\sum Q$ between inductive loads ($S \cdot \sin(\varphi)$) and reactive power generation (Q_{lineC}) in present overhead distribution networks, generation is typically overweighed by the consumption. Example loads consuming reactive power include motor loads (e.g., increasing numbers of heat pumps in the future in comparison to conventional direct electric heating), fluorescent lamps and thyristor drives. Reactive power is also consumed in the distribution transformers (Q_{trafoL}), including consumption of the no-load magnetization branch and of the serial component related to power flow through the transformer, and in the line reactances

(Q_{lineL}). Especially with large conductors, the inductive reactance is rather close to the magnitude of the resistive component of the line impedance. Cables do have much higher capacitance than overhead lines and thus for extensive medium voltage cable networks, the ratio between consumption and generation of reactive power moves strongly towards surplus of generation. Related to this, the operating point (load), where the reactive power generated by the line capacitance is entirely consumed by the line reactance, referred to as *natural load of a line*, is exceeded in geographically large cable networks.

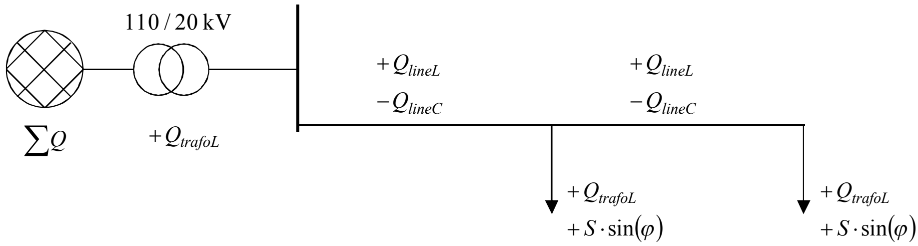


Figure 6.3. Accumulation of reactive power, i.e., sum of generation (-) and consumption (+), on a simple radial feeder with two secondary substations

Reactive currents consume the economic (and technical) load capacity of the lines and therefore distributed compensation must be considered in the case of extensive cable networks. Ohmic losses of the line resistances are lower the closer to the point of generation the reactive power is consumed. A brief study, with an aim to estimate the quantity of this aspect, is presented in Appendix 7. Voltage rise might become an issue with long cables with small load as well. Further, problems may arise as a consequence of resonating LC-circuits, where, e.g., harmonic currents might become significant.

The characteristically strong capacitances of cable networks also have an impact in terms of large earth fault currents. Related to increased levels of earth fault currents is an increased rate of auto-reclosings in the overhead line networks and overhead sections of mixed line type network topologies, due to the lower probability of self-extinction of the arc at higher currents and increased difficulty in meeting the touch voltage safety regulation demands. Earth fault current can be lowered by using Petersen coils for resonant earthing the system neutral. However, with significantly large quantities of earth fault current the Petersen coil can only be tuned to compensate the capacitive component of the current, leaving the resistive component, which might then become an issue [Gul09]. Consequently, using distributed compensation seems unavoidable in extensive cable networks. Another proposed solution could be the use of solid neutral point earthing [Gul09], which, however, would be a major system change. As discussed earlier, in Finland systems with an isolated or a resonant earthed neutral are, by far, the most common medium voltage distribution systems.

6.4 Geotechnical considerations

Medium voltage cable installations are typically placed rather close to the surface, i.e., in the case of roads and roadsides at a depth of 0.7 m and in the case of fields, forests and the rest of the terrain at a depth of 0.7…0.9 m [Sen93]. When using trenchless techniques, e.g. horizontal directional drilling or micro-tunneling, the installation is typically situated deeper. These special techniques, however, are considered to be more feasible in densely built urban environments, where lack of space is a problem, or in certain special circumstances in rural areas, such as installations passing rivers from underneath. Generally, the soil close to the surface is the most important with regard the cable installation. For overhead line structures soil properties are considered less important.

Geotechnically considering, soils divide into two main categories: mineral soils and organic soils. The last glacial period greatly affected the landforms appearing in Finland. Ridges, moraines, etc., have developed in relation to glaciers. However, organic soils, most commonly mires, have developed during the postglacial period. Common and important soil types in the context of network planning in Finland include: poorly graded mineral soils (e.g., moraines), organic soils (e.g., mires), graded mineral soils (e.g., sand, silt and clay) and rock exposures (which is basically the same as a lack of soil).

Moraines are mixtures of mineral soils and they are the most common soils in Finland, covering over 50 percent of land areas in total. Moraines are also commonly found overlaid with layers of other soils. Moraines were formed as glaciers detached material from the bed rock and crushed it into varying sized particles and mixed it with other preexisting soils, making a mixture of particles from clay sized fine grained particles up to large boulders. Boulders and rocks, along with the compacted structure of moraines, make excavation, along with all earthwork, demanding. Also, most moraines are frost-susceptible soils [Gsf07].

Clays are the most common sort of graded soil, i.e., homogeneous soils consisting of uniformly sized particles. Clays consist of fine mineral soil particles, which result in the characteristically turbid grayish color of the rivers flowing through clay plateaus. In Finland, the majority of the clay plateaus, having formed in relation to land areas being awash by the earlier seas, are centered in the southern part of the country. Approximately nine percent of all land area in Finland is covered with clay [Gsf07].

In Finland, mires are very common, covering over 30 percent of all land areas [Gsf07]. Especially in certain areas in the central and northern parts of Finland, mires are very characteristic. Mires, as explained, are organic soils formed during the post glacial era. Forests tend to be plentiful on terrains with underlying peaty soil. At the other extreme, there are open mires lacking trees and other taller vegetation.

Bedrock is exposed in three percent of all land areas, making bare rock exposures. In addition to this, bedrock is commonly found under a varying thickness of subsoil (most often moraine), under mires and under lakes [Gsf07]. These areas, sometimes referred to as rocky soils in the case of moraines, are somewhat problematic, e.g., for underground installations of power distribution infrastructure, as the spatial prediction of the actual depth of the subsoil is difficult. The coastal regions in the south of Finland have numerous rock exposures and, consequently, rocky soils.

Information concerning the geotechnical aspects, i.e., soil can be acquired using

- geological data (Geological Survey of Finland),
- topographical data (National Land Survey of Finland),
- locally applied means, e.g., ground penetrating radar (GPR),
- airborne geophysical mapping and
- locals knowing the local circumstances.

Geological data contain information about the soil properties and can be beneficial when planning cable routing. However, the most accurate soil maps are only available for about one third of Finland, being concentrated in the southern parts of the country.

Ground penetrating radar (GPR) or georadar scans the underground objects and soil properties using electromagnetic pulses. Considering the applicability of georadars in a wide variety of circumstances, some limitations apply, especially with the depth of the radar pulse penetration with fine grained soils. Also, effective use of georadar requires expertise and experience, especially when concerning the interpretation of the results. Georadar might be useful in detailed final cable routing, e.g., in the terrain planning processes associated with certain initiated network construction projects, once the general planning using other available methods has been carried out.

In Finland, the characteristics of the soil have also been studied using airborne geophysical mapping. There, the soil and rock foundation electrical conductivity, magnetic field strength and natural background radiation can be measured by instrumentation attached to airplanes. This information can be used to infer certain properties of the soil and rock foundation. The systematic mapping of Finland was completed in 2008 [Gsf09].

Generally, considering the reach of the applicability of the results from the case studies, the validity of the parameterization is, of course, in focus. When it comes to the geological aspects of the model, Figure 6.4 presents a generalization of the dominating soil types in Sweden on the left and a corresponding generalization of the soil map of Finland on the right. The averaging in the Swedish case is higher than for Finland, but otherwise the figures can be compared, with certain reservations. Overall, the geotechnical classification systems used in Finland and Sweden are consistent [Har90][8].

As Finland and Sweden are neighboring countries, the similarities in the geographic characteristics of the operational environment are evident. For instance, similar areas to those of Finnish coastal regions can be found in the southern parts of Sweden, where both have large areas of sorted soils, e.g., clay, and exposed rock. Continuing with the similarities, mires are common in certain regions and, in general, most of the land areas are covered with moraines. Overall, the general observations, regarding the strategic development of the power distribution systems in sparsely populated areas, can to some extent be applied in similar geographical and regulatory operational environments in both countries.

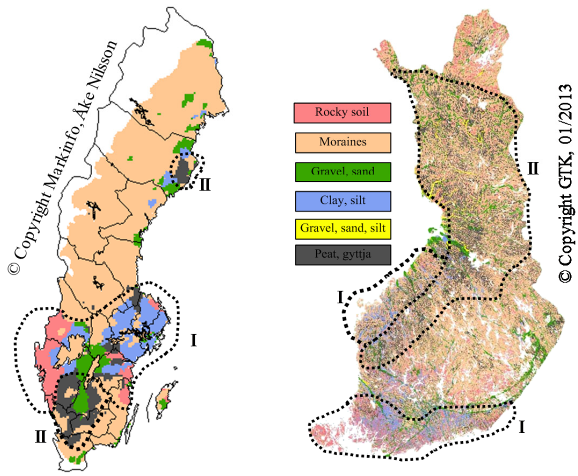


Figure 6.4. Dominating soil types in Sweden[3] (left) and generalization of the soil map over Finland (right). Zones with seemingly similar characteristics are circled: (I) the coastal region in Finland greatly resembles some parts in Southern Sweden, (II) abundance of mires is characteristic in vast areas and overall moraines are common.

6.5 Topographical aspects

To start with, topography and terrain are often used closely as synonyms in this thesis. While the soil characteristics under the ground in general have a greater effect on the cable networks, terrain, referring to the properties above (e.g., the land use, fields, forests, roads, etc.) strongly influences the overhead structures. Generally, soil and terrain have a

[3] Swedish Forest Soil Inventory, http://www-markinfo.slu.se/sve/mark/jart/jartdom.html

strong correlation. For example, as discussed earlier, fields tend to occur on certain graded soils. Mires have basically completely consistent definitions, in terms of considering the mire in terms of terrain and soil.

In this thesis, orography, which is a sub discipline of topography, referring to the elevation of the terrain, is not considered. The importance of the characteristics of ground level elevation affects, e.g., the pole structures and crown snow loads of overhead lines. In general, the importance of ground elevation is rather marginal in Finland [Kor00][37] [Hyv08][33]. As discussed earlier, the latest glacial period has strongly put its mark on the terrain, resulting in, e.g., the harder landforms being commonly the spots that have remained elevated from the rest of the terrain, e.g., rock exposure hills in the coastal region. Thus, an elevation model could be used to indicate certain pronounced unfavorable spots for underground cabling, i.e., crags and cliffs. In sparsely inhabited rural areas the proportion of yards, gardens and buildings is low. Protected areas might limit the routing in certain cases.

Generally, terrain and soil both have strongly spatial characteristics and generalization is often misleading. Further, it is not possible to consider all information in an automated routine, i.e., internodal router application. An automated routine, such as the one introduced and used in this thesis, can find general guidelines and characteristics, but in the end, an experienced planner has to take charge in the interpretation and utilization of the results, i.e., in the terrain planning process.

6.6 Providing the Different Processes with Attribute Surfaces

While the main analyses in this thesis are from the societal point of view, by weighting certain components of the parameterization accordingly the methodologies can be fitted to meet also the planning targets of the utilities. The terms strategic planning and terrain planning are used quite often in this thesis. The methodologies developed in this thesis can be seen to be merely providing tools for the first, the process of strategic planning. However, keeping the different processes of the network utilities strictly separated would not be in line with reality. The needs of the terrain planning process do affect the strategic choices and in utilities the overall planning is a continuous interactive dialogue between the different levels of planning. The products of the analyses made to support the strategic planning processes should also be made available for the processes closer to the operational level at the utilities. Then again, most of the valuable outputs to be further processed as inputs for strategic planning originate from operating, maintaining and constructing the network. Figure 6.5 presents schematically how the different processes of the utilities relate from the view point of this thesis and how they link through the parameterization. Parameterization must here be considered broadly, possibly containing statistical analysis in order to obtain the desired spatially specific parameters.

For instance, taking the terrain planning process, which has gained less weight in this thesis, but which is lightly touched several times, for a certain new construction site usually starts with a map study [Luc01] and later the specific circumstances are viewed on site. During the early phases of the terrain planning process, i.e., during the initial drafting using available maps, dedicated statistically produced *attribute surfaces*, e.g., fault rate surfaces, fixed cost correction surfaces and, finally, life cycle cost surfaces (refer to Figure 5.2 and Figure 5.3), would provide valuable inputs. Utilizing these attribute surfaces would be an efficient means at all stages of the network planning to enhance the utilization potential of freely available sources of geographic information and the quantities of available network data stored in network information systems. Once the different processes of the network planning benefit from consistently produced spatially referenced network specific information, the overall aims of the different planning processes can be brought into line and support each other.

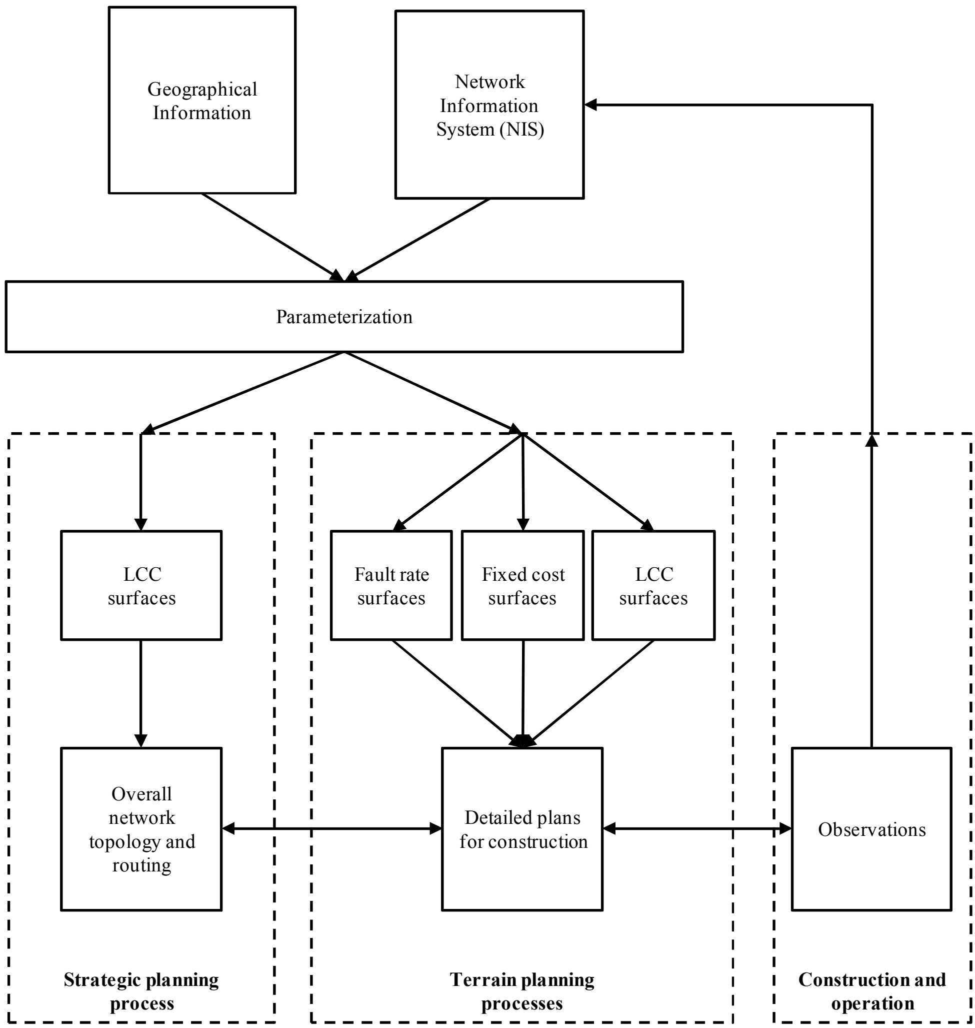


Figure 6.5. Supporting the different processes of network planning with geographic information and recorded network specific data in order to harmonize and align the targets at different levels

Figure 6.6 presents a proposed schematic for the organization for the parameterization in Figure 6.5 in more detail, constituting an approach where different available geographical information combined with data provided by the network information system is efficiently utilized.

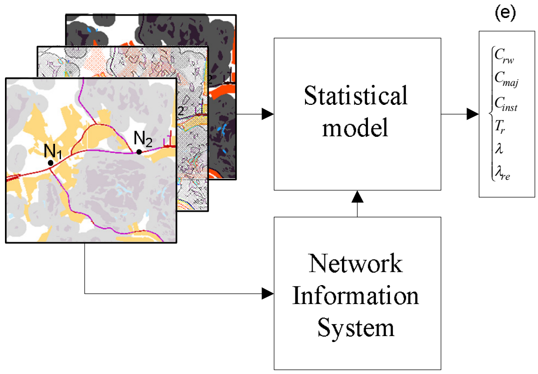


Figure 6.6. Concept for building up the parameterization by efficiently utilizing geographical data and the data from the network information system used in the utilities

Viewing the above concept with a more tangible example, quite often the fault records in the database of the network information system contain information regarding, e.g., location, duration and possible cause of the faults. In the literature, the variables affecting the risk of failure, e.g., snowfall and wind, have been studied [Wal12]. There are also approaches, where logistic regression models have been fitted with aims to predict the risks for faults caused for example by vegetation [Rad02]. Figure 6.7, which can be viewed as a numeric example of the above concept and should be considered as such, presents a *fault rate surface* obtained by fitting the fault observations of a network utility covering the all overhead line segments of the entire network into a logistic regression model provided with seven predictor variables as introduced in Table 6.1. (Linear regression approaches have been proposed in [Xu06], though, with much fewer data points and in [Rad02], where no geographic information were applied but rather only weather attributes)

Table 6.1. Coefficients for a logistic regression model

Predictor variable	Note	Standardized *b*	p-value
intercept		-3.5844	0
deciduous trees crown coverage	logarithm	0.089766	1.19e-04
distance to road less than 30 m	dummy	-0.14631	1.43e-11
open mires	dummy	-0.1009	7.78e-04
spruce biomass	logarithm	0.064524	1.25e-02
elevation of the ground		0.086793	2.10e-05
slope	logarithm	0.1054	3.02e-07
height of forest exceeding 10 m	logarithm	0.14579	2.12e-11

The fault data constitutes all recorded observations over the entire network area of the utility in Kainuu region over the period of 2004-2012[4]. The total number of medium voltage line segments (mainly bare conductor overhead lines) in the data is approximately 95 thousand and the total number of fault incidents (with sustained faults and reclosings all included) is approximately 10 thousand.

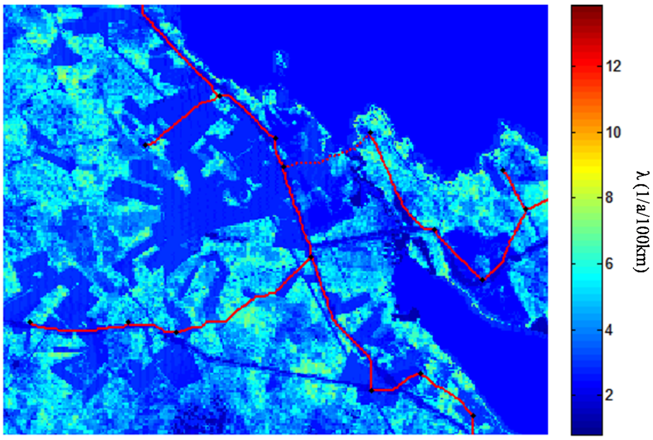


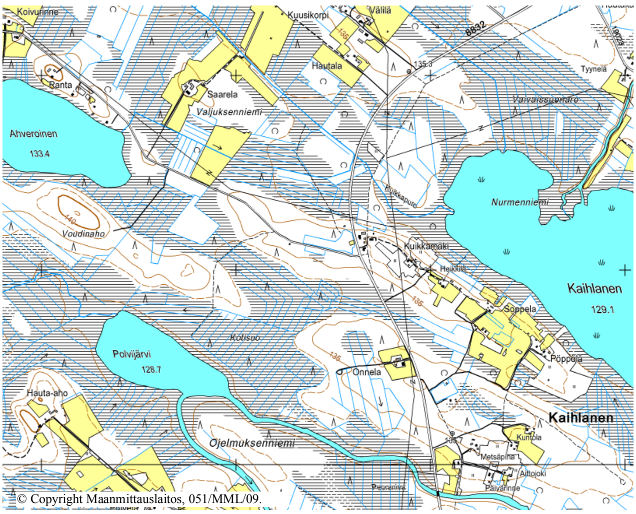
Figure 6.7. A fault rate surface and examples of internodal overhead line routings

Figure 6.7 functions merely as a numeric example to demonstrate how broadly the parameterization must be considered, possibly containing statistical analyses. The network simulations in the case studies of this thesis are carried out using a static topographically referenced geographic model of the operational environment introduced in detail in Chapter 7. The new concept presented above to obtain spatially referenced location specific attribute values for the calculation of the internodally individual cost surfaces, and broader attribute surfaces for the different processes of network planning in general, seems very promising, yet further analyses, especially concerning the availability of suitable and consistently collected data for all concerned line types, are required in order to be able to proceed to actual implementation.

[4] Data provided for this research by E.ON Kainuun Sähköverkot Oy. / Jussi Niskanen, network design engineer and network development manager

Chapter 7

Operational Environment in Terms of Topography



This chapter introduces the proposed topographically referenced parameterization applied in the case studies. Many aspects, related to the contribution of the topography on distribution network planning, have been discussed earlier in this thesis. Chapter 7, for those parts, is merely a framework or anchoring point, which aims to sort out and position, but not to repeat, these earlier observations. The proposed numeric representation of the parameterization forms the closure of this chapter.

7.1 Categorization of the terrain

The different categories of the topographic model are viewed in terms of the various related variables, i.e., the parameters related to geographical data introduced along with the used algorithms in Chapter 5 and specifically the cost function (5) on page 61. The terrain over the network areas is divided into the following categories:

- forests
- roads
- fields
- mires
- rock exposures
- water bodies

The following additional categories are obtained as derivations from the previous ones based on the observations made earlier in this thesis with regard to the parameterization:

- forests proximate to rock exposures
- roads proximate to rock exposures
- areas of shallow water (i.e. shore zones)

As put earlier, terrain and topography in this thesis are used as synonyms. The above categories are later in this thesis referred to as *terrain types*. Next, the terrain types listed above are discussed in view of the modeling the operational environment for the applied algorithms. Each terrain category has a listing of affected factors, in the form of tables, at the end of each corresponding section. As always in comparative studies, establishing a reference is the first task. In these comparisons, the different cost drivers and related aspects are compared against a reference terrain type of *road*.

7.1.1 Roads

Classes of the Topographic Database included in terrain type of *roads* are:

- 12111 road Ia
- 12112 road Ib
- 12121 road IIa
- 12122 road IIb
- 12131 road IIIa
- 12132 road IIIb

In Finland there are around 78 000 kilometers of public roads, and another approximately 305 000 kilometers of private roads, i.e., municipal and forest truck roads [Tie12]. For comparison, the total length of the medium voltage electricity distribution network in Finland is roughly 150 000 kilometers [Lak08].

Concerning the benefits the road system can provide, in general, the improved mobility evidently provides many advantages. The construction of the lines and, further, the inspections of the lines can be carried out with fewer efforts. Considering the contingencies, the repair times, especially during winter, might be shorter near the roads.

When considering the use of a road base for burying cables, the road constructions techniques might be somewhat against this. In order to carry the loads of the traffic, the road bed is often constructed using compacted boulders. Further, in areas where, e.g., the bed rock provides a sufficient base for the road, no further road bed is needed [Har01]. Thus, road bases might not offer an easy environment for underground installations, nor are the road owners often welcoming of any procedures disrupting the road structures. Then again, if underground installations must be placed outside the road area, geotechnically considering, there cannot be seen much difference in comparison to the surrounding untreated environment.

In many studies all roads are lumped together as if they all were the same when considering their characteristics from the point of view of network planning. However, low priority roads are often routed following the details of the terrain, resulting in a high number of curves and, consequently, shorter spans of the line segments, both of which contribute to higher costs. High priority roads are often constructed straighter using more resources, e.g., smoothing the elevation by filling in the hollows on the route. Underground cables installed into the foundation of high priority roads, e.g., using protective tubing, could be at an advantage as such road structures are planned and constructed to prevent the harmful effects of ground frost. The groundwork of low priority roads, such as forest truck roads (excluded from the above list), conversely, is often made with less care. For both underground and overhead installations, the characteristics of small roads are actually closer to the characteristics of untreated soil outside roads rather than roads, in terms of the meaning with which they are characterized here [Sen93]. Considering the typical practices in the rural network planning of the present overhead line networks, the trunk lines are often placed along high priority public roads. When overhead lines are installed next to roads, the fault frequencies are reduced significantly [Lak08] [Par06] [Loh10].

7.1.2 Forests and mires

Classes of the Topographic Database included in terrain type of *mires* are:

- 35300 mire, peat-covered area
- 35411 mire, passable, treeless
- 35412 mire, passable, forest growing
- 35421 mire, difficult terrain, treeless
- 35422 mire, difficult terrain, forest growing

The list above contains the classes of the Topographic Database included in the terrain type of *mire*. Basically, all areas that are not included in any of the other terrain types are considered *forest* in this study. In Finland, forest covers around 75 percent of all land area [Met04]. The vast majority of Finnish forests are utilized as production forests. Mires and forests are, in this context, considered concurrently, as these two often overlap.

One of the aspects related to, e.g., installing underground cables through forests, is the soil preparation procedures, e.g., drainage in order to enhance the water management and overall the forest economy [Vaa07]. Figure 7.1 presents an example from the Kainuu region. In Finland, roughly 60 percent of all mires, which cover nearly 30 percent of all land areas, have been drained. Further, in production forests, certain preparation procedures also take place in the drier soil types (other than mires), e.g., scarifying soil in order to speed up the renewing of new tree generation. The above aspects might be worth bearing in mind, raising different concerns e.g., from the point of view of reliability of underground cable and overhead line networks.

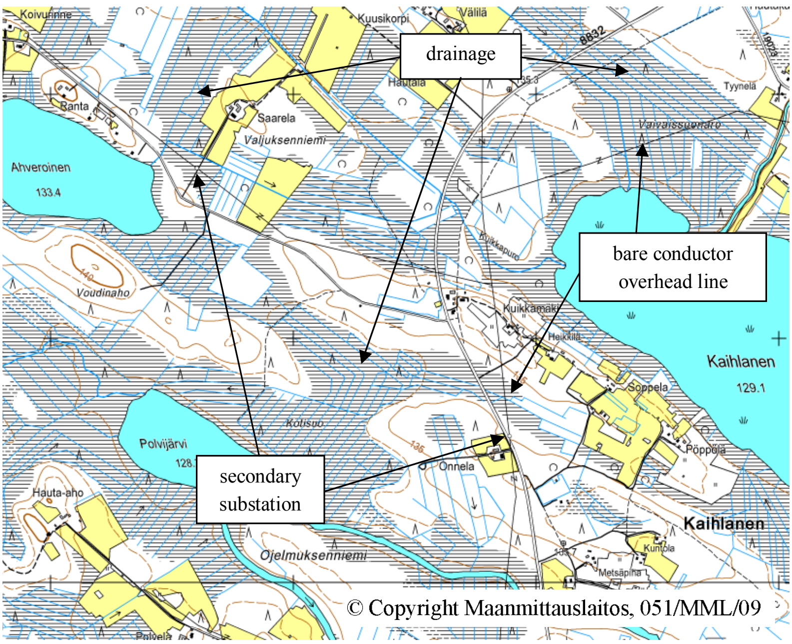


Figure 7.1. A topographical view on a typical sparsely populated area

Considering the overhead line networks and what was discussed concerning the network faults in Chapter 6 on page 69, the height of the forest might correlate unfavorably with faults due to wind and storm and snow and ice. However, faults due to lightning might be reduced in case of overhead lines having sufficient shielding from tall trees. Again referring to what was discussed early in this thesis in Chapter 1 starting from page 18, concerning the different properties of the forest forestry maps concerning the shares of the deciduous versus coniferous trees might be valuable information to be further processed for the purposes of network planning. Refer to Table 7.1 and Table 7.2 for a summary of the concerned terrain types.

Table 7.1. Qualitative parameterization: forests

C_{inst}	underground	≈	Poorer mobility
	overhead	-	Fewer turns in the routing.
λ	underground	≈	Forestry
	overhead	++	Trees on both sides (refer to commonly problematic wind directions). Possibly safer considering lightning.
T_r	underground	+	Poorer access with machinery. Snow conditions in winter, finding fault location.
	overhead	+	Fault locating, patrolling in terrain, difficult access with machines, cranes etc.
λ_{re}	underground	≈	Not considered with cables.
	overhead	++	Refer to permanent faults (λ).
C_{maj}	underground	≈	Not considered with cables.
	overhead	++	Refer to permanent faults (λ). Emphasis on expected storm wind directions.
C_{rw}	underground	≈	
	overhead	≈	
+, ++	attribute is expected to: increase, increase significantly		
-, --	attribute is expected to: decrease, decrease significantly		
≈	attribute is expected to: have no change		
o.	obstruction		

Table 7.2. Qualitative parameterization: mires

C_{inst}	underground	o.	Possibly lower costs due to soft organic soil. Access might be limited to seasons with frozen soil.
	overhead	-	Fewer turns in the routing (-). More costly mire poles needed (+).
λ	underground	++	Forestry, soil preparation works
	overhead	++	Refer to *forest*.
T_r	underground	+	Refer to *forest*.
	overhead	+	Refer to *forest*.
λ_{re}	underground	≈	Not considered with cables.
	overhead	++	Refer to *forest*.
C_{maj}	underground	≈	Not considered with cables.
	overhead	++	Refer to *forest*.
C_{rw}	underground	≈	
	overhead	≈	

7.1.3 Fields

Classes of the Topographic Database included in the terrain type of *fields* are:

- 32611 cultivated land, field
- 32612 cultivated land, garden
- 32800 meadow

Especially in densely inhabited parts of Finland, a great part of the favorable area for cultivation, typically consisting of fine grained graded soils such as clay and silt has been taken into agricultural use. Installation of underground cables in fields is presumably not costly. The draining structures (water management of the field) must be paid attention to in the planning as they might easily be damaged during cable installation.

Overhead lines routed through fields are safe from incidents related to trees. Snow and snowy trees are a major cause of faults for overhead lines. The windy conditions on open terrain have been proposed as one of the reasons preventing snow from clinging to the line structures [Par08]. Major disturbances would probably not have any significant effect on overhead lines. On the other hand, overhead lines in fields are more exposed to lightning. Refer to Table 7.3 for a summary of the concerned terrain types.

Table 7.3. Qualitative parameterization: fields

C_{inst}	underground	--	Favorable soil for low cost installation methods: ploughing, etc.
	overhead	-	Fewer turns in the routing.
λ	underground	+	Works related to and drain systems
	overhead	≈	No faults related to trees. Lightning strikes, however, might cause faults in increasing numbers.
T_r	underground	≈	
	overhead	≈	
λ_{re}	underground	≈	Not considered with cables.
	overhead	≈	No faults related to trees. Lightning strikes, however, might cause faults in increasing numbers.
C_{maj}	underground	≈	Not considered with cables.
	overhead	--	Safe in all directions from falling trees, which are the main cause of massive destruction in overhead lines.
C_{rw}	underground	+	Harm for harvest during installation and maintenance work.
	overhead	+	Damage caused to harvest. Permanent harm caused by the overhead structures.

7.1.4 Rock exposures

Classes of the Topographic Database included in the terrain type of *rock exposures* are:

- 34100 rock exposure
- 34700 boulders

Evidently installing underground cables in regions with exposed rock is costly. Also, rock exposure indicates an increased risk of colliding with near-surface bed-rock in installation work at its proximity. Soil maps provide information for such regions, but in this study only topographic data is used. Thus, rock exposures (for which data is available in TDB) are used to make an approximation of these higher risk regions.

In geological soil data, areas with less than a 1.0 m layer of subsoil (rocky soil) are separated from areas with more than a 1.0 m layer of subsoil, refer to the right side in

Figure 7.2. On the left side there is shown a visualization of the topographic data used in this study. The approximation used in this study simply considers a radius of 100 m around each raster cell classified as rock exposure. The parameterization can now be adjusted to take into account of these areas, e.g., having a possibly higher risk of costly installation for underground cables.

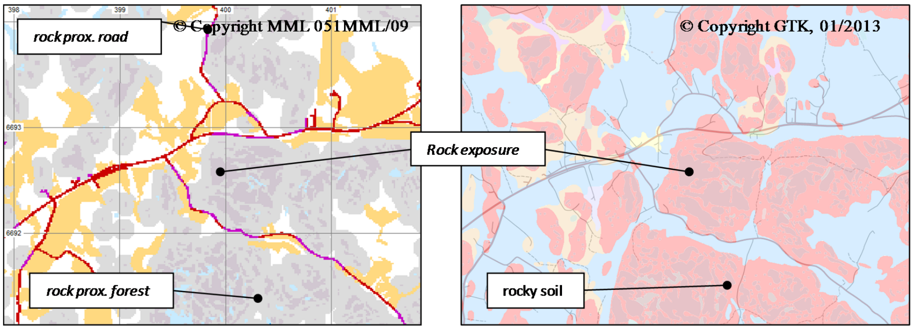


Figure 7.2. The approximation included in the model used in this study (left) compared with a geological soil map (right).

These separate proximity classes are only considered relevant for the terrain types of forest and road. Even if there were rock exposures near, e.g., a field, it is presumed that the argument that an area is field (hence favorable for underground installations) is stronger than the argument that there is rock exposure nearby (risk of costly installation). For overhead lines, poles erected on the rock exposures are supported either by guy wires (less costly, but require more space) or by braces anchored to the rock. Also, if bed rock is encountered closer than 0.7 m from the surface (refer to proximities of rock exposures), then the poles must be erected using the same procedures as on rock exposures [Sen94].

Considering service lifetime, the less moist circumstances at rock exposures might be rather favorable locations for overhead lines. Aesthetically, however, placing overhead lines on rock exposures might be disturbing, as rock exposures are often elevated from the surrounding terrain. Refer to Table 7.4, Table 7.5 and Table 7.6 for a summary of these concerned terrain types.

Table 7.4 Qualitative parameterization: rock exposures

C_{inst}	underground	++	Quarrying or use of e.g. tube or concrete protection needed.
	overhead	≈	Braces or guy wires needed.
λ	underground	≈	Refer to *forest*
	overhead	++	‘’
T_r	underground	+	Refer to *forest*
	overhead	+	‘’
λ_{re}	underground	≈	Refer to *forest*
	overhead	++	‘’
C_{maj}	underground	≈	Refer to *forest*
	overhead	+	‘’
C_{rw}	underground	≈	Refer to *forest*
	overhead	≈	‘’

Table 7.5 Qualitative parameterization: forests proximate to rock exposures

C_{inst}	underground	++	Increased risk of costly installation (near surface bed rock). 80 % excavating, 20 % quarrying
	overhead	≈	Possibly braces or guy wires needed.
λ	underground	≈	Refer to *forest*.
	overhead	++	‘’
T_r	underground	+	Refer to *forest*.
	overhead	+	‘’
λ_{re}	underground	≈	Refer to *forest*.
	overhead	++	‘’
C_{maj}	underground	≈	Refer to *forest*.
	overhead	+	‘’
C_{rw}	underground	≈	Refer to *forest*.
	overhead	≈	‘’

Table 7.6 Qualitative parameterization: roads proximate to rock exposures

C_{inst}	underground	++	Increased risk of costly installation (near surface bed rock). 80 % excavating, 20 % quarrying
	overhead	+	Possibly braces or guy wires needed.
λ	underground	≈	Refer to *forest*.
	overhead	≈	‘’
T_r	underground	≈	Refer to *forest*.
	overhead	≈	‘’
λ_{re}	underground	≈	Refer to *forest*.
	overhead	≈	‘’
C_{maj}	underground	≈	Refer to *forest*.
	overhead	≈	‘’
C_{rw}	underground	≈	Refer to *forest*.
	overhead	≈	‘’

7.1.5 Water bodies

Classes of the Topographic Database included in the terrain type of *water bodies* are:

- 36200 water with no flow
- 36211 sea water
- 36313 flowing watercourse

In Finland the total area of inland lakes (fresh water) is 35 thousand km^2, which is roughly 10 percent of the total land area of [Nls09]. The abundance of water bodies are often of benefit in terms of using them for laying underwater cables. In addition to the inland fresh water bodies, the Baltic Sea in the south and west coast of the country offers plenty of underwater routing potential. The coast lines, as well as all the water bodies, are often fragmented, which further promotes or requires the use of underwater connections between islands and peninsulas.

The cable types used for undersea installations might need to be stronger than the cable types used for inland underwater installations [Kor00][34]. Reasons for this might be the stronger sea currents, larger waves and heavier water traffic. For inland underwater installations a normal underground cable is often sufficient. However, ice floes during spring times might be problematic.

Considering, e.g., recreation aesthetic issues may become increasingly important. Generally, considering the long review period and the temporary characteristics of the harm caused during construction, a cable might be less disturbing, when compared to an overhead line.

Repairing underwater cable failures is time consuming, especially during certain times of the year when there are difficult ice conditions. For overhead lines, short sections crossing over waterways are common but they are usually considered to be visually disturbing. For both underwater cables and overhead lines, waterways need to be considered carefully, noting, with regard to terrain planning processes and the expenses for acquiring the right of way, that obtaining permission for such locations may cause extra work and cost.

There are typically certain initial costs related to underwater installations, e.g., bringing the cable from underwater to underground requires excavating and divers are usually required to verify the quality of the underwater installation. Also, related to what was discussed above, considering the aesthetics, the shorelines might be pronounced sensitive. These aspects may be considered using a separated terrain type of shore zones (40 m). Refer to Table 7.7 and Table 7.8 for a summary of these terrain types.

Table 7.7. Qualitative parameterization: water bodies

C_{inst}	underground	+	No need for making a trench. Possible need for extra armoring of cable. Varies depending on the location.
	overhead	o.	Constructing poles in water (> 2 m). Rafts etc. needed for the working over water.
λ	underground	+	Rather stable temperatures year round. Water traffic.
	overhead	≈	Open space, refer to *field*.
T_r	underground	++	Requires special equipment, rafts and boats etc. Certain periods seasonally with difficult access, ice conditions etc.
	overhead	++	‘’
λ_{re}	underground	≈	Not considered with cables.
	overhead	≈	Open space, refer to *field*.
C_{maj}	underground	≈	Not considered with cables.
	overhead	--	Open space, refer to *field*.
C_{rw}	underground	-	Underwater cable is rather unnoticeable.
	overhead	-	Aesthetic immission not considered with MV. In reality, however, sensitive landscapes are valued highly, refer to heuristic obstructions.

Table 7.8. Qualitative parameterization: shore zones

C_{inst}	underground	++	Must be trenched down to 2 meters of depth. Possible need for extra armoring of cable. Varies depending on the location.
	overhead	o.	Constructing pole foundations underwater. Rafts etc. needed for working on water.
λ	underground	+	Refer to *water bodies*.
	overhead	≈	Open space, refer to *field*.
T_r	underground	++	Refer to *water bodies*.
	overhead	++	Refer to *water bodies*.
λ_{re}	underground	≈	Not considered with cables.
	overhead	≈	Open space, refer to *field*.
C_{maj}	underground	≈	Not considered with cables.
	overhead	--	Open space, refer to *field*.
C_{rw}	underground	-	Underwater cable is rather unnoticeable. Possible short-term harm after installation.
	overhead	-	Refer to *water bodies*.

7.1.6 Summary of the qualitative parameterization

Table 7.9 summarizes the terrain types with regard to the variables in Equation (5) concerning the generation of the internodally individual cost surfaces.

Table 7.9. Summary of the qualitative parameterization

		forests	roads	fields	water bodies	mires	rock exposures	forests proximate to rock exposures	roads proximate to rock exposures	Shore zones
C_{inst}	underground	≈	reference	--	+	o.	++	++	++	++
	overhead	-	‘ ’	-	o.	-	≈	≈	+	o.
λ	underground	≈	‘ ’	+	+	++	≈	≈	≈	+
	overhead	++	‘ ’	≈	≈	++	++	++	≈	≈
T_r	underground	+	‘ ’	≈	++	+	+	+	≈	++
	overhead	+	‘ ’	≈	++	+	+	+	≈	++
λ_{re}	underground	≈	‘ ’	≈	≈	≈	≈	≈	≈	≈
	overhead	++	‘ ’	≈	≈	++	++	++	≈	≈
C_{maj}	underground	≈	‘ ’	≈	≈	≈	≈	≈	≈	≈
	overhead	++	‘ ’	--	--	++	+	+	≈	--
C_{rw}	underground	≈	‘ ’	+	-	≈	≈	≈	≈	-
	overhead	≈	‘ ’	+	-	≈	≈	≈	≈	-

+, ++ attribute is expected to: increase, increase significantly

-, -- attribute is expected to: decrease, decrease significantly

≈ attribute is expected to: have no change

o. obstruction

7.2 The topographic model quantified

While above the categorization into the terrain types was presented and these terrain types were discussed qualitatively, now the actual numeric values are given compactly.

7.2.1 General parameters

The general economic and other general parameters used in the simulations are gathered in Table 7.10. The cost for each type of sectionalization device and other general cost components are listed in Table 7.11.

Table 7.10. Basic parameters

Paramater	
p (interest rate, 1/a)	0.06
ρ (load growth, 1/a)	0.0012
t (review period, a)	40
c_h (energy loss cost, €/kWh)	0.05
length correction to direct internodal distances	1.2 (initial)

Table 7.11. Cost of certain general components

Cost of device (k€)	
Disconnector, manual	3.27
Disconnectors, remote, cost per station (fixed cost)	4.92
Disconnectors, remote, cost per switch (variable cost)	10.64
Reclosers, cost per station (fixed cost)	4.92
Reclosers, cost per recloser (variable cost)	13.37
Fixed cost for each outgoing feeder	19.20

Line type and conductor size specific technical and economic parameters are listed in Table 7.12. Expenses due to earth fault and capacitive reactive currents are shown in Table 7.13. The costs due to reactive power generation of the line capacitances are based on the approximation presented in more detail in Appendix 7.

Table 7.12. Conductor specific parameters of the studied line types

			r (Ω/km)	x (Ω/km)	susceptance (µS/km)	ampacity (A)	Line cost (€/km)
UGC	1	AHXAMK 25 mm^2	1.200	0.160	40.841	110	20660
	2	AHXAMK 50 mm^2	0.641	0.145	50.265	155	22940
	3	AHXAMK 95 mm^2	0.380	0.129	65.973	235	27030
	4	AHXAMK 150 mm^2	0.250	0.123	75.398	300	32040
	5	AHXAMK 240 mm^2	0.150	0.110	94.248	385	40240
	6	2 x AHXAMK 240 mm^2	0.075	0.055	188.496	770	80480
OHL	1	Al/Fe 34/6 (Sparrow)	0.847	0.383	2.985	210	19190
	2	Al/Fe 54/9 (Raven)	0.535	0.368	3.142	280	22750
	3	Al/Fe 85/14 (Pigeon)	0.337	0.354	3.142	360	24560
	4	Al/Fe 106/25 (Suur-Savo)	0.279	0.344	3.456	430	27660
	5	2 x Al/Fe 106/25	0.140	0.172	6.912	860	55320
CC	1	PAS 70 mm^2	0.493	0.302	3.770	310	27750
	2	PAS 120 mm^2	0.288	0.284	4.084	430	31690
	3	PAS 185 mm^2	0.188	0.270	4.398	560	36812
	4	2 x PAS 185 mm^2	0.094	0.135	8.796	1120	73624

Line costs presented in Table 7.12 are to be paired with the topographically referenced installation costs and right of way costs introduced later in Table 7.17 on page 97.

Table 7.13. Line type related costs due to capacitive and earth fault currents

	Cost, earth fault (€/m)	**Cost, capacitive current** (€/m)
OHL, all sizes	0.00	0.00
CC, all sizes	0.00	0.00
UGC, 3x25 mm^2	3.26	2.04
UGC, 3x50 mm^2	3.26	2.17
UGC, 3x95 mm^2	3.26	2.70
UGC, 3x150 mm^2	3.26	3.02
UGC, 3x240 mm^2	3.26	3.78
2 x UGC, 3x240 mm^2	3.26	7.24

Table 7.14 and Table 7.15 list the attributes concerning interruptions, reconfiguration of the networks and repair times and expenses. Table 7.16 sums up the most important references for the initial data being processed for the final values presented in this chapter.

Table 7.14. Interruptions and reconfiguration

Customer interruption cost	
a (interruption cost for power, permanent faults, €/kW)	1.1
b (interruption cost for energy, €/kWh)	11.0
a_{re} (interruption cost for power, reclosings, €/kW)	1.1
Operation times for the sectionalization	
Circuit breaker and recloser operation time (s)	0.5
Remote operated disconnector operation time (min)	10
Manual disconnector operation time (min)	60

Table 7.15. Repair times and costs

Repair costs	OHL	CC	UGC
Repair costs per fault (€/fault)	1600	1600	3200
Repair costs per line length[5] (k€/km)	1.536	0.142	0.439

Table 7.16. The primary references for the general parameters

Attribute	**Primary reference(s)**
Repair costs	[Loh05]
Operation times for reconfiguration	
Customer interruption costs	[Tkk05] [Hyv08][63]
Technical line parameters	[Sfs94] [Sfs08] [Sen94b]
Basic line costs	[Ene10]
Costs due to earth fault management	[Hyv08][119]
Costs due to reactive power	refer to Appendix 7

[5]With using fault rates of 0.80 fault/100km/a for underground cables 0.52 fault/100km/a for covered conductor overhead lines and 5.60 fault/100km/a for bare conductor overhead lines (mean values of Table 7.17), calculated with K(p = 0.05 1/a, 1/a, t = 40 a) = 17.159 a (with ρ = 0 for cost components not proportional to the load growth).

7.2.2 Topographically variable parameters

The considered categorization of the geography, i.e., the categorization following the topography (terrain types), was introduced on page 84. Table 7.17 compactly gathers together all the geographically related parameters, i.e., installation cost (C_{inst}), fault rate (λ), repair time (T_r), reclosing frequency (λ_{re}), major disturbance cost (C_{maj}) and right of way cost (C_{rw}). These parameters are arranged following the proposed topographical model of the operational environment. The installation cost (C_{inst}) and the right of way cost (C_{rw}) can here be referred to as adjustments against the reference of standard conditions, as for overhead lines the basic line cost (Table 7.12) includes also the installation work and the right of way cost for standard conditions. Thus, zero or negative values may occur.

Table 7.17. Geographically related parameters arranged in accordance with the considered line types and topographic model of the operational environment

		forests	roads	fields	water bodies	mires	rock exposures	forests proximate to rock exposures	roads proximate to rock exposures	Shore zones
C_{inst} (€/m)	UGC	9.36	9.36	2.78	14.99	200.00	200.00	47.49	47.49	24.35
	OHL	0.00	1.50	0.00	200.00	0.00	1.40	1.40	2.90	100.00
	CC	0.00	1.50	0.00	200.00	0.00	1.40	1.40	2.90	100.00
λ (1/100km/a)	UGC	0.79	0.78	0.82	0.82	5.00	0.79	0.79	0.78	0.82
	OHL	7.72	3.62	4.08	4.08	7.72	7.72	7.72	3.62	4.08
	CC	0.68	0.33	0.42	0.42	0.68	0.68	0.68	0.33	0.42
T_r (h)	UGC	17	12	12	24	17	17	17	12	24
	OHL	4	3	3	24	4	4	4	3	24
	CC	4	3	3	24	4	4	4	3	24
λ_{re} (1/100km/a)	UGC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OHL	60.00	30.00	30.00	30.00	60.00	60.00	60.00	30.00	30.00
	CC	10.10	5.10	5.10	5.10	10.10	10.10	10.10	5.10	5.10
C_{maj} (€/m)	UGC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	OHL	4.00	2.00	0.40	0.40	4.00	4.00	4.00	2.00	0.40
	CC	4.00	2.00	0.40	0.40	4.00	4.00	4.00	2.00	0.40
C_{rw} (€/m)	UGC	0.23	0.23	0.76	0.00	0.23	0.23	0.23	0.23	0.00
	OHL	0.00	0.00	4.00	-3.60	0.00	0.00	0.00	0.00	-3.60
	CC	0.00	0.00	4.00	-3.60	0.00	0.00	0.00	0.00	-3.60

Table 7.18 lists the references primarily used for acquiring the initial data to be processed for each of the separate parameters of Table 7.17. As comprehensively discussed in Chapter 6 and earlier in this chapter, the parameterization for the case studies is customized for the specific approach, i.e., the use of the dedicated algorithm, and operational environment of this study.

Table 7.18. The primary references for the numeric data being processed to acquire the quantified parameters

		Primary reference(s)
installation cost	C_{inst}	[Ene10] [Ene11] [Sve06]
cost for right of way	C_{rw}	[Mtk00] [Maa03] [Rah06] [Sen92] [Sen93]
major disturbance cost	C_{maj}	[Par06] [Sta05]
fault frequency	λ	[Leh10] [Par06] [Hil05]
repair time	T_r	[Loh05]
reclosing frequency	λ_{re}	[Leh10] [Par06] [Hil05]

7.2.3 Heuristic obstructions

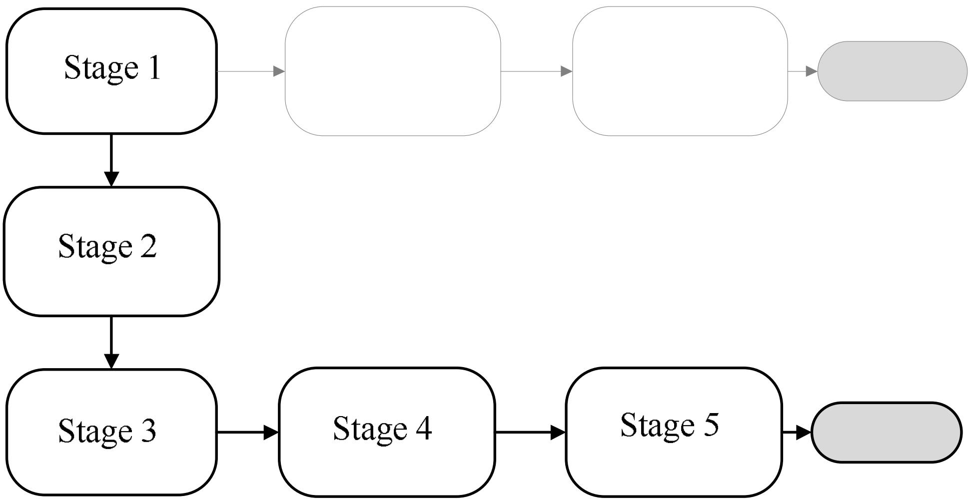
As discussed earlier, e.g., in Chapter 3 on page 49, the different views of network planning might require the use of heuristic obstructions for certain situations. Table 7.19 presents the terrain types not considered feasible for certain line types. These costs are simply added to the relevant installation costs C_{inst} and are included in the values in Table 7.17.

Table 7.19. Heuristic obstructions applied for certain combinations of terrain and line types

Added cost (€/m)	**OHL**	**CC**	**UGC**
forests	0	0	0
mires	0	0	200
roads	0	0	0
fields	0	0	0
rock exposures	0	0	0
water bodies	200	200	0
forests, proximity to rock	0	0	0
roads, proximity to rock	0	0	0
shore zones	100	100	0

Chapter 8

Applying the Methodology to the Case Studies



The methodology, an automated routine for planning distribution network topologies, has been introduced in Chapter 5, and the proposed numeric model used to represent the operational environment in Chapter 7. Chapter 8 now applies these in the case studies, following a general view with a small scale numeric example. Further, this chapter introduces the case study network areas and groups the key points of the results, aiming at a compact presentation. Comprehensive and detailed results concerning the studied network development strategies for each of the network areas can be found in Appendixes 1-5.

8.1 General

Figure 8.1 presents a schematic of the study plan for the case studies. The reference network without considering the geographical aspects affecting the optimal network topology would be mainly intended to motivate the use of internodal data, as those results could be compared against the results obtained using a proper geographic model of the operational environment in the topology optimization process, following the lower branch of the study plan. In order for such a comparison being fair and to be able to cost both of the networks consistently and equitably, the reference network must also be encumbered with the realistic geographically referenced parameterization while computing the cost of the network. The results later presented in Appendixes 1-5 and later in this chapter can be considered as the results for the final network of Figure 8.1.

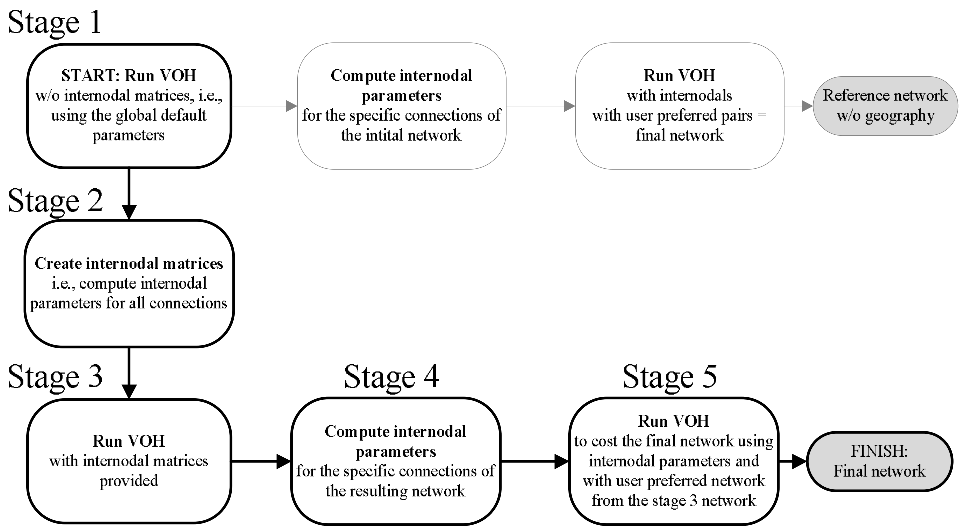


Figure 8.1. Schematic study plan showing the roles and relations of the used algorithms

Simulations are first run with two optional line types, of which one is underground cable and the other is either bare conductor overhead line or covered conductor overhead line (simulations A and B). As there are plenty of water bodies in all of the studied network areas, using overhead structures alone (simulation with one line type only) would not make a realistic network (refer to the set obstructions of Table 7.19 on page 98). However, two simulations with underground cable as the only line type are considered: simulations C1 and C2. The simulations A, B and C1 are run with the objective of a cost-optimal network with cost-optimal reserve connections and cost-optimal sectionalization. Strategy C2 involves full backup, i.e., reserve connections for all load nodes and full switching (i.e., full sectionalization). Table 8.1 summarizes.

Table 8.1. Guidelines for the network development strategies

Development strategy	Line type 1	Line type 2	Reserve connections	Sectionalization
A	UGC	OHL	cost-optimal	cost-optimal
B	UGC	CC	cost-optimal	cost-optimal
C1	UGC	N/V	cost-optimal	cost-optimal
C2	UGC	N/V	full	full

8.2 Decoding the study with an example network

The following small demonstration illustrates the specific routines of the study plan in terms of applying the methodologies presented in Chapter 5 for the cases studies. The network used in this example is the same made-up network (7 nodes in total, including 1 primary substation and 6 secondary substations) already familiar from Chapter 4 on page 56, where it functioned as the means to introduce the overall tasks related to network planning. The network data used in this example are given in Table 8.2.

Table 8.2. Demonstration network area general parameters

Network	NW5
Name	Hindsby
Primary substations	1
Secondary substations	6
P (per sec. subst., kW)	20
cos(φ)	0.999
Latitude (degrees)	60.33... 60.36
Longitude (degrees)	25.13... 25.24
Dimension, West-East (km)	6
Dimension, South-North (km)	3
Area (km^2)	20

Figure 8.2 illustrates the initial network (Stage 1 in Figure 8.1) used for the computation of the topology related parameters C_f, C_{re}, C_{msw}, C_{rsw}, C_{bas} and C_{rep}. In this case the initial network is radial and does not have any reserve connections or sectionalization included. The only primary substation is the node referred to with number 0.

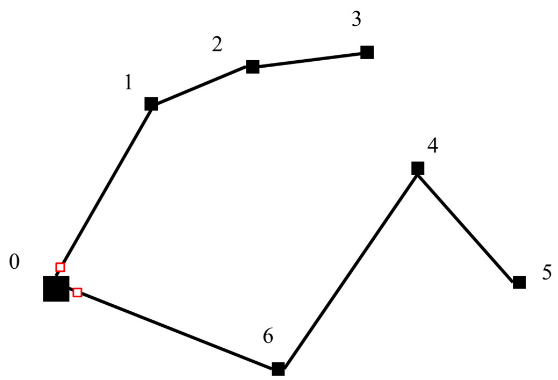


Figure 8.2. Stage 1 initial radial network without switching

Figure 8.3 presents all the internodal connections of the network, each following the node-to-node optimal routing through the graph generated using the individually generated cost surfaces, aiming towards the overall optimum network, in accordance with the objective cost function (5) presented earlier in Chapter 5 on page 61. For this network, the total number of individual internodal optimization tasks is 21.

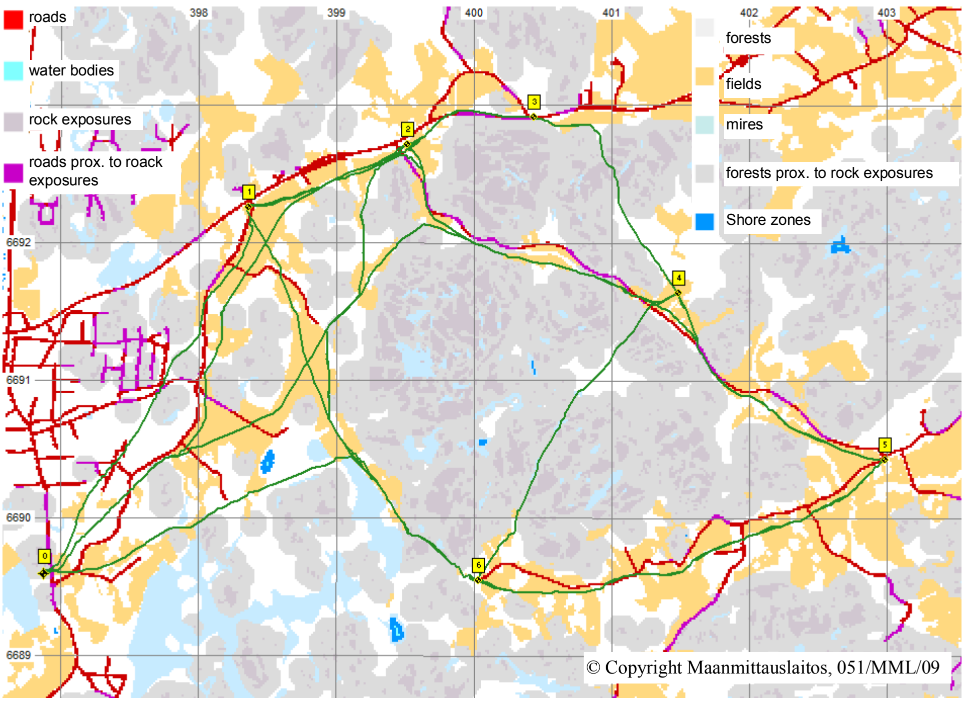


Figure 8.3. 21 possible internodal connections, resulting from Stage 2, as considered overall optimal in terms of total network cost

The optimal routings are only shown for a single line type of underground cable (green lines). If mixed line type network topologies are to be studied, the same routines are run separately for two route options. Table 8.3 lists the terrain types and the per unit (p.u.) lengths of each of the edges (refer to Equation (6) on page 61) making the least-cost-path connecting the nodes 1 and 2. The lengths of the edges vary from 1.000 p.u. to 6.083 p.u., as the first, second and sixth neighbors were considered in the generation of the graph from the cost surface. These per unit values of the edge lengths are converted to real geographically referenced lengths using the scale factor valid for the specific applied geographic data.

Table 8.3. The least-cost-path from node 1 to node 2

Edge	Terrain	Length	Edge	Terrain	Length	Edge	Terrain	Length
1	Forest	2.236	12	Field	2.236	23	Field	2.236
2	Road	2.000	13	Field	2.236	24	Field	5.385
3	Road	1.000	14	Field	2.236	25	Field	5.385
4	Forest	1.000	15	Field	2.236	26	Field	5.385
5	Forest	1.000	16	Field	2.236	27	Field	1.414
6	Field	5.385	17	Field	2.236	28	Forest	2.828
7	Field	1.000	18	Field	2.236	29	Forest	1.414
8	Field	6.083	19	Field	5.385	30	Road	1.414
9	Field	5.385	20	Field	1.000	31	Forest	1.414
10	Field	6.083	21	Forest	2.236	32	Field	1.414
11	Field	2.236	22	Forest	1.000			

The internodal parameters, introduced earlier in Chapter 5 on page 60 as the means to describe the geographically referenced characteristics of the operational environment for the NTOA, are now calculated following the steps of the overall network optimal least-cost-paths shown in Figure 8.3 and listed for a single node-to-node path (from node 1 to node 2) in Table 8.3. Basically, these internodal parameters, except the internodal distances, can be seen as distance weighted averages over the optimal path. Distances simply refer to the length of each of the paths.

The internodal matrices, containing the internodal parameters for all the possible internodal connections, are internodal distances (Table 8.4), internodal fault frequencies (Table 8.5), internodal fixed cost corrections (Table 8.6), internodal reclosing frequencies (Table 8.7) and internodal repair times (Table 8.8). Each of the individual connections, 21 connections in this example, has an individual set of these six parameters, which are used in the NTOA in order to find the optimal network topology following the main objective function (1). Connections used in final network are in bold print.

Table 8.4. Internodal (N_1, N_2) distances (m)

N_1 \ N_2	0	1	2	3	4	5	6
0	-999	**3356**	4443	5473	6073	7270	3927
1	3356	-999	**1317**	2347	3886	5905	3453
2	4443	1317	-999	**1027**	**2650**	4683	3916
3	5473	2347	1027	-999	1932	4111	4932
4	6073	3886	2650	1932	-999	**2176**	2680
5	7270	5905	4683	4111	2176	-999	**3314**
6	3927	3453	3916	4932	2680	3314	-999

Table 8.5. Fault frequencies (1/a/100km)

N_1 \ N_2	0	1	2	3	4	5	6
0	-999	**0.803**	0.807	0.806	0.806	0.809	0.805
1	0.803	-999	**0.814**	0.810	0.810	0.811	0.815
2	0.807	0.814	-999	**0.801**	**0.809**	0.81	0.81
3	0.806	0.810	0.801	-999	0.796	0.806	0.809
4	0.806	0.810	0.809	0.796	-999	**0.814**	0.796
5	0.809	0.811	0.81	0.806	0.814	-999	**0.813**
6	0.805	0.815	0.81	0.809	0.796	0.813	-999

Table 8.6. Fixed cost corrections (€/m)

N_1 \ N_2	0	1	2	3	4	5	6
0	-999	**7.86**	6.97	6.88	11.37	8.65	11.92
1	7.86	-999	**4.57**	5.43	10.58	9.80	9.85
2	6.97	4.57	-999	**7.19**	**13.23**	11.08	10.18
3	6.88	5.43	7.19	-999	17.72	12.44	9.42
4	11.37	10.58	13.23	17.72	-999	**7.77**	27.27
5	8.65	9.80	11.08	12.44	7.77	-999	**4.75**
6	11.92	9.85	10.18	9.42	27.27	4.75	-999

Table 8.7. Reclosing frequencies (1/a/100km)

N_1 \ N_2	0	1	2	3	4	5	6
0	-999	**0**	0	0	0	0	0
1	0	-999	**0**	0	0	0	0
2	0	0	-999	**0**	**0**	0	0
3	0	0	0	-999	0	0	0
4	0	0	0	0	-999	**0**	0
5	0	0	0	0	0	-999	**0**
6	0	0	0	0	0	0	-999

Table 8.8. Repair times (h)

N_1 \ N_2	0	1	2	3	4	5	6
0	-999	**13.67**	13.44	13.57	13.84	13.51	14.26
1	13.67	-999	**12.60**	13.23	13.09	12.93	12.81
2	13.44	12.60	-999	**14.63**	**13.24**	12.98	13.64
3	13.57	13.23	14.63	-999	15.51	13.88	13.71
4	13.84	13.09	13.24	15.51	-999	**12.44**	15.92
5	13.51	12.93	12.98	13.88	12.44	-999	**12.72**
6	14.26	12.81	13.64	13.71	15.92	12.72	-999

The Stage 5 optimal network topology of the example network is shown in Figure 8.4, and is basically equal to the Stage 3 topology, except for which more accurate and realistic, topology specific, internodal parameters are acquired in Stage 4, combined with the optimal internodal routing from Stage 4. Now that the internodal data is available, and has benefitted the topology algorithm, the resulting network is somewhat different than that of Stage 1 in Figure 8.2. The routing of this underground network seems to be following the terrain types having feasible installation circumstances, e.g., fields, and rock exposures and their proximities yielding an indication of possibly costly installation are avoided. In the final network, there is one manual disconnector placed along the connection between nodes 2 and 4, more precisely, being physically enclosed in the secondary substation of node 2.

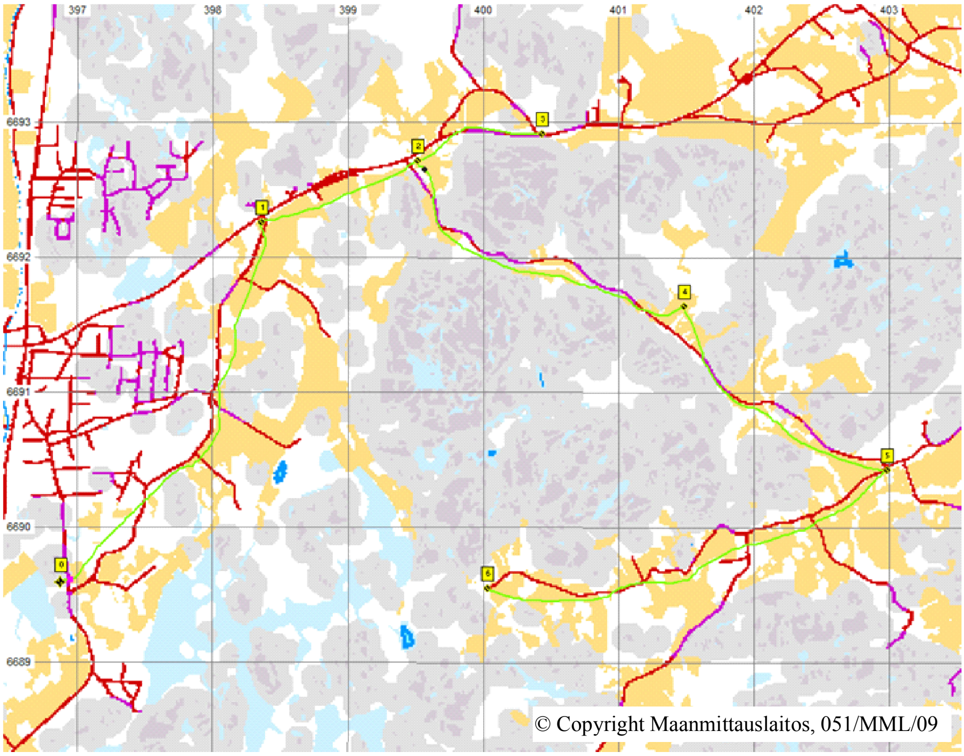


Figure 8.4. The routing of the optimal final network.

As discussed earlier, the optimal routing is basically a compromise between the shortest route and avoiding costly terrain. For example, the connection between nodes 4 and 6 following the route via node 5 would have resulted in lower investment costs relative to length (Table 8.6) but the total length would have more than doubled (Table 8.4), resulting in the most economic routing for that specific connection being rather the direct connection from 4 to 6. However, this connection, being overall expensive, is not utilized in the final network, although it was used in the initial network of Figure 8.3.

This example network has only a very limited number of nodes and its looping ratio is zero meaning a purely radial network. The internodal distances are rather long, varying between 1.0 km and 3.4 km (Stage 4). The maximum interrupted load, i.e., resulting from a line fault along the connection of the nodes 0 and 1, is the sum of all nodal loads, meaning 6 x 20 kW. This demand, being the hourly maximum load, might possibly be within the technical limits of a single reserve power unit. However, as this example network is not a realistic network, further analysis of the results is irrelevant. Nevertheless, to conclude this demonstration properly, Table 8.9 presents the specific information concerning the final network.

Table 8.9. Final network key figures

General	
Line type 1	underground cable
Line type 2	N/V
Line type 1, length (%)	100.0
Line type 2, length (%)	N/V
Network length (km)	13.84
Backup (%)	0.00
Sectionalization	
Reclosers (excl. the ones at PSS)	0
Remote operable disconnectors	0
Manually operable disconnectors	1
Cost (k€)	
Total cost, C	521.317
Investment and operation, $C_I + C_O$	495.889
Losses, C_L	0.682
Interruptions, C_F	24.746
Routing of the Final Network, terrain types (%)	
forests	19.60
roads	6.89
fields	67.46
water bodies	0.00
mires	0.00
rock exposures	0.00
proximity of rock exposure, forests	4.03
proximity of rock exposure, roads	2.01
shore zones	0.00

8.3 Case study network areas briefly

This section introduces the case study network areas. Refer to Table 8.10 for general data concerning the studied networks.

Table 8.10. Network area nodal data and general characteristics of the areas

	NW1	NW2	NW3	NW4	NW6
Name	Kirkkonummi	Porkkala	Oulujärvi	Keimola	Helsinki
Primary substations	3	3	3	3	2
Secondary substations	320	224	329	186	314
P (per secondary substation, kW)	109	86	20	417	431
cos(φ)	0.951	0.951	0.989	N/A[6]	0.955
Latitude (degrees)	60.09... 60.33	59.96... 60.16	64.19... 64.61	60.28... 60.39	60.20… 60.28
Longitude (degrees)	24.30... 24.63	24.37... 24.67	26.78... 27.83	24.76... 24.93	24.83... 24.97
Dimension, East (km)	18	17	51	9	8
Dimension, North (km)	27	22	47	12	9
Area (km^2)	489	372	2371	115	69

Figure 8.5 presents the terrain characteristics over the studied network areas. The terrain type of *park* is only considered for network 6.

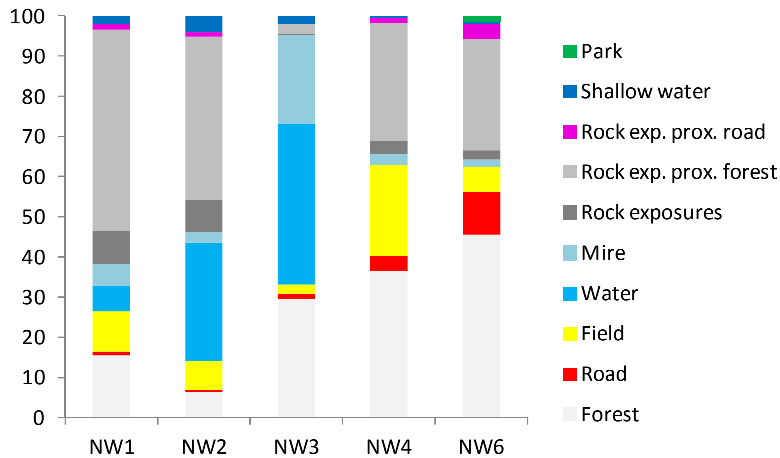


Figure 8.5. Terrain type distribution over the studied network areas

The Kirkkonummi network (NW1) is located North-West from Helsinki. The densely populated urban areas of Kirkkonummi and certain areas next to the coastal main road (road 50) are excluded as they would most likely be fed by separate dedicated urban

[6] Not available, value of 0.951 will be used to approximate the reactive power consumption

feeders. The Kirkkonummi area can be characterized as strongly polarized. Fields are rather common, which makes favorable circumstances for underground installation. On the other hand, rock exposures are common everywhere in the area.

The Porkkala network (NW2) area lies west of the Helsinki metropolitan area and south of the Kirkkonummi network area. The terrain is very rocky, which makes it a representative example of the southern coastal region in Finland. As the area is supplied through feeders from primary substations in the north and the peninsula of Porkkala abuts on the Baltic Sea in the south, this makes a rather clear and naturally outlined area. There are also some loads in the islands of the archipelago connected to the network, which is an interesting special feature of this network region.

The Oulujärvi network (NW3) lies in the middle of Finland, approximately 500 km north from Helsinki. This area is dominated by the lake Oulujärvi. Other than that, the area is characterized by the abundance of mires, of which the majority is heavily prepared for forestry purposes. In fact, more than a fifth of the studied area is considered mire. Rock exposures, however, are not common and fields are also rather rare, covering less than 3 percent of all terrain. Typically, distances between load points, i.e., secondary substations, are long and the network load density is the lowest among the studied networks.

The Keimola network (NW4) is located at the Northern outskirts of the Helsinki metropolitan area. The loads on the secondary substations are very high for a rural network. However, viewing a map of the study area gives a strongly rural impression. A large proportion of fields is one of the characterizing features of this region, as well as rock exposures. Water bodies cover only a small number of areas. The river Vantaa passes through this area as a narrow, yet ecologically and socially important, corridor.

Network 5, Hindsby (NW5), is the made-up example network, used for demonstration purposes in Chapter 4 and Chapter 8. Nevertheless, the actual geographic area is located to the east of the cities of Helsinki and Vantaa.

Network 6, Helsinki (NW6), cannot be characterized as rural by any means. For this reason, the parameterization is adjusted accordingly, refer to Appendix 5 for details. The area is characterized as a partially densely built-up urban and partially sub-urban area. The results must only be seen as suggestive due to the building up of the parameterization in this thesis being more relevant for the rural networks. However, bringing in this considerably different network definitely gives a valuable perspective when analyzing the results for the rest.

8.4 Main results of the case studies

For details, refer to Appendixes 1...5. Table 8.11 presents the network total cost and its composition in terms of the different life cycle cost components. Simulations were carried out using either two optional line types (LT1 and LT2) or only one line type (LT1). Simulation A refers to a mixed network of underground cable (LT1) and bare conductor overhead line (LT2), B to a mixed network of underground cable (LT1) and covered conductor overhead line (LT2), C1 to a cable network with optimal backup and C2 to a cable network with full backup (forced for all secondary substations, i.e., full switching and reserve connections). Refer also to Table 8.1 for a summary of the strategic choices.

Table 8.11. Network costs

Cost of NW1 (M€)	A	B	C1	C2
Investment	13.652	8.641	13.421	17.718
Losses	0.667	0.934	0.893	0.755
Interruptions	2.028	2.138	1.314	0.684
Total cost	16.347	11.712	15.629	19.157
Cost of NW2 (M€)				
Investment	8.118	6.015	9.852	12.294
Losses	0.163	0.117	0.131	0.207
Interruptions	1.813	1.060	0.932	0.448
Total cost	10.094	7.192	10.916	12.949
Cost of NW3 (M€)				
Investment	13.252	11.796	13.942	19.136
Losses	0.259	0.207	0.237	0.204
Interruptions	1.298	1.055	0.960	0.415
Total cost	14.809	13.059	15.139	19.755
Cost of NW4 (M€)				
Investment	5.495	4.087	5.767	7.874
Losses	0.821	0.797	0.763	0.568
Interruptions	1.017	1.025	0.885	0.474
Total cost	7.333	5.909	7.415	8.916
Cost of NW6 (M€)				
Investment	N/V	N/V	10.813	15.504
Losses	N/V	N/V	0.757	0.587
Interruptions	N/V	N/V	1.790	0.750
Total cost	N/V	N/V	13.360	16.840

Table 8.12 lists the line types in the final networks from each simulation and Table 8.13 sums up certain key figures from the results.

Table 8.12. The division among the line types

Line types (%)	LT	NW1	NW2	NW3	NW4	NW6
A	1 (UGC)	86.58	60.63	83.02	84.92	N/V
	2 (OHL)	13.41	39.38	16.98	15.09	N/V
B	1 (UGC)	1.69	4.35	4.45	4.78	N/V
	2 (CC)	98.30	95.65	95.55	95.23	N/V
C1	1 (UGC)	100.00	100.00	100.00	100.00	100.00
C2	1 (UGC)	100.00	100.00	100.00	100.00	100.00

Table 8.13. Network length against the shortest network, network cost against the lowest cost network, extra cost per length against the lowest cost network, backup ratio and the sectionalization

Length per shortest	NW1	NW2	NW3	NW4	NW6
A	1.13	1.08	1.02	1.00	N/V
B	1.00	1.00	1.02	1.06	N/V
C1	1.10	1.06	1.00	1.02	1.00
C2	1.32	1.25	1.25	1.41	1.41
Cost per least cost					
A	1.40	1.40	1.13	1.24	N/V
B	1.00	1.00	1.00	1.00	N/V
C1	1.33	1.52	1.16	1.26	1.00
C2	1.64	1.80	1.51	1.51	1.26
Extra cost (k€/km)					
A	18.276	16.586	4.942	17.039	N/V
B	0.000	0.000	0.000	0.000	N/V
C1	15.953	21.710	6.004	17.632	0.000
C2	25.115	28.559	15.476	25.511	28.396

Continue Table 8.13. Network length against the shortest network, network cost against the lowest cost network, extra cost per length against the lowest cost network, backup ratio and the sectionalization

Extra cost[7] (€/kWh)	NW1	NW2	NW3	NW4	NW6
A	0.0039	0.0035	0.0134	0.0005	N/V
B	0.0000	0.0000	0.0000	0.0000	N/V
C1	0.0040	0.0062	0.0182	0.0005	0.0000
C2	0.0071	0.0098	0.0474	0.0011	0.0012
Average internodal distances of the final network (m)					
A	783	764	1069	460	N/V
B	702	723	1063	463	N/V
C1	758	752	1047	442	271
C2	890	873	1295	581	367
Load density[8] (kW/km^2)					
	235	161	17	1943	5924
Backup (%)					
A	52.68	50.00	59.27	46.24	N/V
B	25.87	28.13	50.15	41.40	N/V
C1	64.04	47.77	40.43	52.69	34.71
C2	100.00	100.00	100.00	100.00	100.00
Penetration of reserve connections (%)					
A	2.16	2.19	0.91	3.11	N/V
B	0.62	0.88	0.60	3.11	N/V
C1	2.16	1.75	0.60	3.63	2.48
C2	4.94	3.07	3.93	8.81	7.76

Sectionalizers[9]	NW1			NW2			NW3			NW4			NW6		
	man	rem	rec	man	rem	rec	man	rem	rec	man	rem	rec	man	rem	rec
A	199	28	3	130	18	3	103	21	3	133	20	4	N/V	N/V	N/V
B	56	16	3	48	0	3	41	10	3	58	1	3	N/V	N/V	N/V
C1	192	25	2	122	12	2	100	16	2	144	13	1	218	22	6
C2	621	29	2	445	3	3	662	15	1	381	0	1	639	0	2

The regionally varying attribute of load density (Table 8.13) is overall one of the key figures, strongly affecting many of the strategic choices in distribution network planning. While seeming such a straightforward task, there are some issues regarding the computation of this attribute, i.e., the ratio of the demand and the width of the

[7] The increase of the energy cost **w/o interruption and major interruption** costs when compared against the network of lowest cost. The cost here is only intended for comparing the different strategies, as the true cost of the network would also include certain cost components irrelevant for the comparison, e.g., the investment and operational costs for the primary substations, secondary substations and low voltage network.

[8] Load density = average nodal load per (kW) average of internodal distances squared (km^2). The spread of loads in rural areas typically resembles a string of pearls, whereas in cities the urban structure could better be characterized as homogenous. This special characteristic of sparsely populated areas has been considered by using the internodal distance as a measure for the width of the area instead of direct area limited, e.g., by the max and min values of the nodal coordinates. E.g., in the area of city of Helsinki, the load density figures would be somewhat different if the archipelago inside the borders of the municipality would be included, or if Lake Oulujärvi were included in the case of the Oulujärvi network.

[9] manual disconnectors (man), remote disconnectors (rem), reclosers (rec)

geographical area where the load points are spread. The load densities in Table 8.13 (and later in Figure 8.6) were calculated using the internodal distances (Euclidean metric) as the basis for calculating the area. As each network area more or less contains zones which heuristically could be excluded when considering the magnitude of the actual accessible and effectively available area, another approach, than simply a rectangular area based on the minimum and maximum values of the nodal coordinates, is used. Excluded areas would include, e.g. lakes and the sea but, then again, even these overall infeasible zones are often used for routing the lines to some extent. Thus, instead of using heuristics in selecting which areas to include and which to exclude, the internodal distances are utilized. The effective area being covered by the load nodes is estimated simply by the average of the internodal distances squared. Figure 8.6a represents the situation in a homogenous area, where the effective area equals the whole of the network area and Figure 8.6b represents a strongly heterogeneous case, where certain areas can be considered as obstructed. Using the direct approach of using the minimum and maximum values of the nodal coordinates would result in load densities of (a) 10 p.u. and (b) 0.0042 p.u., whereas using the internodal distances as the basis results in load densities of (a) 10 p.u. and (b) 0.01 p.u. In cities these considerations might seem less relevant, however, e.g., Helsinki is located in a peninsula and considering the electrified islands of the near archipelago would probably result in quite dubious figures concerning the load densities on a rectangular area basis. Especially in sparsely populated areas, the population tends to be concentrated in the shape of a string of pearls along favorable environments. Similar issues have been recognized in the literature and dealt with, e.g., using a zoning approach [Hyv08][73]. However, the proposed approach of using the internodal distances is easy and convenient to use and to reproduce, compared to the possibly more laborious approach of heuristically creating boundaries between different zones.

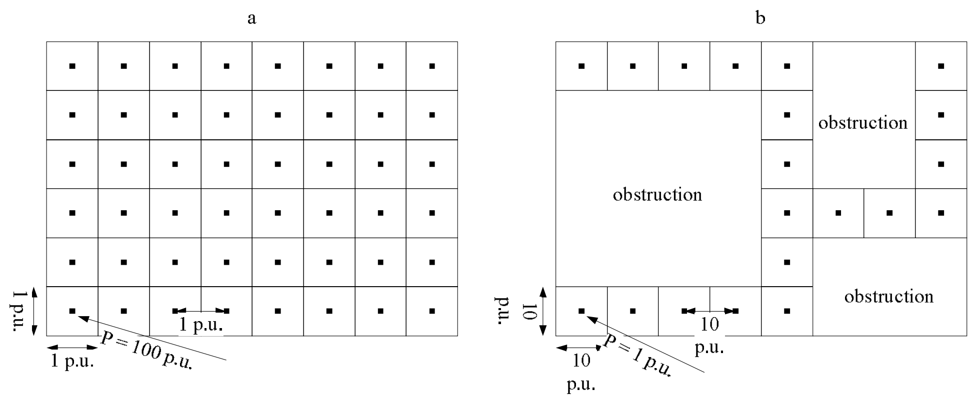
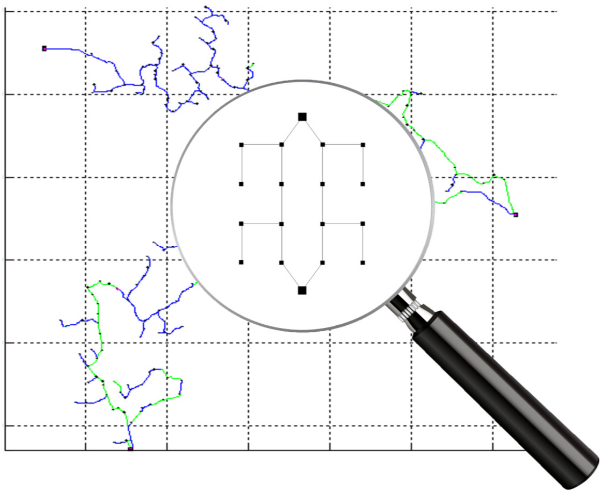


Figure 8.6. Calculating the load density using the internodal distance.

Chapter 9

Findings and Conclusions



This chapter discusses and analyzes the main contributions of this thesis, consisting of three main components: the novel approach of providing a network planning algorithm with an accurate dynamic geographic model of the operational environment, i.e., *methodology*, the comprehensive numeric representation of the operational environment, i.e., *parameterization*, and the case studies providing perspectives on the strategic planning of the power distribution networks in sparsely populated areas, i.e., *case studies*. As the last mentioned is basically an outcome from applying the two previous, the chapter proceeds in reverse order and starts with viewing the case studies. It then aims to verify the two others based on the observations and with regard to the literature. The results and observations are further processed into main conclusions and recommendations. Views on potential future research focus areas are provided at the end of this chapter.

9.1 Distribution network development strategies

In the case studies, 18 different networks were created, four independent networks for each of the network areas 1-4 and two for network area 6. Each of the networks was created with the aim to find the best network in terms of the full objective of life cycle cost, with given strategic guidelines, i.e., available line types comprising appropriate conductor families and possible preferences concerning, e.g., requiring backup. 18 different networks make a starting point for viewing the different strategic choices in different environments.

Figure 9.1 presents the studied network areas in terms of two important variables: the fixed cost correction for the different network areas and the load density. The fixed cost correction here simply refers to the distance weighted average of the internodal fixed cost corrections (i.e., installation cost C_{inst}, refer to (5)-(7) on pages 61-62) of all the connections of the Stage 4 final network routing for strategy C1. Fixed cost correction is considered as an indicator for the geographical difficultness of the network areas. Fixed cost corrections are used here directly, rather than, e.g., corresponding per distance unit mean value over the least cost path through the cost surfaces (refer Eq. (7) on page 62 for the cost over the path), as cost surfaces also have the topology specific parameters as inputs, while here the aim is to obtain an indicator value only related to the geographical characteristics of each of the studied network areas. Final network routing can be seen as representing the overall best available usage of the available terrain and, thus, can be considered as a valid basis for computing the indicator values for each of the network areas, i.e., the distance weighted fixed cost corrections. For consistency, a strategy of only a single line type, i.e., underground cable, is chosen as the basis for the computation of the indicator values.

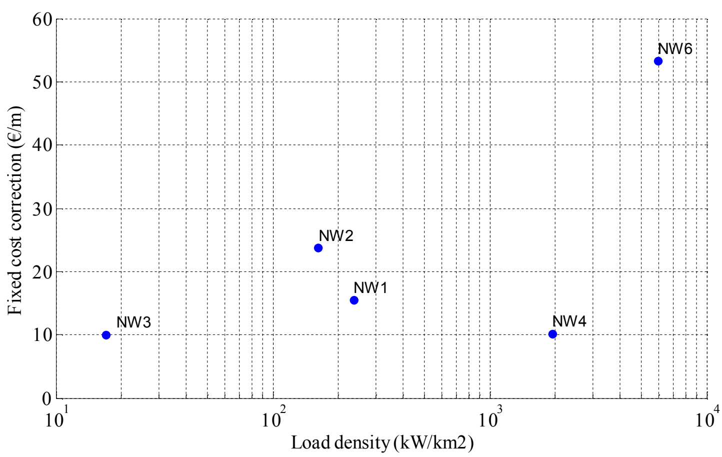


Figure 9.1. The fixed cost correction for the development strategy C1 as a function of the load density

Overall, viewing all of the studied line types, covered conductor overhead lines seem worth considering in a wide variety of circumstances, whereas bare conductor overhead lines do not, which can be concluded from the results regarding strategy A, in which underground cable is dominantly the more feasible line type. Figure 9.2 presents the total network cost for the cable network with optimal backup against the network of lowest total cost. Underground cabling alone results in more costly network for all the studied networks, varying between 16…52 percent higher total cost over the review period in comparison with the least cost baseline, i.e., network combining covered conductor overhead lines and cabling. This observation is well in line with the literature [Las10] [Las07b]. The strategy of cabling alone seems especially costly for the networks 1 and 2 with the terrain being overall costly. The costly environment directly affects the construction cost of the cable network, whereas for overhead line networks the impact is less. Overall, the geographical special characteristics of each individual network area affect each line type differently, thus resulting in differences in the mutual relation of the feasibility of the different strategic choices. Evidently, case specific geotechnical and geographical considerations must take place in order to find an optimal network structure in each case.

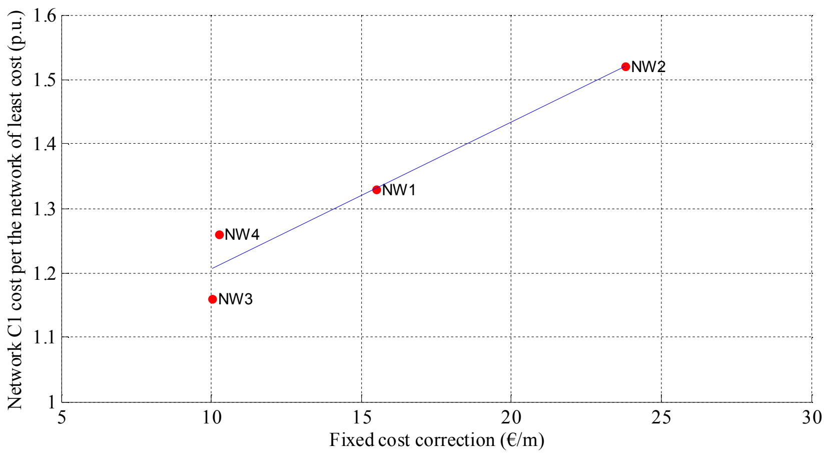


Figure 9.2. Cost of optimally backed-up network against the least cost baseline network

Logically, heuristically narrowing down the space of available solutions by requiring full backup results in higher total cost when comparing against a cost-optimally backed-up network, the difference in costs varying between 18…30 percent (comparing total cost for C2 against the total cost for C1 in Table 8.11). For instance, for the network area 4 the investment costs are 5.8 M€ and 7.9 M€ and interruption costs 0.9 M€ and 0.5 M€, for C1 and C2, respectively. Even with the interruption cost roughly halved, the 38 percent longer fully backed-up network, equipped with full switching against an optimal switch penetration of 41 percent, does not pay back in terms of savings in the interruption costs as valued using the given customer interruption cost parameters. In addition to being longer and requiring full switching, the fully backed-up network might require larger conductors in order to be able to cope with the reserve supply requirements during contingencies [Saa12]. Figure 9.4 presents examples of the final cable network topologies for two of the studied network areas, areas 1 and 3, having the load point characteristics of Figure 9.3a-b and the load densities of 235 kW/km^2 and 17 kW/km^2, respectively.

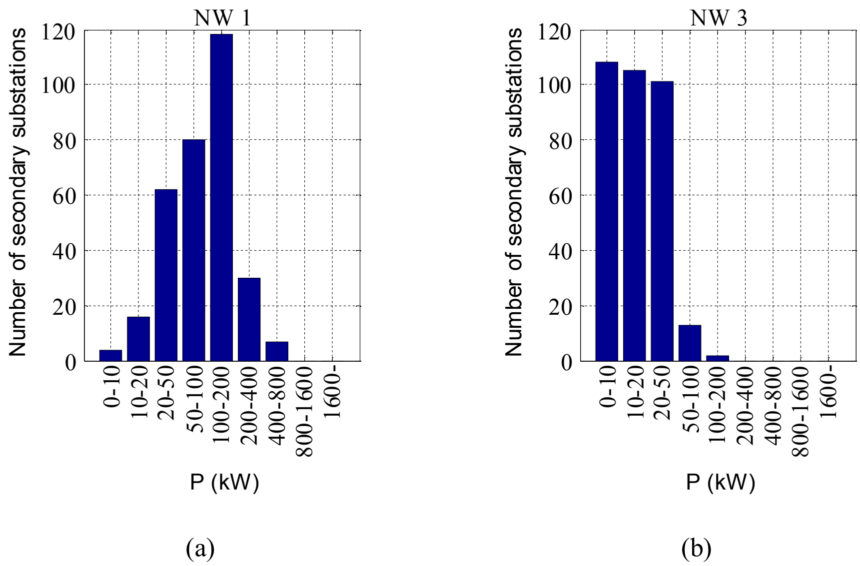


Figure 9.3. Sparsely populated area networks of different load point characteristics: network area with considerably high nodal demands (a) and a network area with considerably low nodal demands (b)

For a network area with considerably high load densities (Figure 9.4a-b), the smaller conductor sizes cannot be utilized in the fully backed-up network topologies and, overall, the cable sizing is rated larger (Figure 9.4b) compared to the optimally backed-up network (Figure 9.4a), where the laterals could be dimensioned on an economic basis by comparing the savings in the line losses with the corresponding increment of investment cost tied with upgrading the cable to one with a larger conductor. Then again, for a network with lower load densities (Figure 9.4c-d), some of the cable sections can actually be downsized for the fully backed-up network (Figure 9.4d), benefitting from the overall larger number of outgoing feeders, e.g., compare the single outgoing main feeder trunk from each primary substation in Figure 9.4c to the two outgoing feeders in Figure 9.4d, splitting the load of the outgoing trunk lines in half.

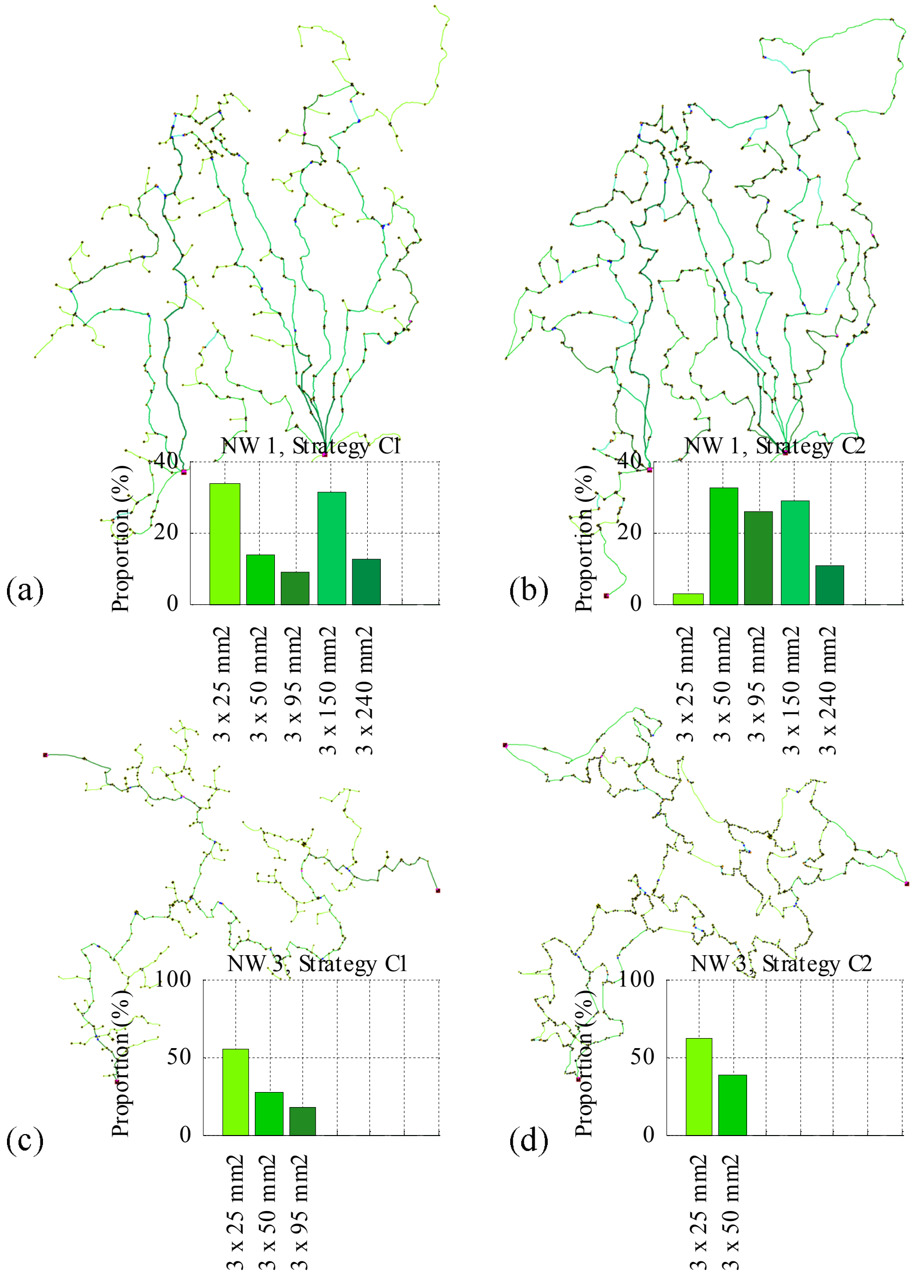


Figure 9.4. Comparing sparsely populated area cable networks of different load densities: densely loaded area network (NW1) with (a) optimal backup and (b) with full backup, and a sparsely loaded cable network (NW3) with (c) optimal backup and (d) full backup.

Figure 9.5 aims to visualize the above observation with regard to the different technically feasible and, if constraints are not violated, economically optimally dimensioned network topologies for network areas of different load densities. In densely loaded sparse populated area networks the trunk line sections must always be designed to thermally meet the power flows during contingencies, but the laterals can be dimensioned smaller (a). Having full backup, on the other hand, leads to larger dimensioning overall and to a larger number of outgoing feeders (b). In low loaded sparse populated area networks the small conductor cross sections can be utilized both in optimally backed-up networks (c) and in fully backed-up network topologies (d).

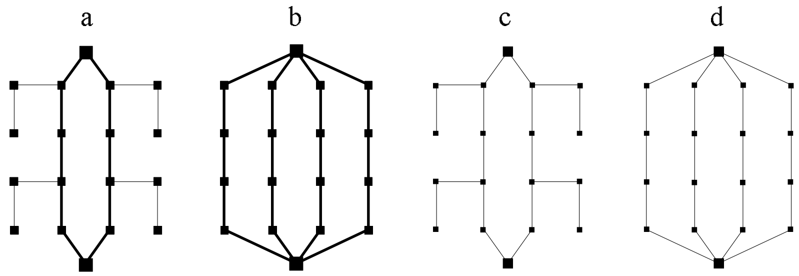


Figure 9.5. Comparing sparsely populated area networks of different load densities: densely loaded area network with (a) optimal backup and (b) with full backup, and a sparsely loaded cable network with (c) optimal backup and (d) full backup. Thin lines represent small and thick lines large conductor cross sections.

Figure 9.6 shows the switch penetration for the different development strategies. Here, the switch penetration is simply referred to as the ratio of the sum of all switches (manually and remotely operated disconnectors and reclosers) divided by the number of switches for full switching (i.e., corresponding sum for C2). Considering the impact of an individual installed switch, i.e., remote or manual disconnector or recloser, the internodal distances directly affect the annual fault rates the device experiences. The longer the point to point distances, the more probable faults on each line section are and the more probably each sectionalizer is needed for effective fault isolation and reconfiguration. As the load point densities have a strong positive correlation with the nodal demand (i.e., in areas with short internodal distances the nodal demands are high), the effectiveness of each individual sectionalizer is increased along with the increment in load point densities. Overall, the latter outweighs the effect of incrementing the internodal distances and for all development strategies the cost-optimal penetration of switches increases as the load densities of the network areas increase. Further, the lower the fault rates and the shorter the repair times, e.g., B being dominantly a network of covered conductor overhead lines having favorable parameters for both, the less steep the slope of the curve. However, a growing trend can clearly be observed for the switch penetration as the load density increases. The only data point for network area 6 is for strategy C1, for which the parameterization was adjusted as a response to the overall different characteristics of the operational environment there, thus making it not directly comparable with the other data points in the series of C1.

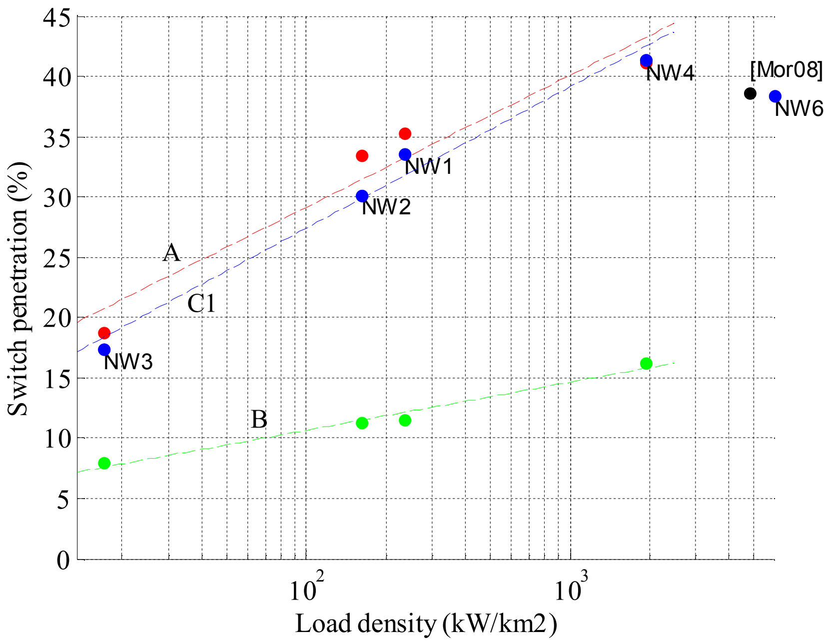


Figure 9.6. Optimal switch penetration for the different development strategies, A, B and C1

In the literature, the optimal placement of switches has been the focus of quite many papers, some of which have been dealing more in terms of automatic switches [Cel99] [Che06] or cases where distributed generation is present [Fal09]. However, apart from these papers, which focus on the methodologies and algorithms overall [Gar06] [Ma10], there are fewer but some relevant case studies available that quantify the effectiveness of sectionalization using real networks from realistic environments. A study proposing methodologies for optimal switch placement for distribution systems [Mor08] verified their approach by using the IEEE 123 node (85 load nodes) test system [Ker01], with a load density of 4700 kW/km^2 (calculated with the internodal distances squared using the approach applied to the case studies in this thesis) and ended up with an optimal switch penetration of approximately 39 percent (13 breakers, 29 sectionalizers and 2 loop switches in 114 possible locations, refer to Figure 9.6). However, with no other data points with different load densities being available, further analysis of these results is irrelevant, especially given that the level of the curve depends on the parameterization, e.g., the customer interruption costs and the costing and operation times of the switches, to mention some. Considering the available case study results from their corresponding environments, sectionalization has, generally, been found to be an efficient means for the mitigation of the interruption costs for Finnish rural area networks [Låg07] [Mar09].

Considering the optimal backup ratio of the networks, i.e., the effective combination of the sectionalization and the reserve connections, the penetration of switches can, as shown, be explained mostly with load density. The characteristics of the terrain do not affect the costing of the switches; however, this is not the case with reserve connections. The cost of each reserve connection strongly depends on the length of each connection and on the construction costs, which are line type specific in relation to the geotechnical characteristics of the terrain, and overall on the characteristics of the network area, i.e., spread of the load nodes affecting the potential locations for the tie lines. Then again, the benefits of backing-up overall depend on the load density and the fault rates of the network in relation to the internodal distances. Further, the distribution of the nodal demands (e.g., Figure 9.3) affects, how the trunk lines of the optimally backed-up networks can pick up the largest load nodes, while leaving the less critical loads without reserve connections on the lateral parts of the network. These aspects can be observed from the network figures in Appendixes 1-5. Viewing the backup ratios presented in Figure 9.7 as a function of the load density, no distinctive pattern seems apparent. While the switch penetration clearly correlates positively with the load density, the backup ratio would almost seem to show the opposite trend. Clearly the overall complex character of backup as a whole cannot be explained in terms of the load density only, but perhaps also the special geographical characteristics of the network area, i.e., the spread and density of the load points, the overall accessibility of each of the load nodes and the availability of potential locations for the tie lines, all have their impact on this.

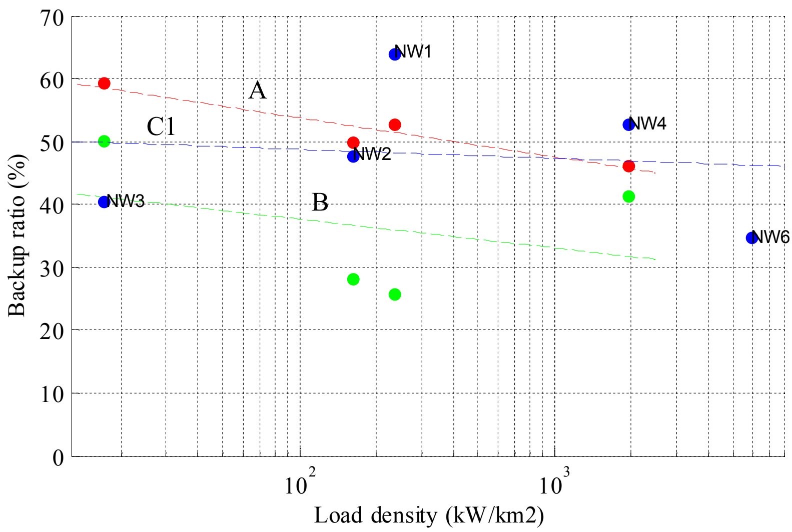


Figure 9.7. Optimal backup ratio as a function of the load density

One of the major strategic means, often considered with regard to improving the reliability of overhead line networks, is the optimal placing of the lines in order to lower the expected fault rates, especially the tendency towards the use of roadsides, whenever possible, as the preferred places for feeder corridors [Las06] [Las07] [Las07b] [Haa12]. Considering the parameterization proposed in this study, there can be seen at least two obvious reasons why placing overhead lines next to roads should be favored. First, next to roads the expected fault rates are lower due to the road side of the feeder corridor being open terrain, which eliminates a great part of the faults related to forest. Second, the repair times, including locating the fault, might be expected to be somewhat shorter next to roads. Then again, the longer routing often resulting from the use of small and curvy roads and the need for special structures for the turns more often required in routings following the roads have the opposite effect. The proportions of the total length of covered conductor overhead line for the strategy of mixed network of covered conductor overhead line and underground cable (B) installed next to roads are presented in Figure 9.8.

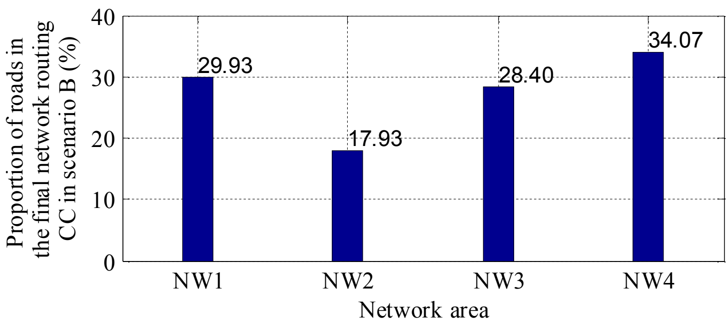


Figure 9.8. Proportion of roads (i.e., roadsides) for the covered conductor overhead lines (Scenario B) in the routing of the final network , for the different network areas

Roughly one third of the line sections planned as covered conductor overhead lines were placed next to roads. One of the aspects partly explaining the somewhat exceptionally low proportion of roads utilized in the routing for network area 2 might have to do with the overall characteristics of the terrain of that area. This area is, in general, very fragmented with plenty of rock exposures (Figure 8.5), which often relates to quite diverse patterns also with regard to the elevation of the terrain. Not only are such characteristics challenging for underground cable network construction (refer to Figure 9.2), but partly the same challenges must also be met in the planning and construction of other infrastructures, such as road networks. Thus, it might be that in this area the routing of roads has more than normally been compromised between distance and avoiding obstacles, thus not providing short point to point routings for overhead line networks either. Broadly considering, the results concerning the usage of roads and roadsides for the distribution feeder routing do support the results presented in the literature [Las06]

[Las07] [Las07b] [Haa12]. However, new patterns, with regard to the geographic characteristics of each of the individual network areas, were observed too.

The studied areas greatly differ in terms of load point and load densities (Figure 9.1). While the differences between the network development strategies seem rather significant in terms of absolute investment costs (k€/km) for all network areas, proportioning the cost further with regard to the strength of the customer base, i.e., computing the cost per delivered energy over the review period (€/kWh), brings up new perspectives. The values for the extra cost in Table 8.13 simply refer to the difference of the network cost for the different development strategies excluding the interruption and major disturbance costs with regard to the supplied energy over the review period. This extra cost can be considered as the minimum of the increment in the network fees the customers must be prepared to pay (refer to willingness to pay) when upgrading the network strategy with regard to the reference strategy providing the least overall cost over review period. For instance comparing the strategy of cabling alone, with the optimal baseline strategy being the combination of covered conductor overhead lines and cabling (Figure 9.9), load density, indicating the overall strength of the customer base, correlates strongly with the sensitivity of all increments in the inputs, i.e., the changes in network cost, which can be referred to by an indicator, the fixed cost correction.

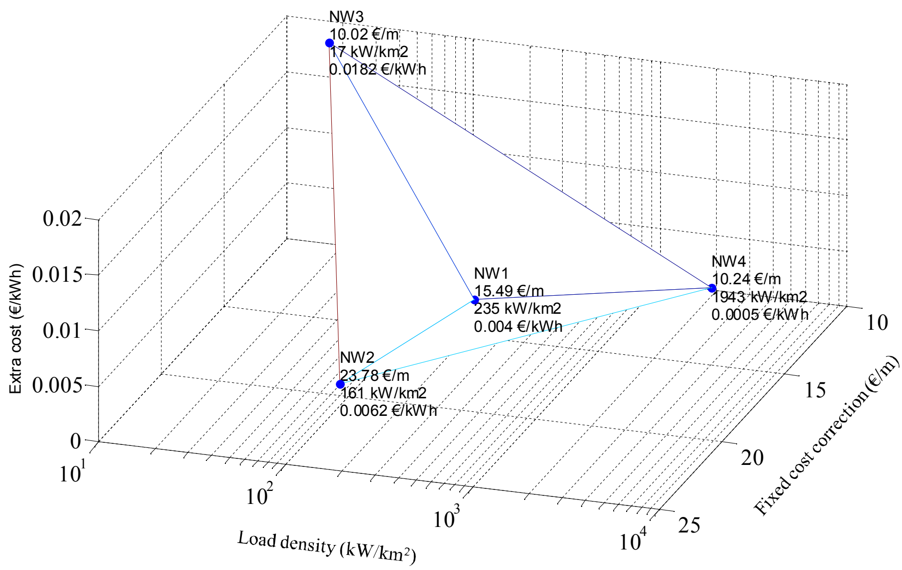


Figure 9.9. The impact of load density and the overall geographic characteristics of the operational environment (OE) on the expected network fees

Continuing this line of thought, the most sparsely loaded network areas with the weakest customer base combined with an overall geographically challenging operational environment might face the biggest challenges with regard to restraining the network fees within tolerable limits, e.g., given the legislative framework for preparing the network infrastructure to be immune against all risks related to adverse weather. Figure 9.10 aims to visualize this concern related to the impact on the network fees as a function of the two attributes given the strategic guidelines: the network area specific geographic characteristics, i.e., overall geotechnical difficulty, and the load densities as an indication of the overall strength of the customer base.

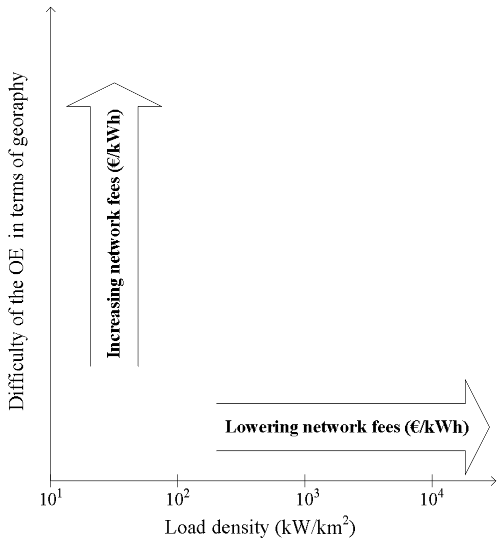


Figure 9.10. The impact of load density and the overall geographic characteristics of the operational environment (OE) on the expected network fees

As brought up in the literature review, when considering the overall topology of the network, some propose, e.g., strong cabled trunk lines making secure feeding points into the network area, i.e., partly performing as distributed primary substations [Loh05], or simply layouts where the more densely loaded parts of the network are fed by backed-up cable trunks and the more sparsely loaded parts of the area are left for overhead line laterals, usually separated from the trunk by reclosers [Låg07]. While these kinds of topologies intuitively seem rational, they do involve heuristic pre-determination and thus it would be interesting to examine whether these kinds of network topologies appear in the cost optimal networks that are generated without such heuristics. Viewing, e.g., the network areas in Figure 9.11 there, indeed, can be observed similar layouts to the ones described above. The network 2A presented in Figure 9.11 is the network combining underground cabling and bare conductor overhead lines for the network area 2 (refer to Appendix 2 for details), making a particularly good example for two reasons. First, these are the two line types that make the strongest contrast, clearly showing that in the more fault prone overhead lines are often situated in the low loaded peripheral laterals of the network. Second, this network area has a quite an average distribution of nodal demands, where the largest nodal demands are concentrated in the northern parts of the area and the least loaded secondary substations are located in the southern outskirts of the area. Similar topologies can also be observed for the other networks (refer to Appendixes 1-4), especially with the strategies of combining two line types of high contrast in terms of fault proneness. As expected, the customer interruption costs are clearly the main driver in the trunk line sections leading often to the selection of cable (green line segments) but construction costs are weighing more in the lateral parts separated via reclosers, leading often to the selection of overhead line (red line segments). Similarly, for network 4B, with a combination of covered conductor overhead lines and underground cabling, reclosers often separate the lower loaded lateral parts from the trunk line sections picking up the largest secondary substations. Now that the parameterization is favorable for the covered conductor overhead lines (blue line segments), there cannot be seen such a strong polarization between the two line types as with the previous network 2A.

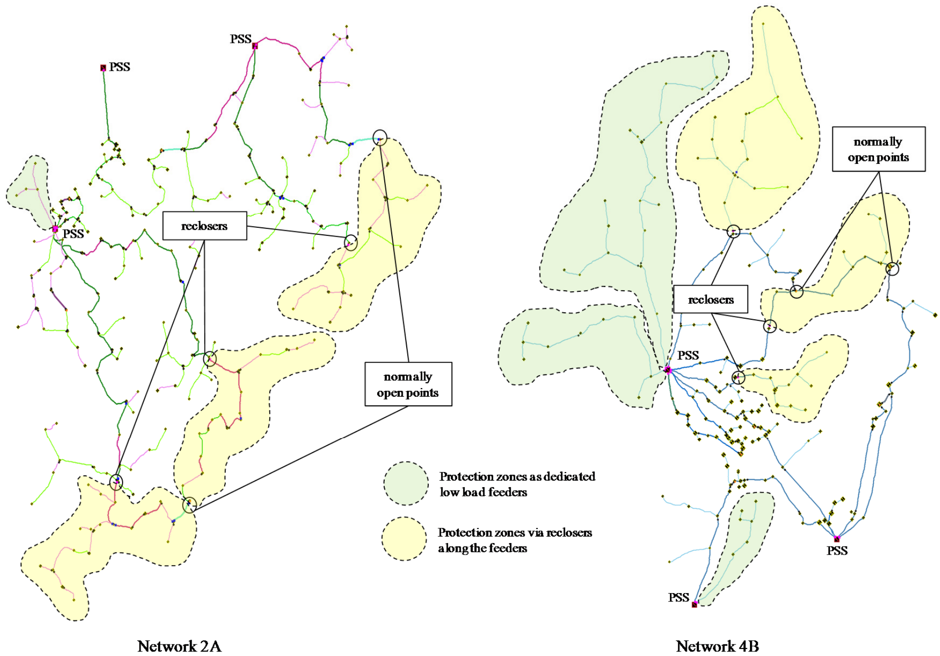


Figure 9.11. Strong cable trunk lines making secure feeding points in the network area and bare conductor overhead line laterals making separate protection zones via reclosers (Network 2A) and covered conductor overhead lines dominating in a network with protection zones separated with reclosers and also dedicated feeders with low priority loads making separate protection zones (Network 4B)

The above observation of having such polarized characteristics for the final network 2A might also have to do with the overall difficult terrain in the peripheral parts of the network. The cabled trunk lines more often can use lower cost installation environments, but for the lateral parts, in addition to being low loaded, these aspects related to geography might have an impact.

9.1.1 Discussion

Overall, for an individual customer, the impact on the network fees, having willingness to pay with regard to improved reliability as the counterweight, in the end, is probably the best measure for the feasibility of the different development strategies. Then again, this is strongly affected by the overall customer base sharing the expenses, e.g., networks that also have urban areas along with sparsely populated areas might have less pressure for increasing the network fees, even with regard to development strategies putting weight on heavy investment in terms of improving the reliability. When it comes to equitable quality of service, e.g., in terms of immunity against major disturbances, zonal thinking, with the overall areas being divided into zones in which the above mentioned equitable service quality principle is then separately applied, might be an option. To some extent it might be reasonable to even out the differences in the geographic accessibility of certain load nodes, but on the other hand, the other view would be to consider applying the polluter pays principle. In the end, political steering, i.e., regulation, will strongly affect the choices being available. Further, considering the main objective of maximizing the socio-economic welfare, strict obligations will unavoidably lead to a suboptimum result, though, it must be brought up what was earlier discussed with regard to the need for giving an impetus in an operational environment encumbered with existing systems (refer to the overall discussion regarding the strategic development of rural power distribution systems on page 32 in Chapter 2), i.e., the differences in the overall planning philosophies applied to Greenfield versus Brownfield planning.

Bringing back what was mentioned in the literature review, e.g., the present customer interruption cost parameters would have to be 4-5 times higher in order to be able to even out the difference in the costs of a fully cabled network against an optimal network [Las07b], yet a question left open was the consideration of the major disturbances and their future weight in the regulatory regime [Las07b]. Further, if full cabling of all present overhead lines were to be implemented, the distribution fees have been estimated to be under pressure to be raised by 30…50 percent depending on, e.g., the scheduling of the investments [Las07]. Overall, these previous results seem rather consistent with the ones obtained from the case studies in this thesis. Further, remembering the discussion concerning the impact which changing the view point can make overall [Haa12] [Alv11], the results of this study support earlier observations. Alternatives that aggressively place weight on investments might, while being accepted by the authorities and if, e.g., financing of the construction projects does not become a constraint, be seen as an attractive alternative for the utilities. Then again, for the individual customers, the willingness to pay, e.g., for immunity against major disturbances, is the decisive measure. Noting the major differences in the geotechnical feasibility of the operational areas of the different utilities, being tied too strictly to one single strategic option might result in an overall far from optimum network infrastructure.

Estimating realistic service lifetimes for underground cable installations is one of the partly unanswered important questions. The ageing of XLPE insulations has been examined theoretically and in laboratories [Ber02] [Dan96] [Hyv13], however, facing the real challenges of the operational environment, e.g., ground frost or the pressure of traffic for installations placed into the road structures might, in the end, greatly affect the overall performance of the cable installations. Then again, keeping in mind the characteristics of the case study section being a comparative study, for overhead lines the process of ageing is better known. Often the failures in cable network might be resulting from improper installation work [Hyv13]. Other than that, the modern extruded XLPE insulated medium voltage cables are known to be extremely reliable if not exposed to any external causes leading to failure. In this study the review period for all the studied strategies was 40 years. The significance of the differences in the expected service lifetimes is affected by the interest rate. The impact of the difference in service lifetimes is narrowed along with increasing the interest rate. Further, uncertainties, e.g., related to load growth, might in the end strongly affect the economic service lifetimes, regardless of the technically available service years.

Regulatory obligations, e.g., concerning requirements for reliability, might, as discussed, rather rapidly shake the operational environment. In the end, e.g., the appreciation of the customer interruption costs has its true force through the regulation. As stated in the literature, the customer interruption parameters would have to be increased quite significantly in order to initiate a major technological transition [Las07b]. However, similar strict regulatory constraints, as implemented in Sweden [Wal11], would force this. The appreciation of immunity against major disturbances might exclude overhead line types from future network development strategic portfolios. In general, if customer interruption costs are aggressively increased or strict upper limits are imposed for the duration of customer interruptions, an overall higher degree of backup might result and, perhaps, the placement of cable networks in locations having shorter repair times. Other means, e.g., reserve supply units, could also be seen as a means to affect the overall experienced durations of the interruptions. The use of reserve power units, where applicable, provides the means to restore the supply in a shorter time than it would take to repair a faulted cable. If a faulted cable section can be replaced by a temporary by-pass cable or a reserve power supply unit, one of the major recognized cost drivers limiting cable routing, the repair time, becomes less dependent on the terrain. Having these kinds of means making it possible to meet the possibly stricter guidelines of the regulatory framework in the future might have significant effect on the overall network planning philosophies, on the resulting network topologies and, consequently, on the network fees, especially in areas of weak customer base.

9.2 Providing an NTOA with accurate geographic data

The case studies proved that the developed methodology [Saa13] can cope with realistically sized network planning problems. The main incentives for developing the methodology can be seen as being related to the reported challenges pointed out in the literature regarding the complexity and overall inter-relational characteristics of the task of distribution system planning [Låg12]. In general, developing methodologies for planning optimal network structures has gained very much attention in the literature, as shown in the literature review. This alone, being such an endless process with continuous incremental improvements being reported, is a very complex and challenging task. Encumbering the task with an extremely large amount of geographically detailed data has undoubtedly seemed as an unreachable task for many. However, using the developed methodology presented in this thesis, practically unlimitedly accurate geographic data can be successfully applied in the network planning process. By considering not only the fixed costs, i.e. installation and construction costs, earlier recognized as cost drivers [Shu12], but also the varying cost components, the full planning objective for network planning can be considered. The varying costs include the cost of losses due to varying network topology dependent line losses, the costs due to interruptions varying independently for each of the individual line sections of the specific network structure, and also the cost of reserve connections and sectionalization,

9.3 The numeric model of the operational environment

The parameterization, which links the methodology and the case studies, was built up and carefully documented, and the results from the case studies were analyzed with regard the earlier observations and results from the literature. Many similarities, e.g., concerning the overall feasibility of different line types, were found. However, many aspects, earlier merely dealt with qualitatively or by using heuristics, e.g., the use of roadsides, often treated rather loosely in the literature, have been properly quantified, by means of the novel methodology presented in this thesis. Overall, many earlier studies focusing on strategic development of power distribution systems have inadequately treated the spatially varying geographic characteristics of the operational environment.

The results being overall in line with earlier observation can be partly viewed as verifying the methodology and the parameterization as a numeric representation for the operational environment. In the parameterization, not only were the topographic data acquired directly from the topographic database, but also certain issues were recognized and reacted to. Overall, the operational environment of the power distribution in sparsely populated areas was comprehensively discussed and needed adjustments were derived from these observations. For instance, the operational environment was first viewed from the geotechnical perspective and, further, from the perspective of the challenges the distribution utilities are facing in their terrain planning processes, e.g., with regard to the overall placement of the power distribution systems into the public space. The main contributions of this analysis were brought into the topographically structured model, e.g., three additional terrain types, derived from the original topographic data but having their grounds in the before mentioned considerations.

Further, the proposed new concept of comprehensively utilizing the spatially referenced data recorded in the network information system can be seen as a further potential development from the topographical model used in the actual case studies of this thesis. Using different relevant available data, e.g., real network specific fault data and network construction project cost data, efficiently combined with available geographic data, e.g., forestry maps, climatic data and geological data, would provide the means to obtain a statistical spatially referenced model for the whole of the network area.

9.4 Main conclusions in brief

The contribution of this thesis can be divided into three parts: first (1.) the new methodology in the topology optimization process, where full life cycle cost driven cost surfaces are used in the internodal parameter computation, second (2.) parameterization, which is an objective and realistic numeric representation of the operational environment to be utilized in the optimization task of finding the most feasible network structures and third (3.) the case studies, which in the end answer the questions regarding the feasibility of different proposed network development strategies in case of different geographical and network operational environments. Following brief summary puts together the main points regarding the scientific contribution.

1. The developed methodology, which provides a network topology optimization algorithm with accurate dynamic geographical model of the operational environment, proved to be a powerful tool in future distribution network planning. Case studies proved the methodology being capable of dealing with network planning tasks of realistic size.
2. The parameterization, which in the end is the exclusive means to describe the operational environment for the algorithm, was verified by comparing the results against earlier observations reported in the literature.
    - Overall the results are well in line with earlier observations, which can be considered as an indication for the credibility of the model.
    - In this study the model of the operational environment constituted of terrain types being based on topographic data but also of additional terrain types having grounds on the observations with regard other geographic data and fitted to cover the geographic area of the case study networks.

- A novel approach of exploiting geographic and network information in order to obtain a spatially referenced geographic parameterization being benefitted in different processes of network planning was introduced. This iterative approach, where network information from the operational processes are fed back as inputs for the rest, could benefit of multiple geographically referenced predictor variables, e.g., forestry maps, lightning data or icing maps, in order to be able to obtain a spatially referenced accurate model of the operational environment and, importantly, to produce information being consistently benefitted in the different processes of network planning.

3. Observations regarding the case studies
    - Covered conductor overhead lines combined with underground cabling seem a worthy option to be considered in a wide variety of environments
    - The feasibility of strategies concerning underground cabling alone strongly depends on the appreciation of the major disturbances, but also strongly on the geographical characteristics of each specific network area.
    - The major guide lines regarding underground cable networks, once the line type is fixed, greatly affect the cost of the final network. Requiring full backup leads to longer networks, and depending on the load densities, possibly also to a network which is overall dimensioned larger.
    - Optimal penetration of sectionalization is greatly affected by the load density. However, the parameterization with regard to reliability affects the basic level of the switch penetration.
    - Network topologies, where trunk lines that have secured supply in terms of reserve connections are combined with lateral parts possible made with lower cost more fault prone line types and separated from the trunk line sections using reclosers was shown to be an overall economically feasible option in many cases.
    - The network fees in sparsely populated areas of extremely low loads are pronounced sensitive to all changes in the network costs. Thus, suiting the network development strategies individually for each network area is needed.

9.5 Future work

In the approach presented in this thesis, the nodes being available for the topology algorithm (VOH) only constituted of the secondary substations. In reality, line types might often change in between these internodal connections. The approach presented in this thesis does have the capability to deal with these kinds of situation using so called no-load nodes. However, placing these nodes efficiently, without too much compromising on the performance of the main process, needs to be carried out carefully. Possible locations for these kinds of no-load nodes might include, e.g., T-branches and different interfaces of the different terrain types, i.e., water-to-forest, forest-to-field, et cetera.

The parameterization completely built up using the available network information and geographic information seems very promising. Yet, plenty of aspects need to be borne in mind, one of which is the need for consideration of the equitability of different line types and availability of sufficient data, when it comes to comparisons of the different strategic choices. Related to previous, plenty of geographical data bases are becoming more easily available, resulting in plenty of potential for utilizing these data sources in network planning.

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Appendix 0
Legend

Overall, the network figures presented in the Appendixes 1 – 5 aim to present the overall network topology and related internodal routing with regard geographic data as detailed as possible. However, as the studied network areas are wide, e.g., network 3 Oulujärvi constitutes of a land area being roughly 50 km wide and as the routing of the internodal connections is based on very detailed geographic data, being in magnitude of roughly 10 meters per pixel, there is no possibility to present all the details in a single figure being fitted into the frames of the page. Figure A1-A3 provide detailed information of the symbols and colors being used in the network figures.

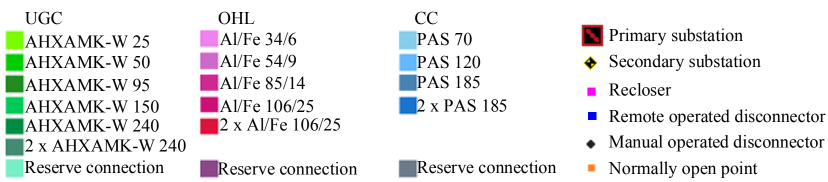

Figure A 1. Line types and associated conductor families and network nodal and sectionalization symbols

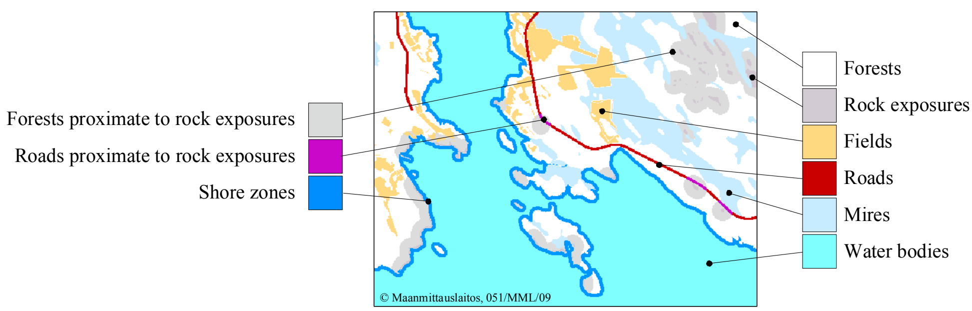

Figure A 2. Terrain types: the main terrain types on the right and the derived terrain types on the left

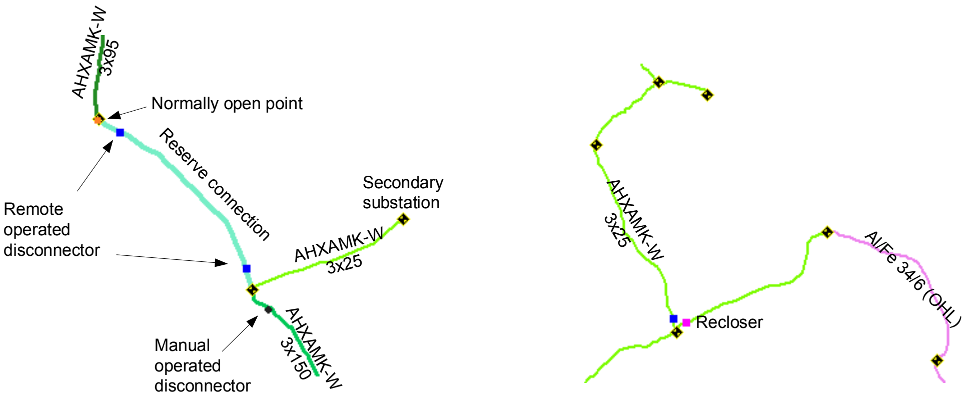

Figure A 3. Line types and sectionalization

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[10]License is available and can be seen at (URL): http://www.maanmittauslaitos.fi/en/NLS_open_data_licence_version1_20120501

Appendix 1
Network area 1: Kirkkonummi

Table A 1. Network area: substations

Network area 1	
Secondary substations	317
Primary substations	3

Table A 2. Network area: terrain types

Terrain types (%)	
Forests	15.27
Roads	1.16
Fields	10.03
Water bodies	6.38
Mires	5.33
Rock exposures	8.39
Forests proximate to rock exposures	49.98
Roads proximate to rock exposures	1.13
Shore zones	2.33

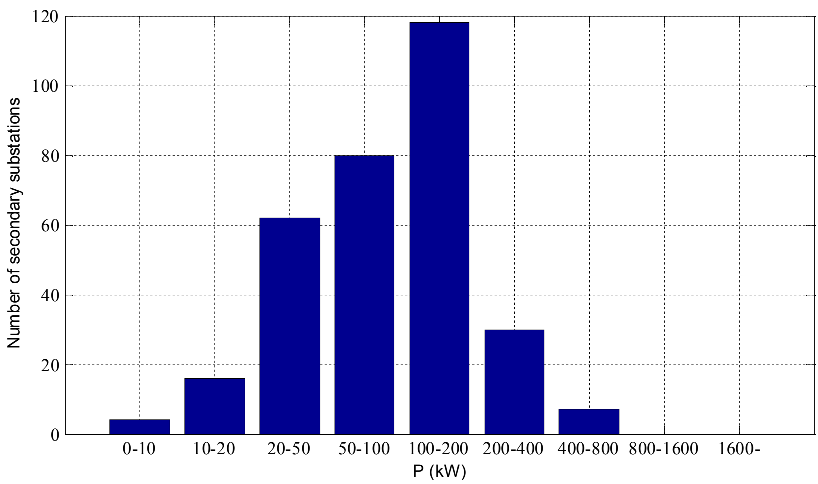


Figure A 1. Network area: secondary substations grouped by the maximum hourly demand

Table A 3. Final network: cost and length

Cost and length	A	B	C1	C2
Total length (km)	253.607	223.765	245.537	296.436
Length per shortest (p.u.)	1.13	1.00	1.10	1.32
Investment (M€)	13.652	8.641	13.421	17.718
Losses (M€)	0.667	0.934	0.893	0.755
Interruptions (M€)	2.028	2.138	1.314	0.684
Total cost (M€)	16.347	11.712	15.629	19.157
Cost per length (k€/km)	64.458	52.341	63.653	64.625
Cost per least cost (p.u.)	1.40	1.00	1.33	1.64
Extra cost per length (k€/km)	18.276	0.000	15.953	25.115

Table A 4. Final network: sectionalization

Sectionalization	A	B	C1	C2
Backed-up sec. substations (%)	52.68	25.87	64.04	100.00
Manual disconnectors	199	56	192	621
Remote disconnectors	28	16	25	29
Reclosers	3	3	2	2

Table A 5. Final network and route options: lengths

	A		B		C1	C2
General	UGC	OHL	UGC	CC	UGC	UGC
Internodal distance (avg., m)	778	816	628	703	758	890
Length (km)	219.33	34.28	3.77	220.00	245.54	296.44

Table A 6. Final network and route options: terrain types

	A		B		C1	C2
Terrain types (%)	UGC	OHL	UGC	CC	UGC	UGC
Forests	30.77	0.28	0.46	16.30	35.29	37.10
Roads	5.47	1.65	0.06	14.50	5.71	4.67
Fields	27.23	0.87	1.16	22.33	33.41	31.56
Water bodies	6.04	0.00	0.00	0.02	4.07	5.32
Mires	0.39	0.22	0.00	1.83	0.01	0.08
Rock exposures	0.71	0.63	0.00	3.61	0.06	0.06
Forests prox. to rock exposures	13.23	3.09	0.00	24.18	17.61	17.80
Roads prox. to rock exposures	1.34	6.76	0.01	15.43	2.41	1.75
Shore zones	1.30	0.02	0.00	0.12	1.43	1.67

Table A 7. Final network and route options: conductor sizes

	A		B		C1	C2
Conductor sizes (%)	UGC	OHL	UGC	CC	UGC	UGC
Conductor 1	35.85	9.07	1.69	66.09	33.79	2.58
Conductor 2	8.61	0.00	0.00	0.97	13.87	32.48
Conductor 3	7.91	2.45	0.00	31.24	8.69	25.48
Conductor 4	11.14	1.89	0.00	0.00	31.08	29.04
Conductor 5	23.07	0.00	0.00	N/V	12.57	10.43
Conductor 6	0.00	N/V	0.00	N/V	0.00	0.00

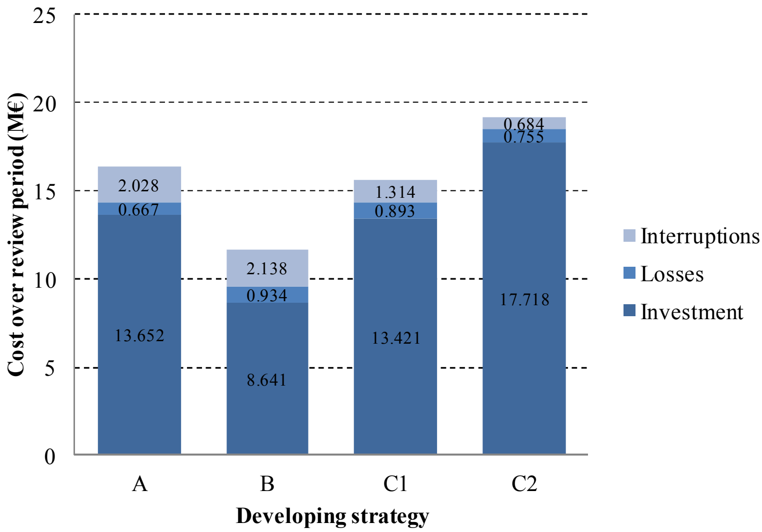


Figure A 2. Final network: cost

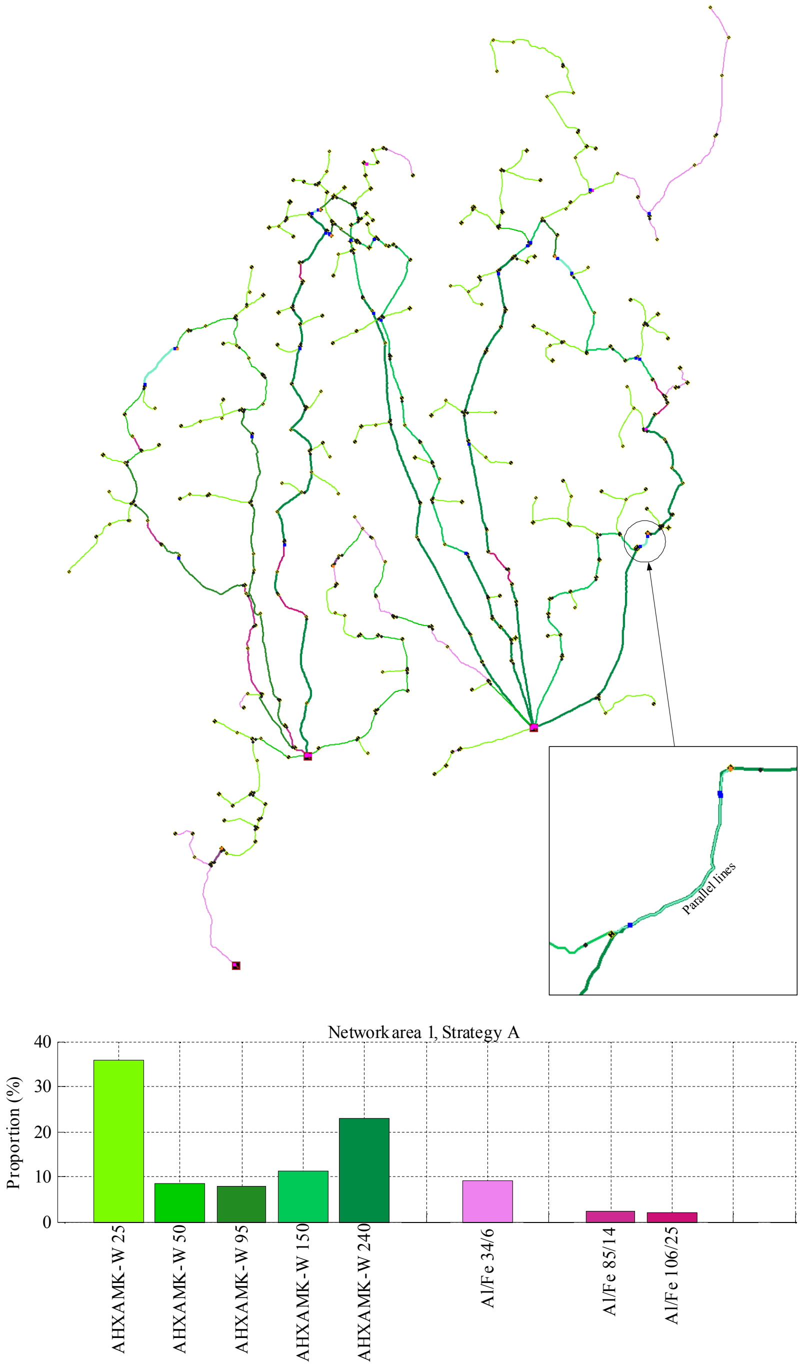


Figure A 3. Final network A: Topology and conductor sizing

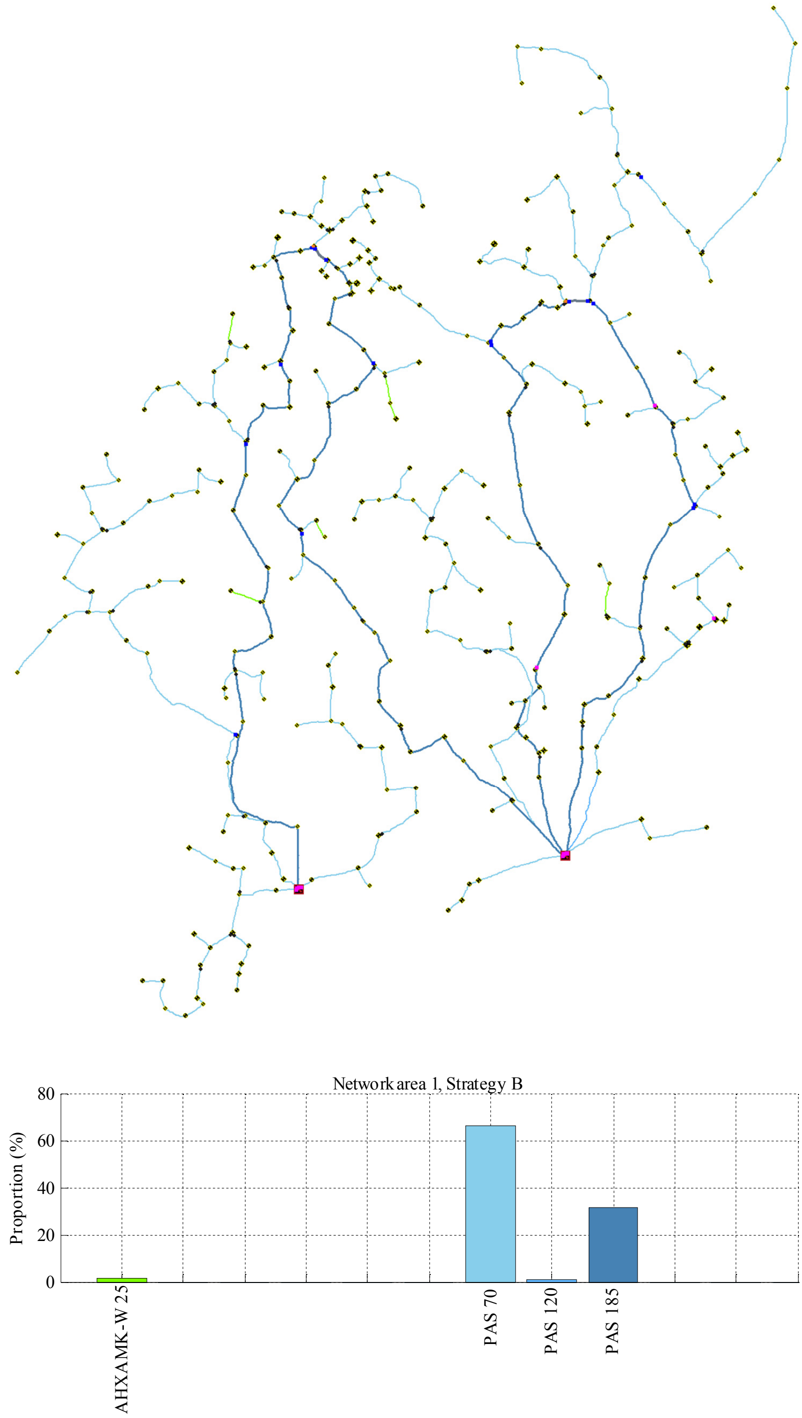
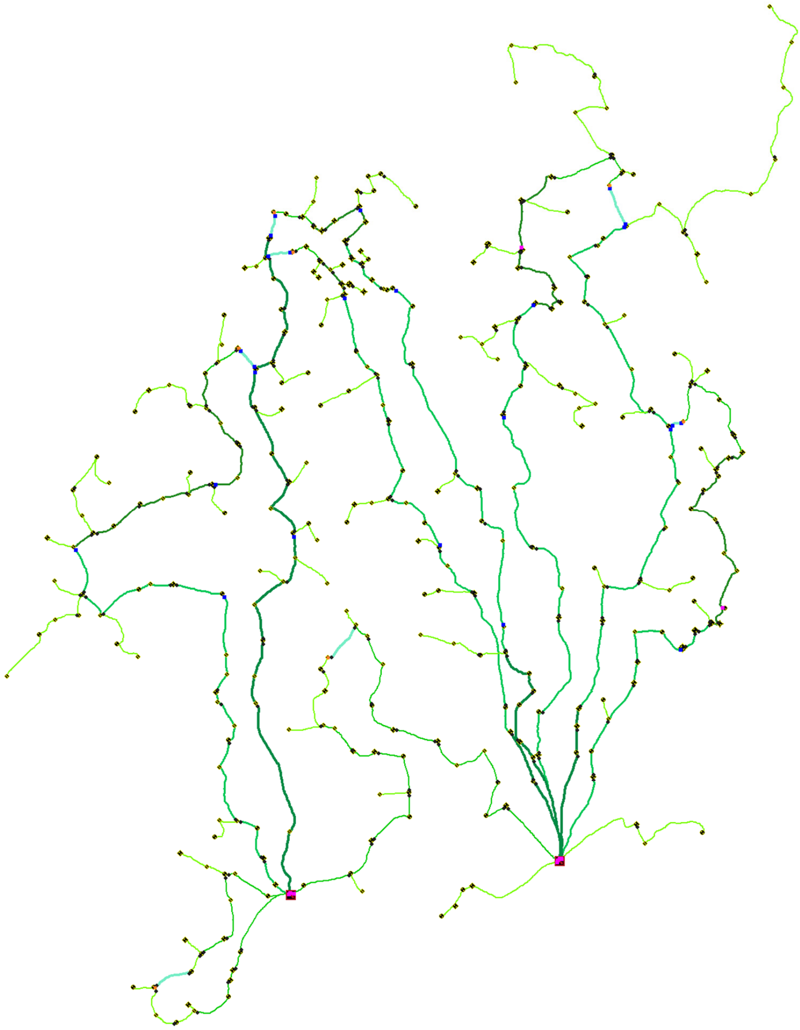


Figure A 4. Final network B: Topology and conductor sizing



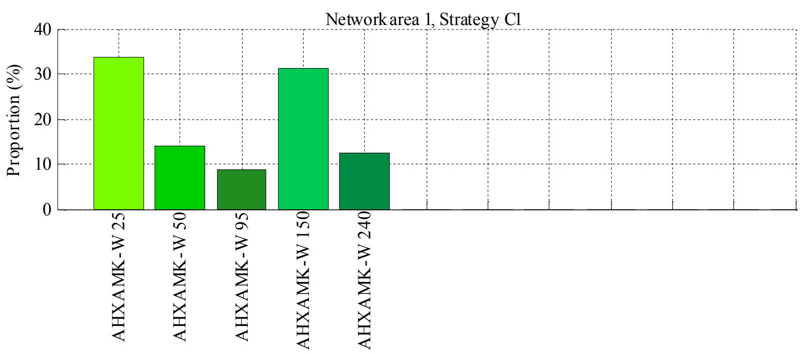


Figure A 5. Final network C1: Topology and conductor sizing

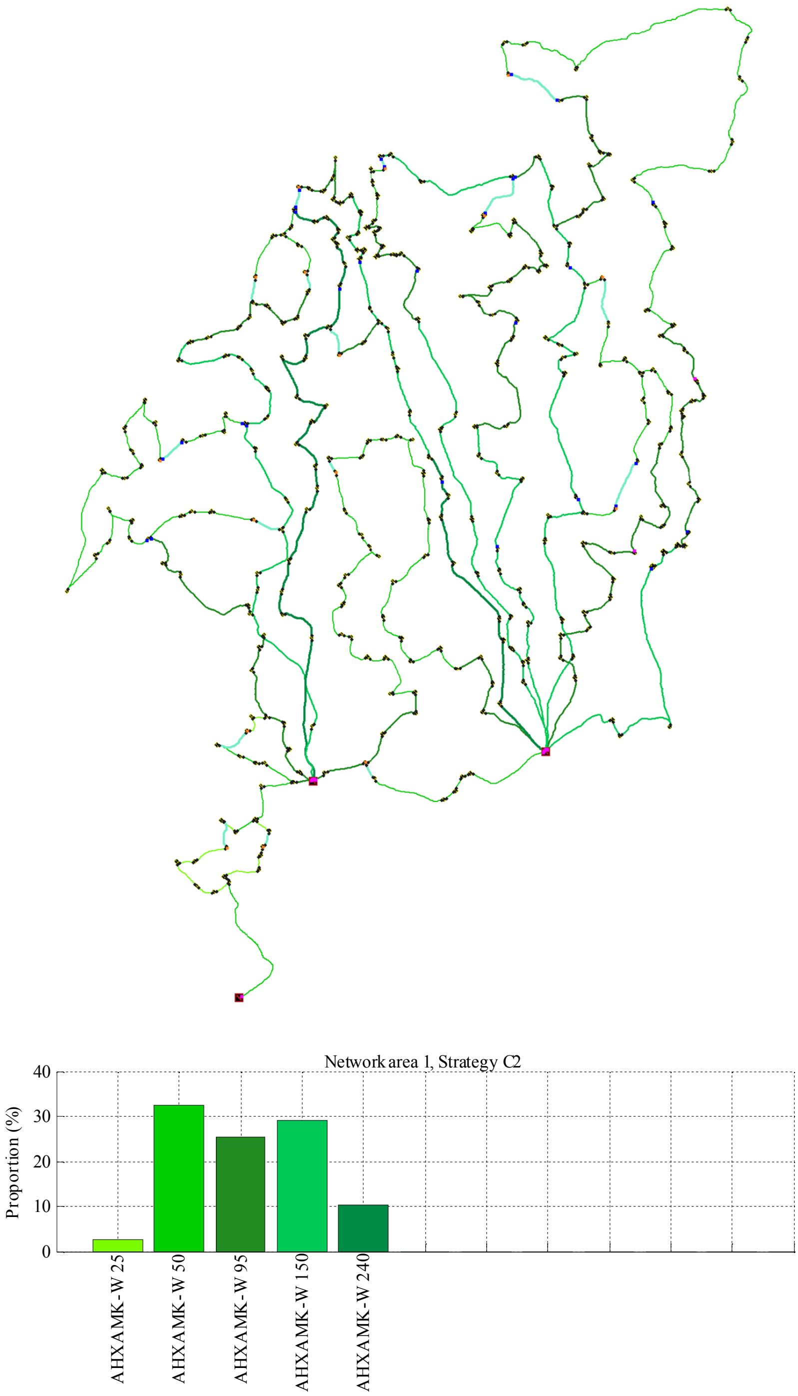


Figure A 6. Final network C2: Topology and conductor sizing

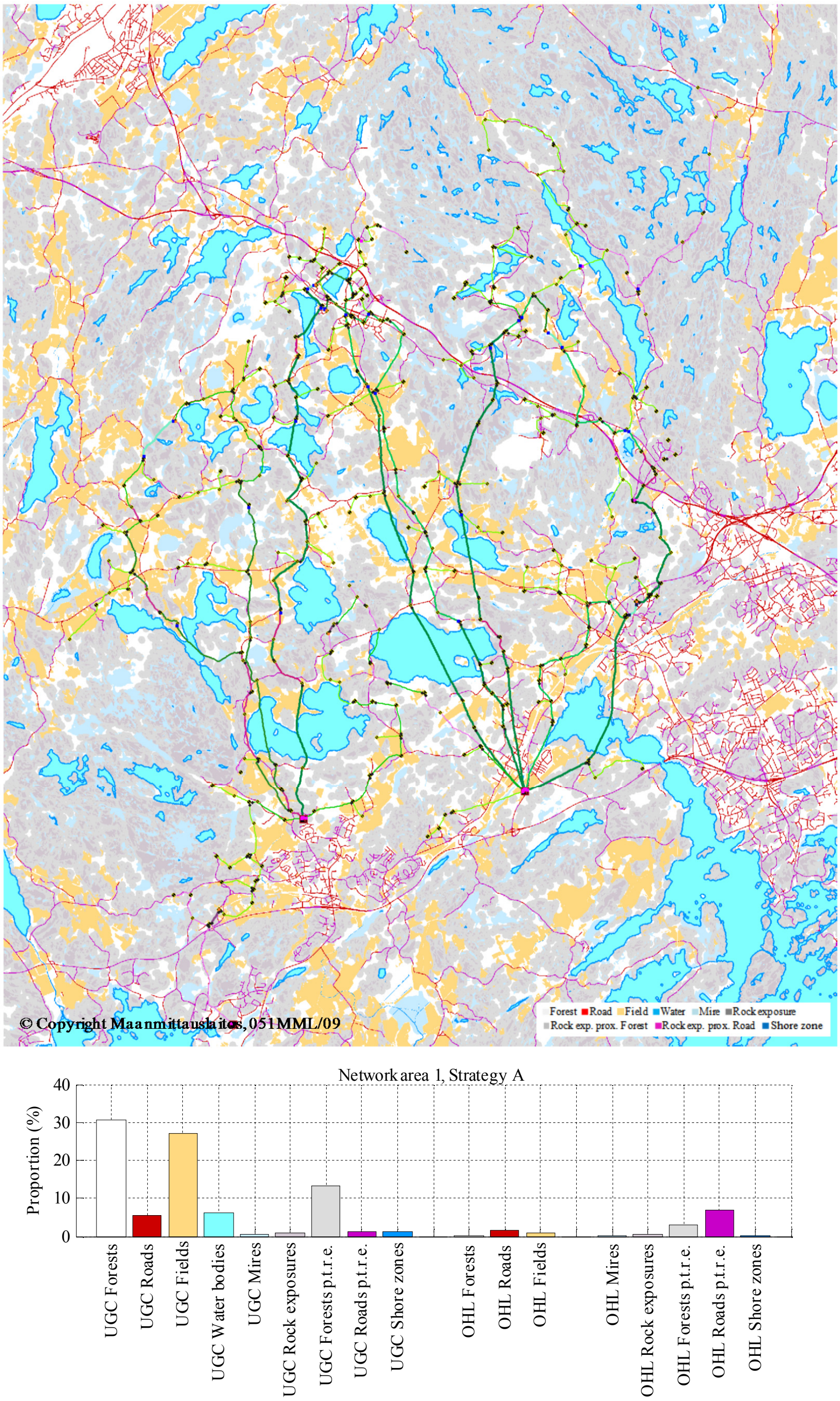
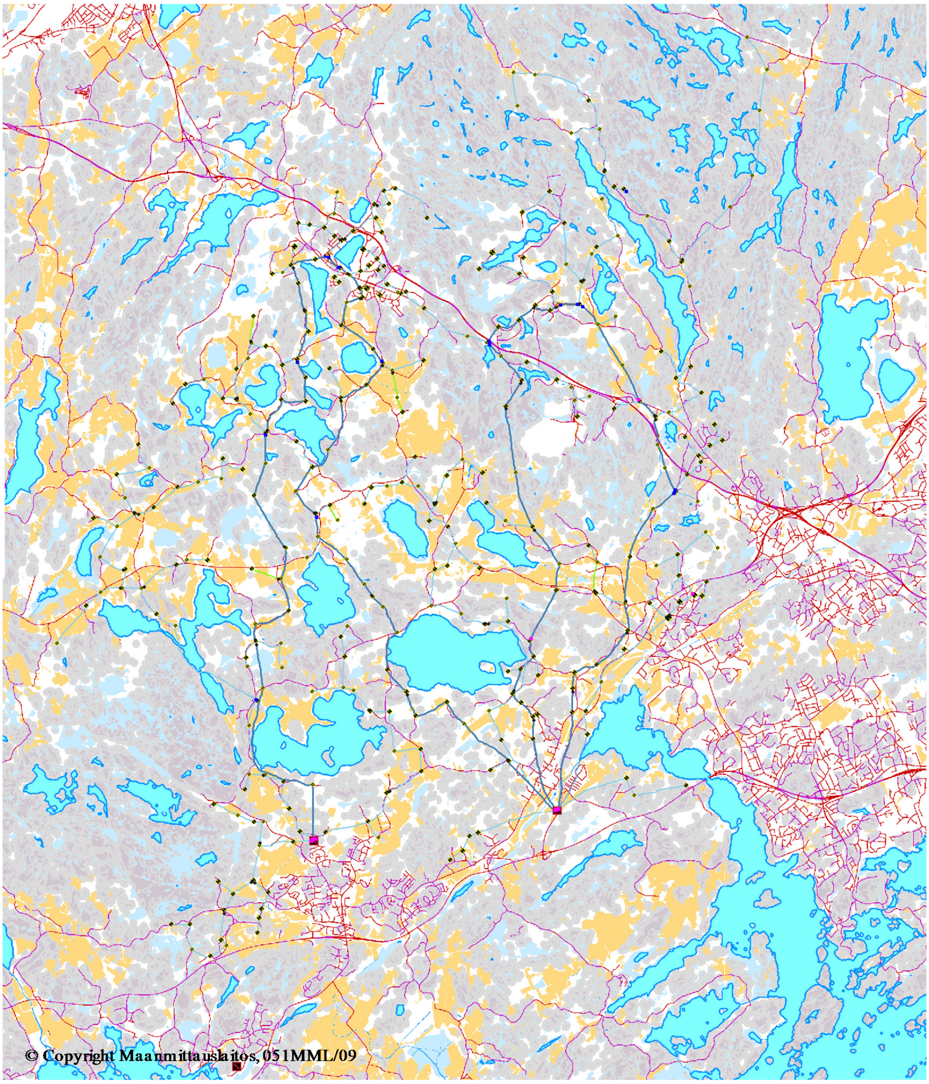


Figure A 7. Final network A: routing of the lines with regard the topography



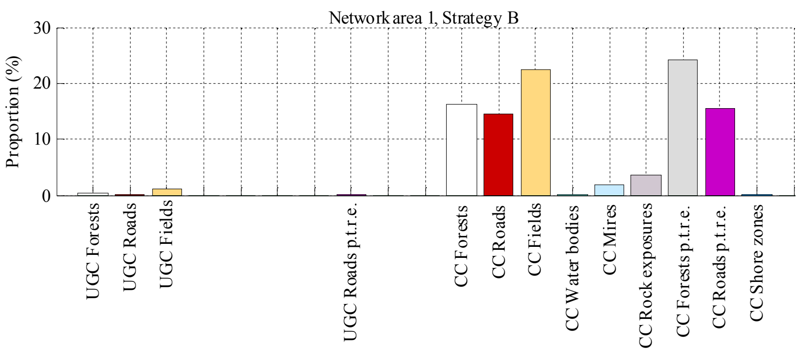
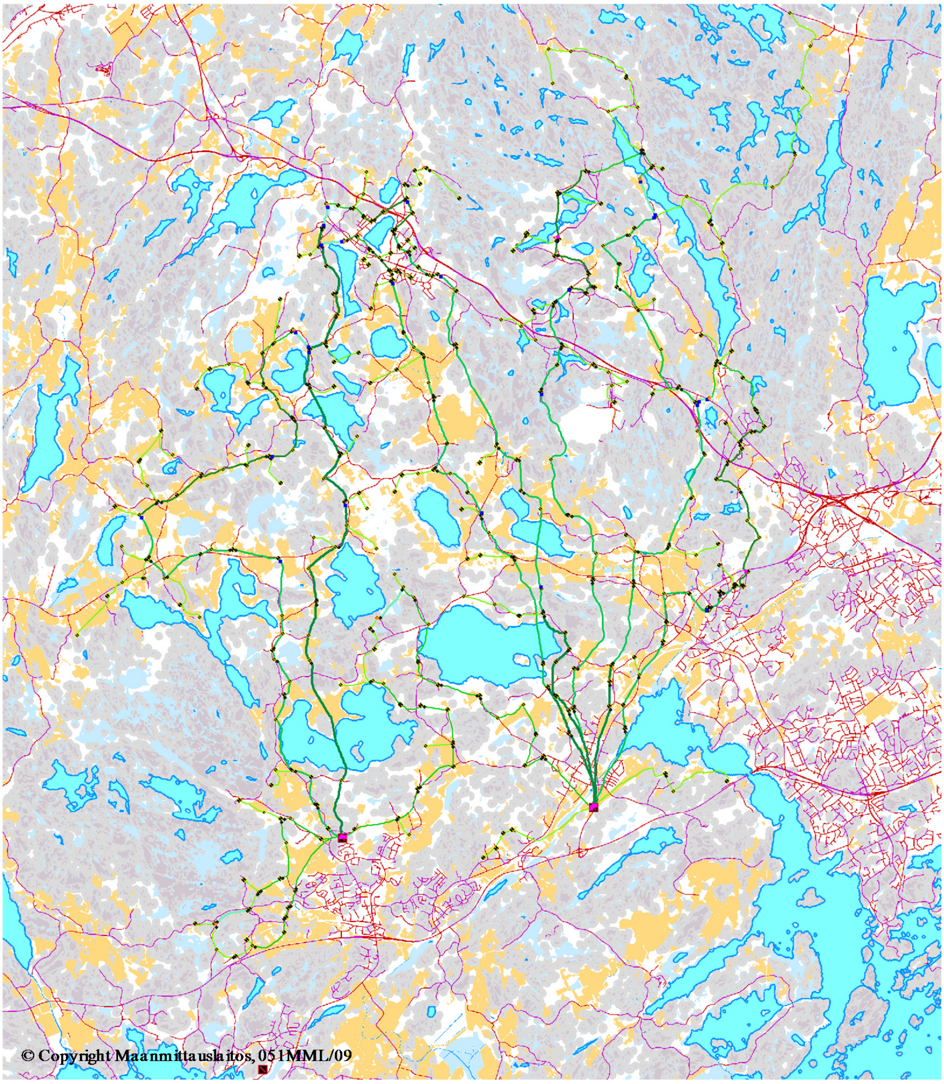


Figure A 8. Final network B: routing of the lines with regard the topography



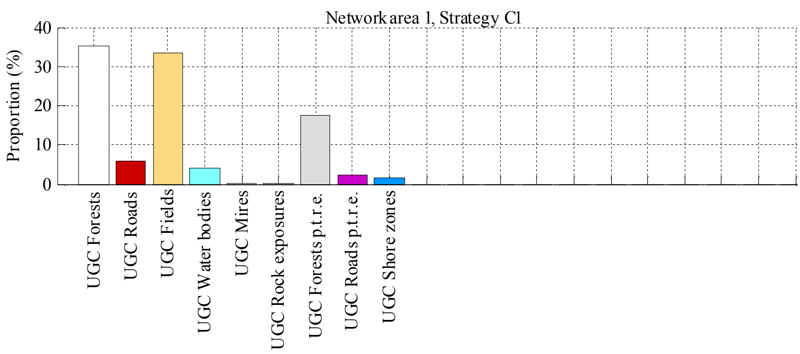
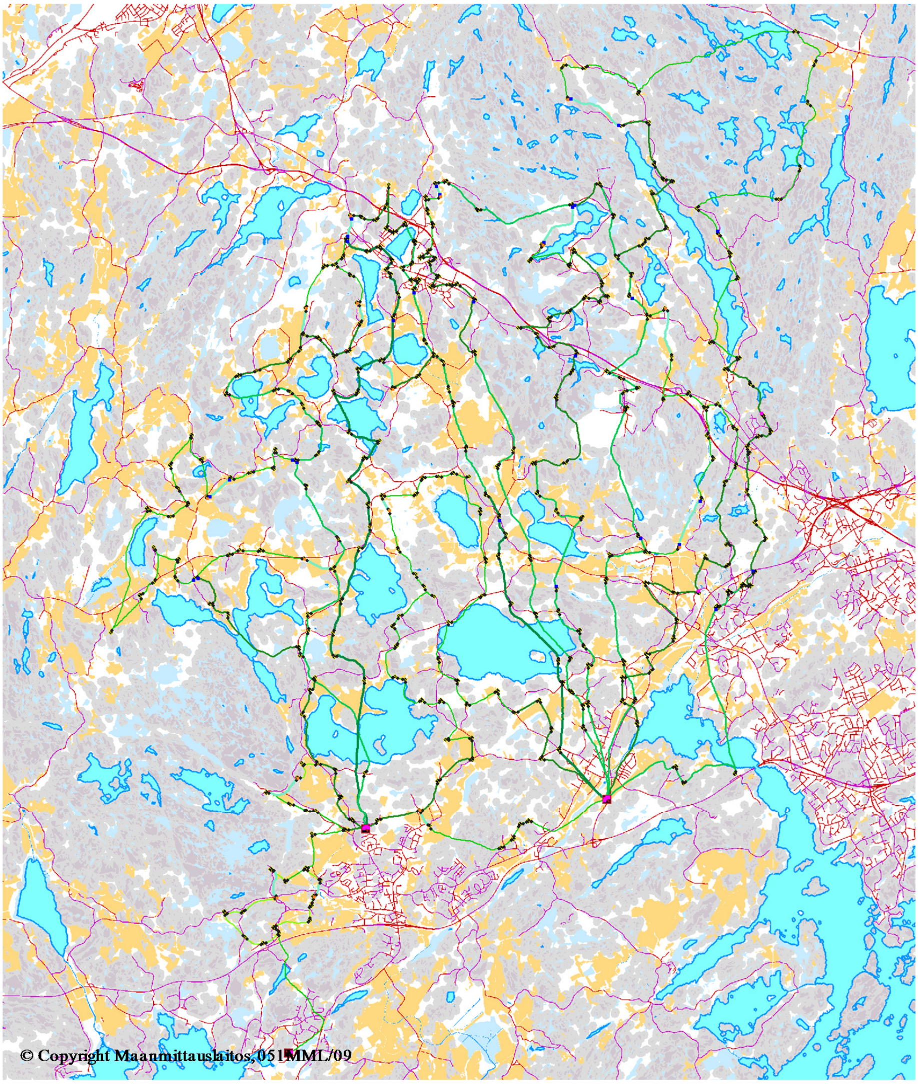


Figure A 9. Final network C1: routing of the lines with regard the topography



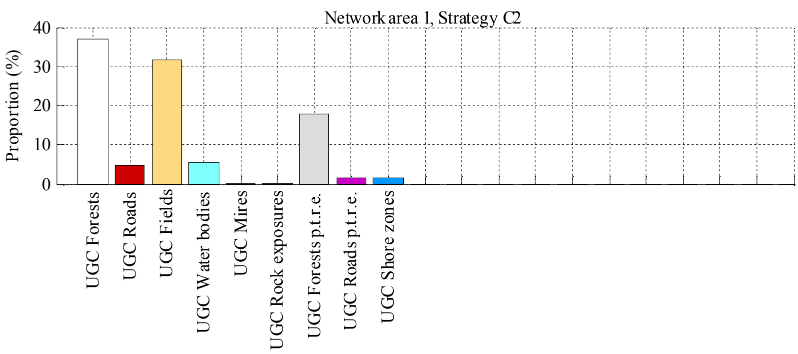


Figure A 10. Final network C2: routing of the lines with regard the topography

Appendix 2
Network area 2: Porkkala

Table A 1 Network area: substations

Network area 2	
Secondary substations	224
Primary substations	3

Table A 2. Network area: terrain types

Terrain types (%)	
Forests	6.28
Roads	0.59
Fields	7.25
Water bodies	29.46
Mires	2.66
Rock exposures	7.86
Forests proximate to rock exposures	40.86
Roads proximate to rock exposures	0.97
Shore zones	4.07

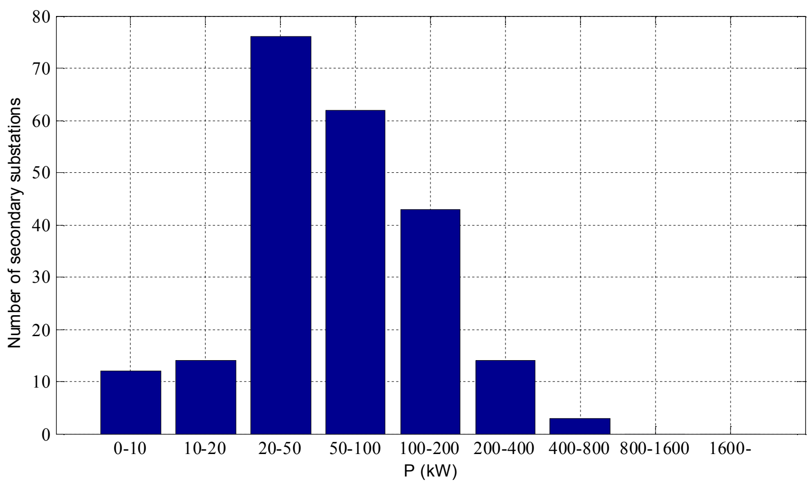


Figure A 1. Network area: secondary substations grouped by the maximum hourly demand

Table A 3. Final network: cost and length

Cost and length	A	B	C1	C2
Total length (km)	174.931	161.636	171.491	201.575
Length per shortest (p.u.)	1.08	1.00	1.06	1.25
Investment (M€)	8.118	6.015	9.852	12.294
Losses (M€)	0.163	0.117	0.131	0.207
Interruptions (M€)	1.813	1.060	0.932	0.448
Total cost (M€)	10.094	7.192	10.916	12.949
Cost per length (k€/km)	57.702	44.497	63.651	64.240
Cost per least cost (p.u.)	1.403	1.000	1.518	1.800
Extra cost per length (k€/km)	16.586	0.000	21.710	28.559

Table A 4. Final network: sectionalization

Sectionalization	A	B	C1	C2
Backed-up sec. substations (%)	50.00	28.13	47.77	100.00
Manual disconnectors	130	48	122	445
Remote disconnectors	18	0	12	3
Reclosers	3	3	2	3

Table A 5. Final network and route options: lengths

	A		B		C1	C2
General	UGC	OHL	UGC	CC	UGC	UGC
Internodal distance (avg., m)	772	752	1165	703	752	873
Length (km)	106.53	68.41	6.99	154.65	171.49	201.57

Table A 6. Final network and route options: terrain types

	A		B		C1	C2
Terrain types (%)	UGC	OHL	UGC	CC	UGC	UGC
Forests	14.79	2.04	0.29	9.83	20.43	21.10
Roads	1.69	2.23	0.00	3.11	2.14	2.14
Fields	18.56	3.13	0.43	14.07	24.99	24.47
Water bodies	6.78	0.02	2.26	0.12	9.36	10.43
Mires	0.06	1.25	0.00	4.30	0.05	0.07
Rock exposures	0.29	4.71	0.01	9.61	0.45	0.43
Forests prox. to rock exposures	14.40	13.89	0.77	39.35	32.54	32.98
Roads prox. to rock exposures	1.94	11.60	0.01	14.82	4.05	3.39
Shore zones	2.39	0.23	0.55	0.45	5.99	5.00

Table A 7. Final network and route options: conductor sizes

	A		B		C1	C2
Conductor sizes (%)	UGC	OHL	UGC	CC	UGC	UGC
Conductor 1	33.49	27.10	3.70	78.61	48.51	24.06
Conductor 2	6.86	0.00	0.65	17.04	24.98	70.69
Conductor 3	20.28	12.28	0.00	0.00	21.94	5.26
Conductor 4	0.00	0.00	0.00	0.00	2.20	0.00
Conductor 5	0.00	0.00	0.00	0.00	2.37	0.00
Conductor 6	0.00	0.00	0.00	0.00	0.00	0.00

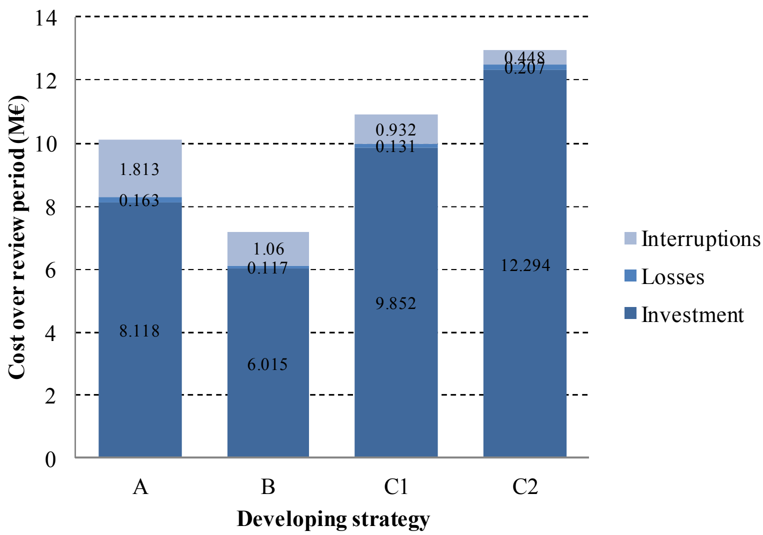


Figure A 2. Final network: cost

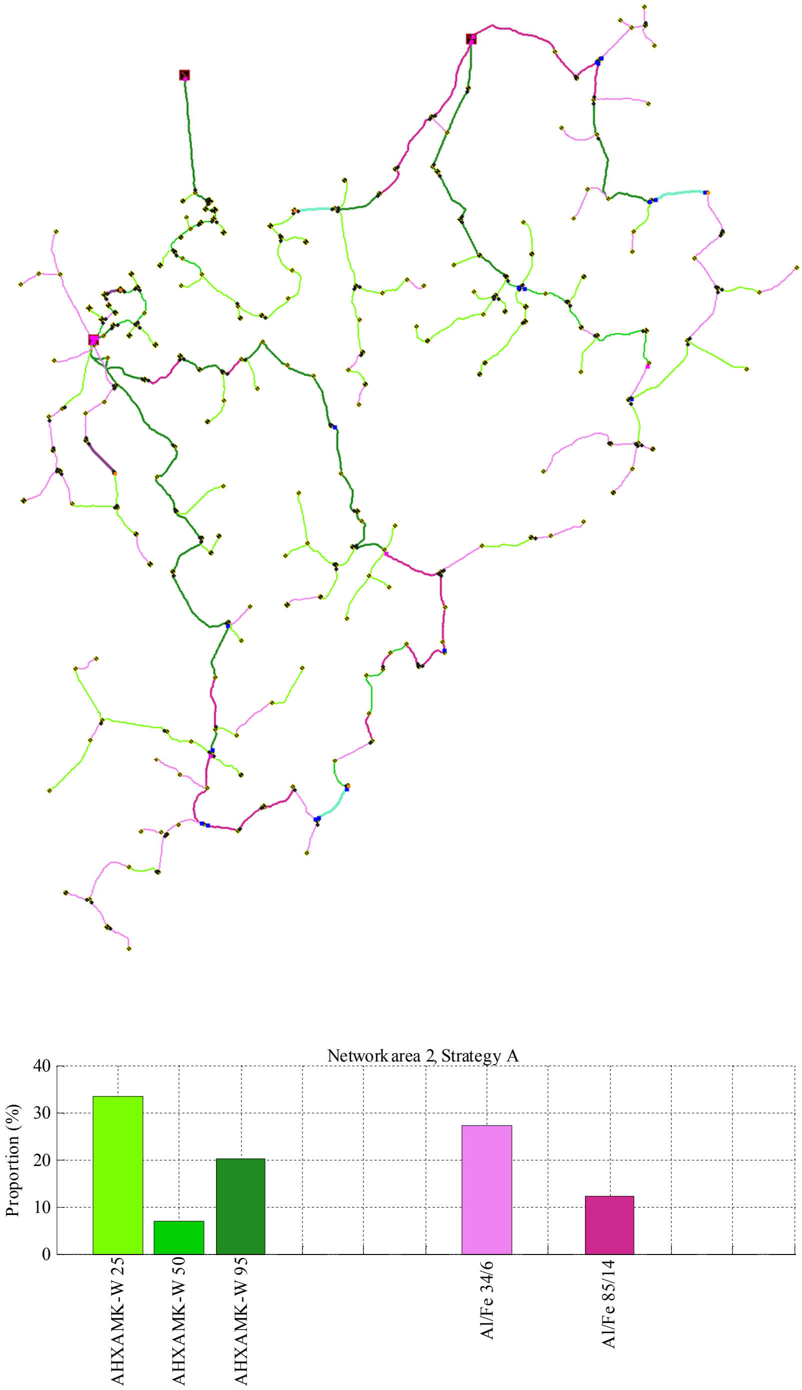


Figure A 3. Final network A: Topology and conductor sizing

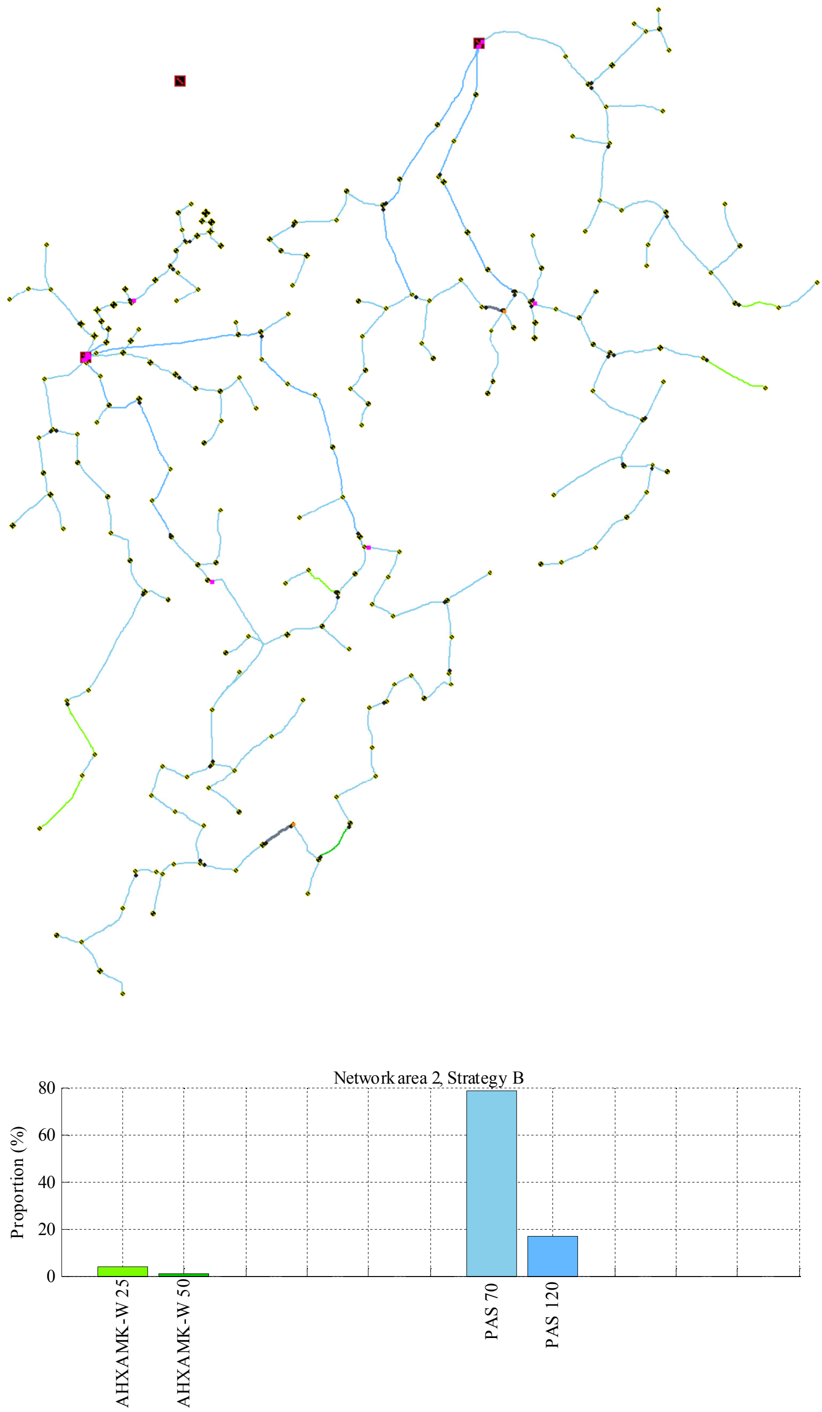


Figure A 4. Final network B: Topology and conductor sizing

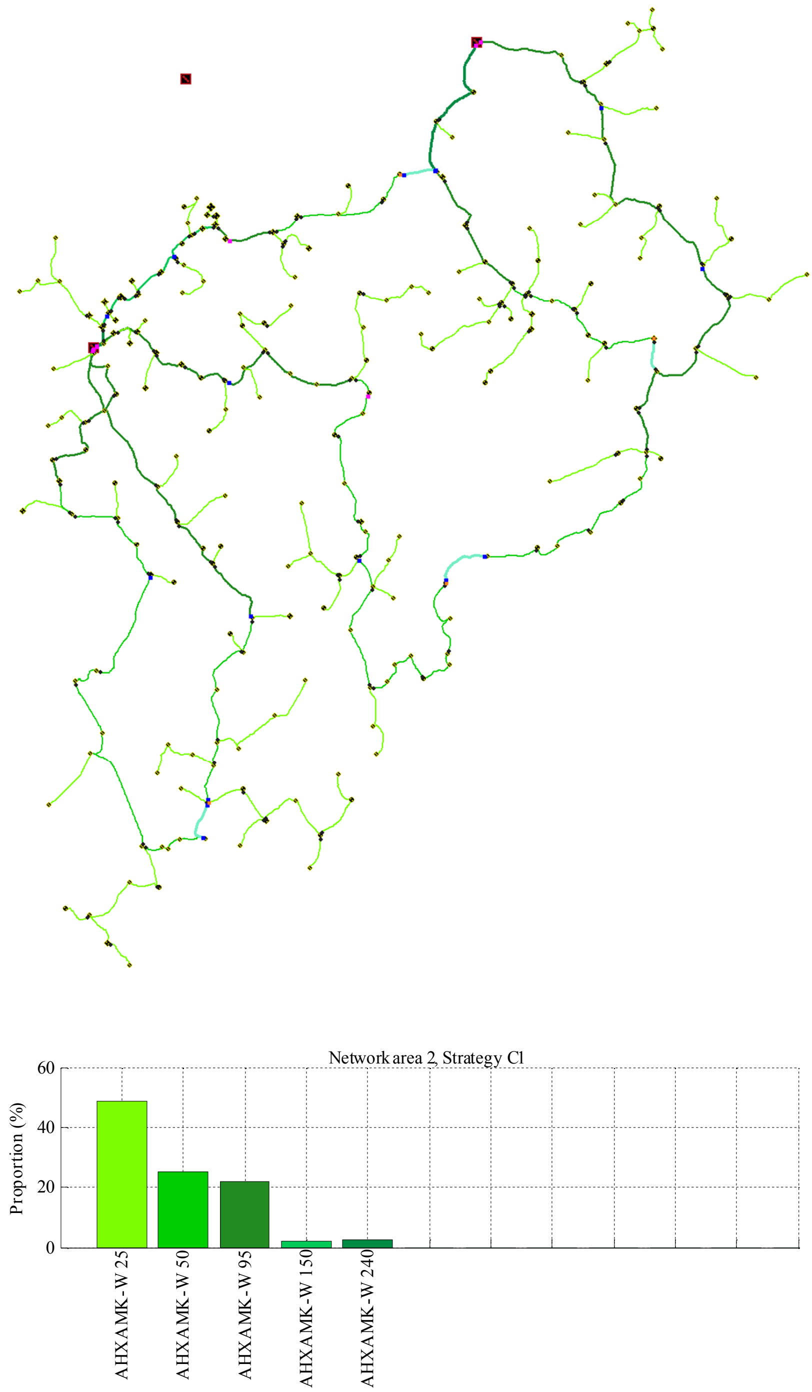
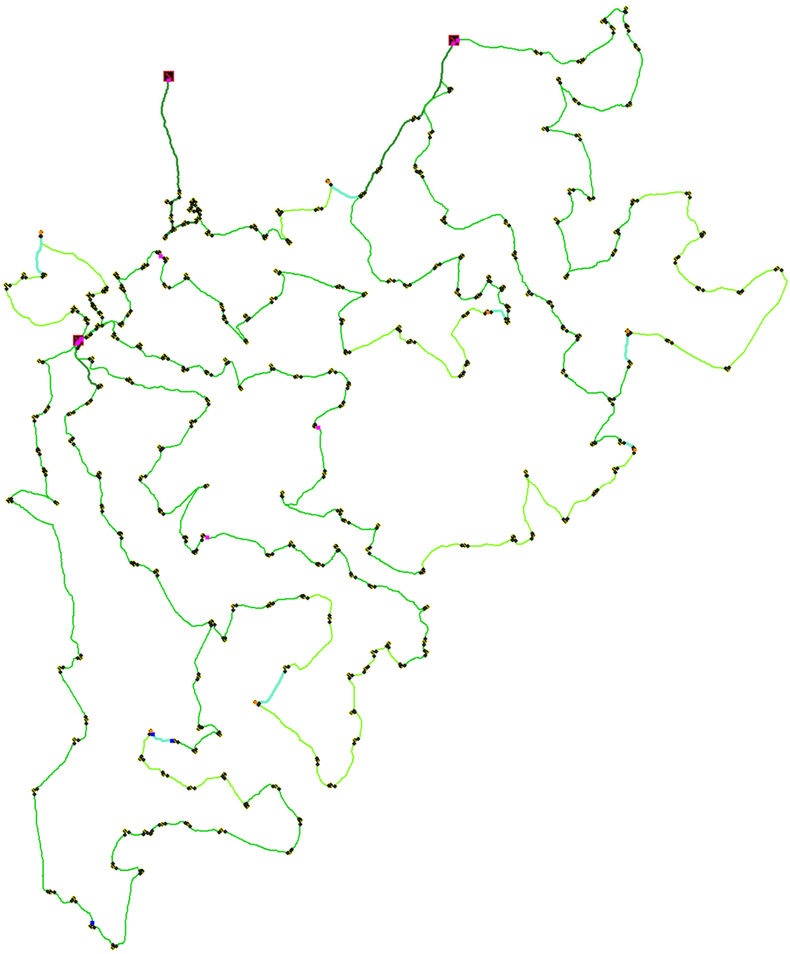


Figure A 5. Final network C1: Topology and conductor sizing



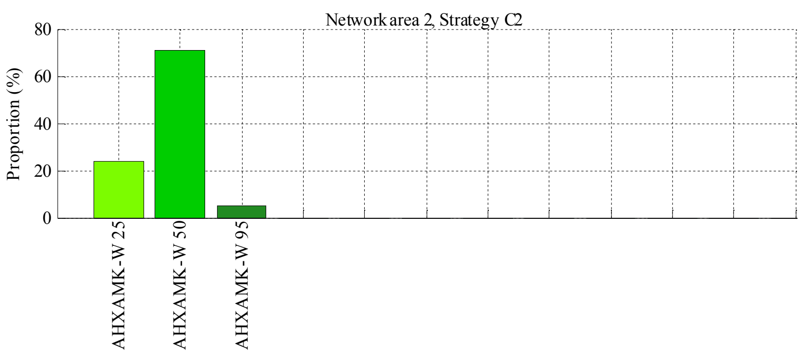
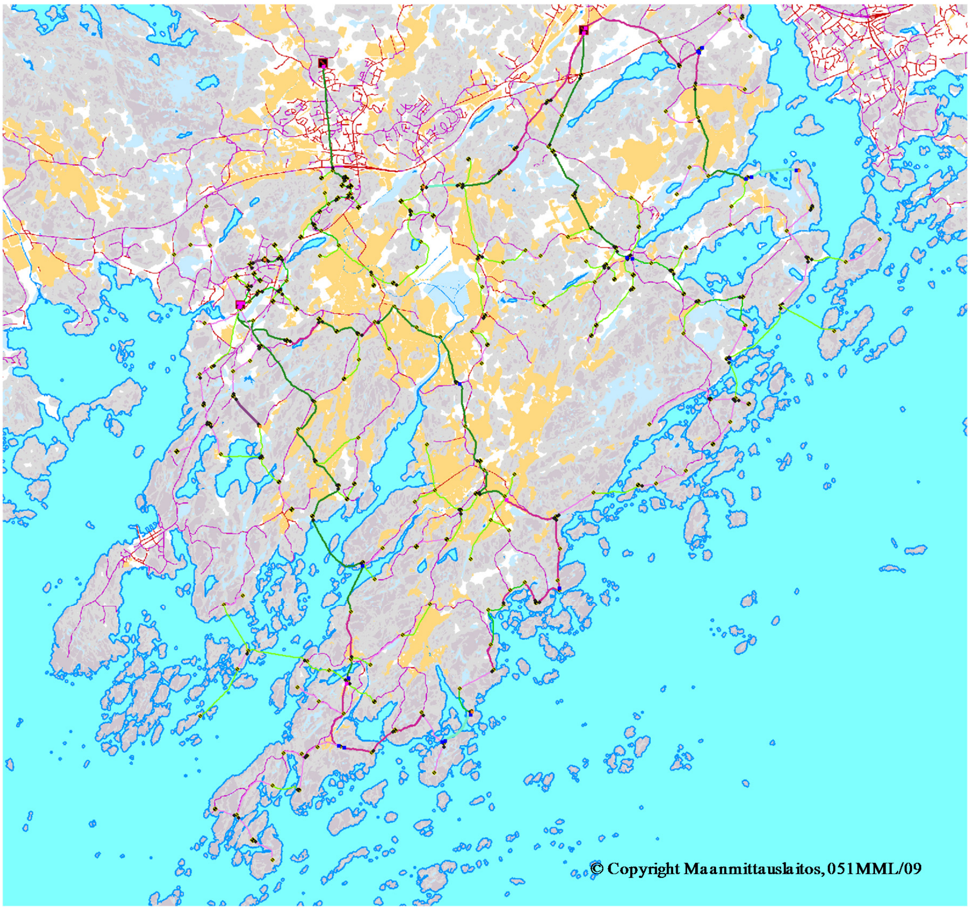


Figure A 6. Final network C2: Topology and conductor sizing



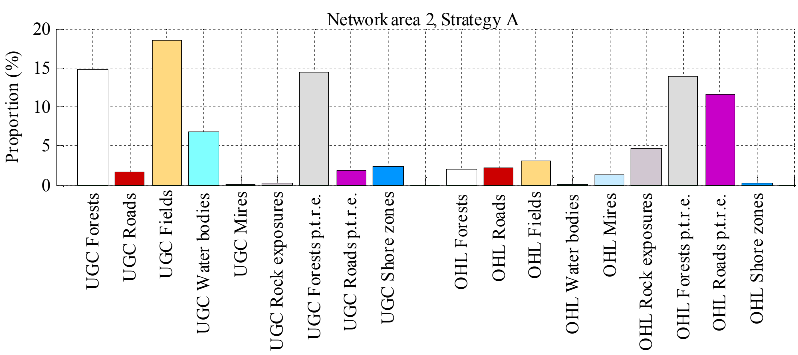
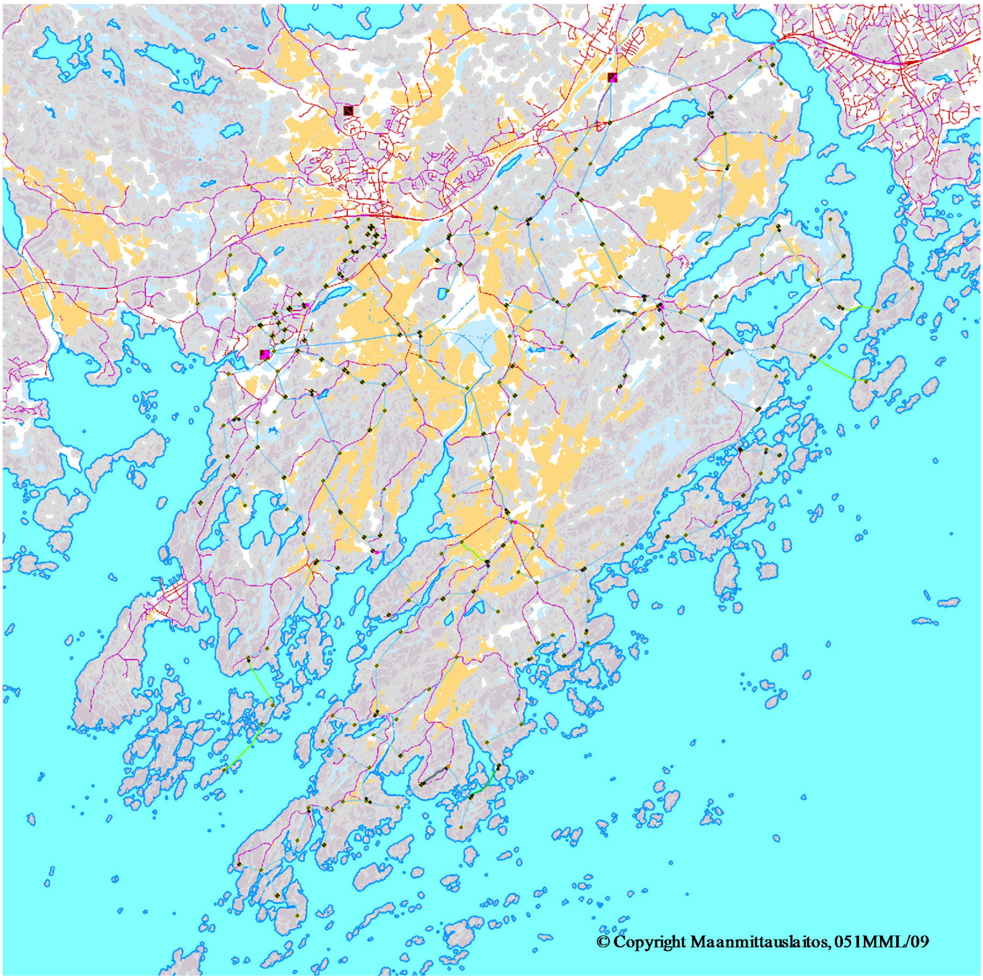


Figure A 7. Final network A: routing of the lines with regard the topography



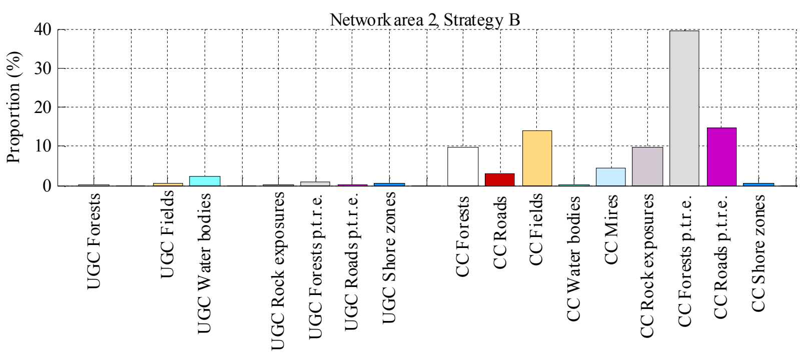
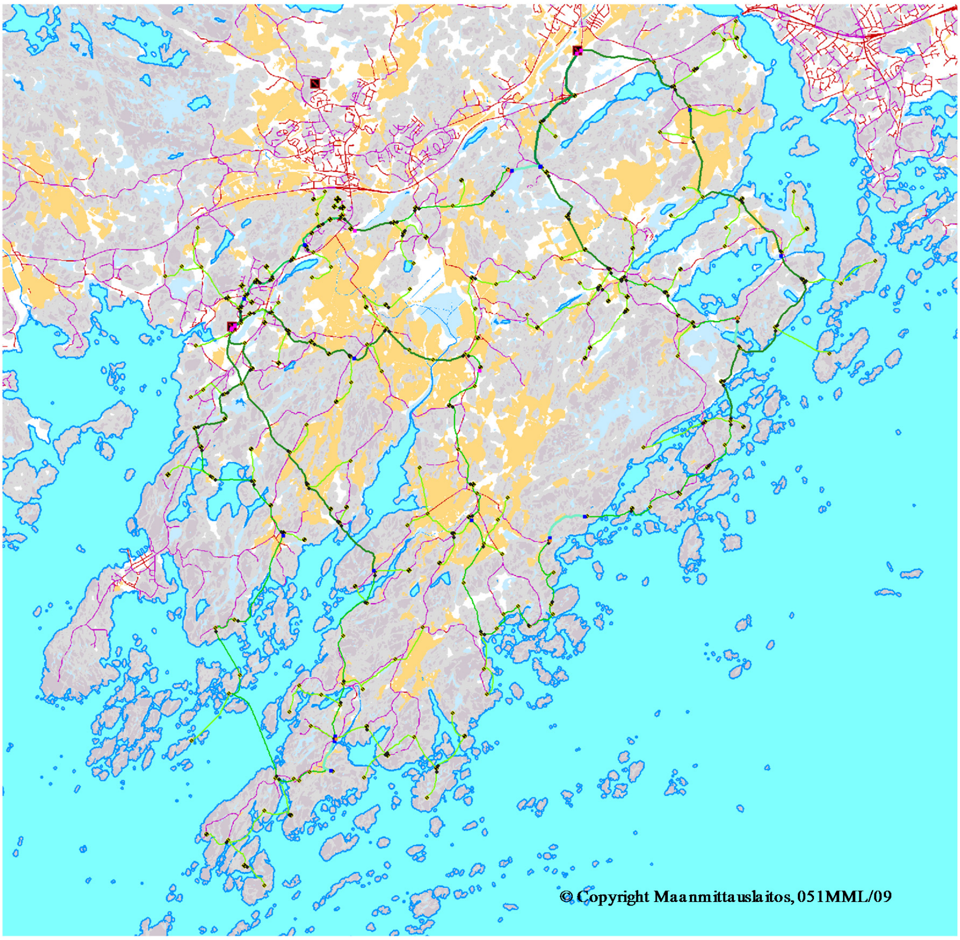


Figure A 8. Final network B: routing of the lines with regard the topography



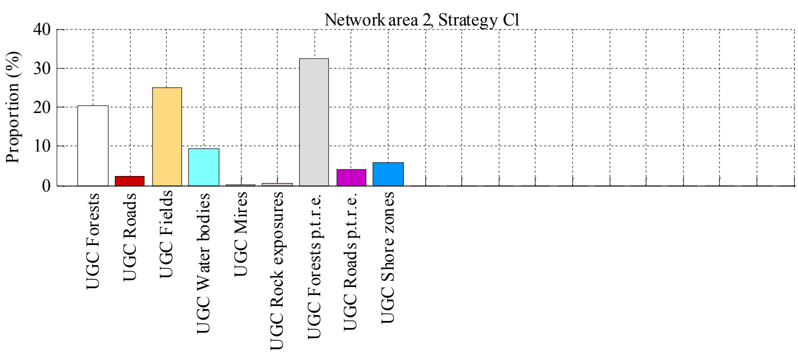
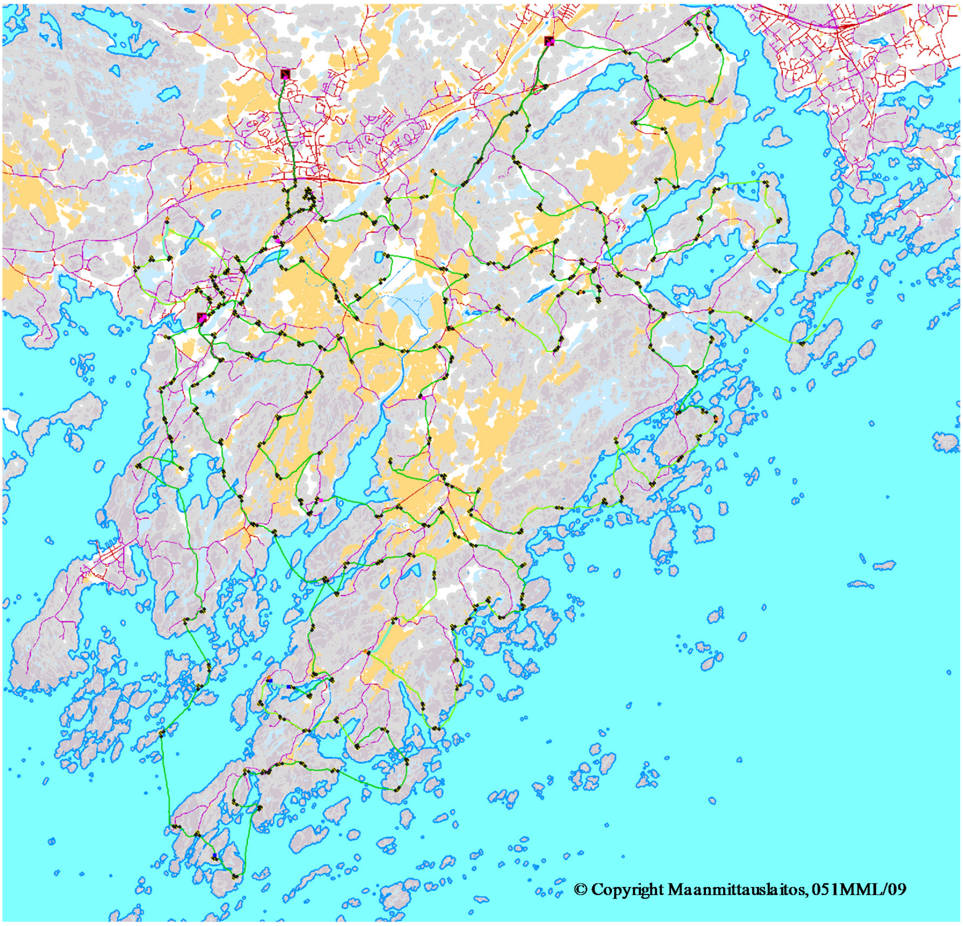


Figure A 9. Final network C1: routing of the lines with regard the topography



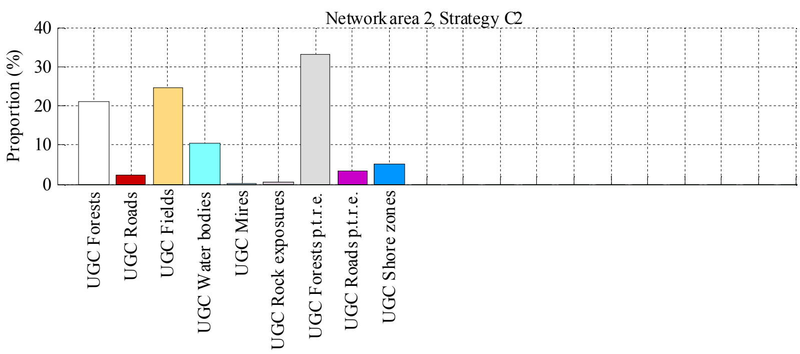


Figure A 10. Final network C2: routing of the lines with regard the topography

Appendix 3
Network area 3: Oulujärvi

Table A 1 Network area: substations

Network area 3	
Secondary substations	329
Primary substations	3

Table A 2. Network area: terrain types

Terrain types (%)	
Forests	29.58
Roads	1.21
Fields	2.24
Water bodies	40.23
Mires	21.92
Rock exposures	0.26
Forests proximate to rock exposures	2.39
Roads proximate to rock exposures	0.03
Shore zones	2.15

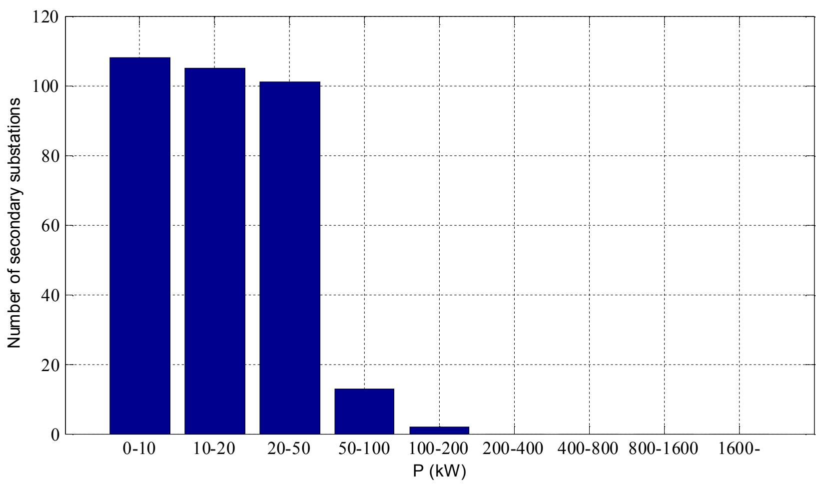


Figure A 1. Network area: secondary substations grouped by the maximum hourly demand

Table A 3. Final network: cost and length

Cost and length	A	B	C1	C2
Total length (km)	354.189	351.794	346.537	432.672
Length per shortest (p.u.)	1.02	1.02	1.00	1.25
Investment (M€)	13.252	11.796	13.942	19.136
Losses (M€)	0.259	0.207	0.237	0.204
Interruptions (M€)	1.298	1.055	0.960	0.415
Total cost (M€)	14.809	13.059	15.139	19.755
Cost per length (k€/km)	41.812	37.121	43.688	45.657
Cost per least cost (p.u.)	1.134	1.000	1.159	1.513
Extra cost per length (k€/km)	4.942	0.000	6.004	15.476

Table A 4. Final network: sectionalization

Sectionalization	A	B	C1	C2
Backed-up sec. substations (%)	59.27	50.15	40.43	100.00
Manual disconnectors	103	42	100	662
Remote disconnectors	21	10	16	15
Reclosers	3	3	2	1

Table A 5. Final network and route options: lengths

	A		B		C1	C2
General	UGC	OHL	UGC	CC	UGC	UGC
Internodal distance (avg., m)	1048	1171	1028	1065	1047	1295
Length (km)	294.49	59.70	15.42	336.37	346.54	432.67

Table A 6. Final network and route options: terrain types

	A		B		C1	C2
Terrain types (%)	UGC	OHL	UGC	CC	UGC	UGC
Forests	47.54	4.87	1.27	43.34	56.42	59.03
Roads	14.08	7.18	0.13	27.87	17.80	14.25
Fields	16.43	1.78	0.74	9.25	18.70	16.93
Water bodies	3.82	0.00	2.00	0.00	4.94	7.65
Mires	0.29	2.79	0.03	13.82	0.70	0.76
Rock exposures	0.00	0.04	0.00	0.05	0.00	0.00
Forests prox. to rock exposures	0.00	0.13	0.00	0.71	0.14	0.08
Roads prox. to rock exposures	0.07	0.06	0.00	0.53	0.13	0.06
Shore zones	0.90	0.01	0.22	0.04	1.16	1.25

Table A 7. Final network and route options: conductor sizes

	A		B		C1	C2
Conductor sizes (%)	UGC	OHL	UGC	CC	UGC	UGC
Conductor 1	42.34	14.92	2.94	95.55	55.48	61.82
Conductor 2	39.33	0.00	1.51	0.00	27.39	38.18
Conductor 3	1.35	2.06	0.00	0.00	17.12	0.00
Conductor 4	0.00	0.00	0.00	0.00	0.00	0.00
Conductor 5	0.00	0.00	0.00	0.00	0.00	0.00
Conductor 6	0.00	0.00	0.00	0.00	0.00	0.00

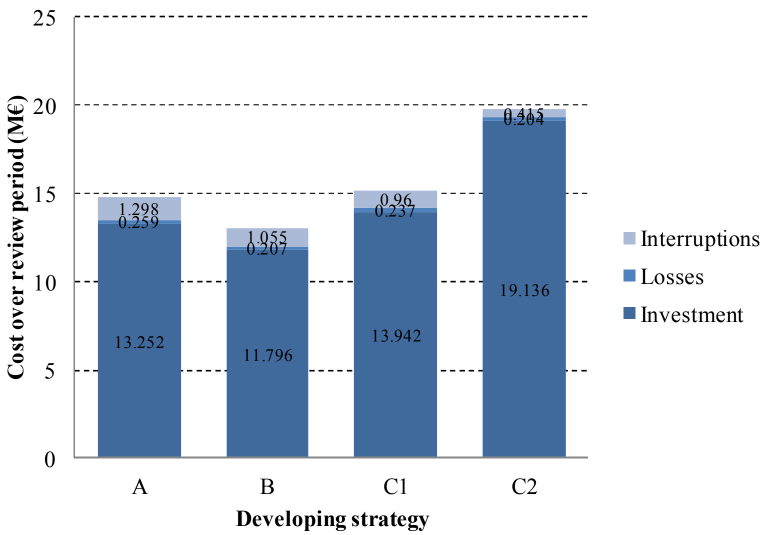
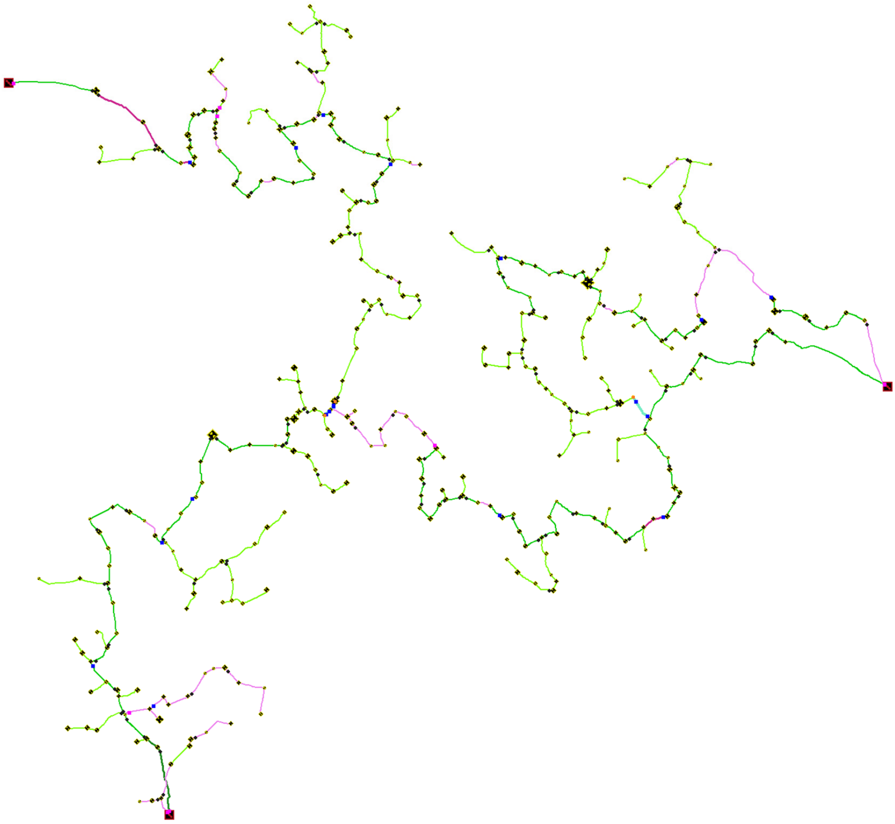


Figure A 2. Final network: cost



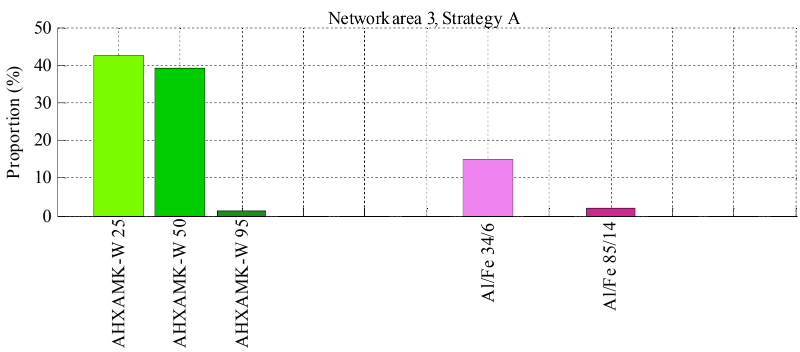


Figure A 3. Final network A: Topology and conductor sizing

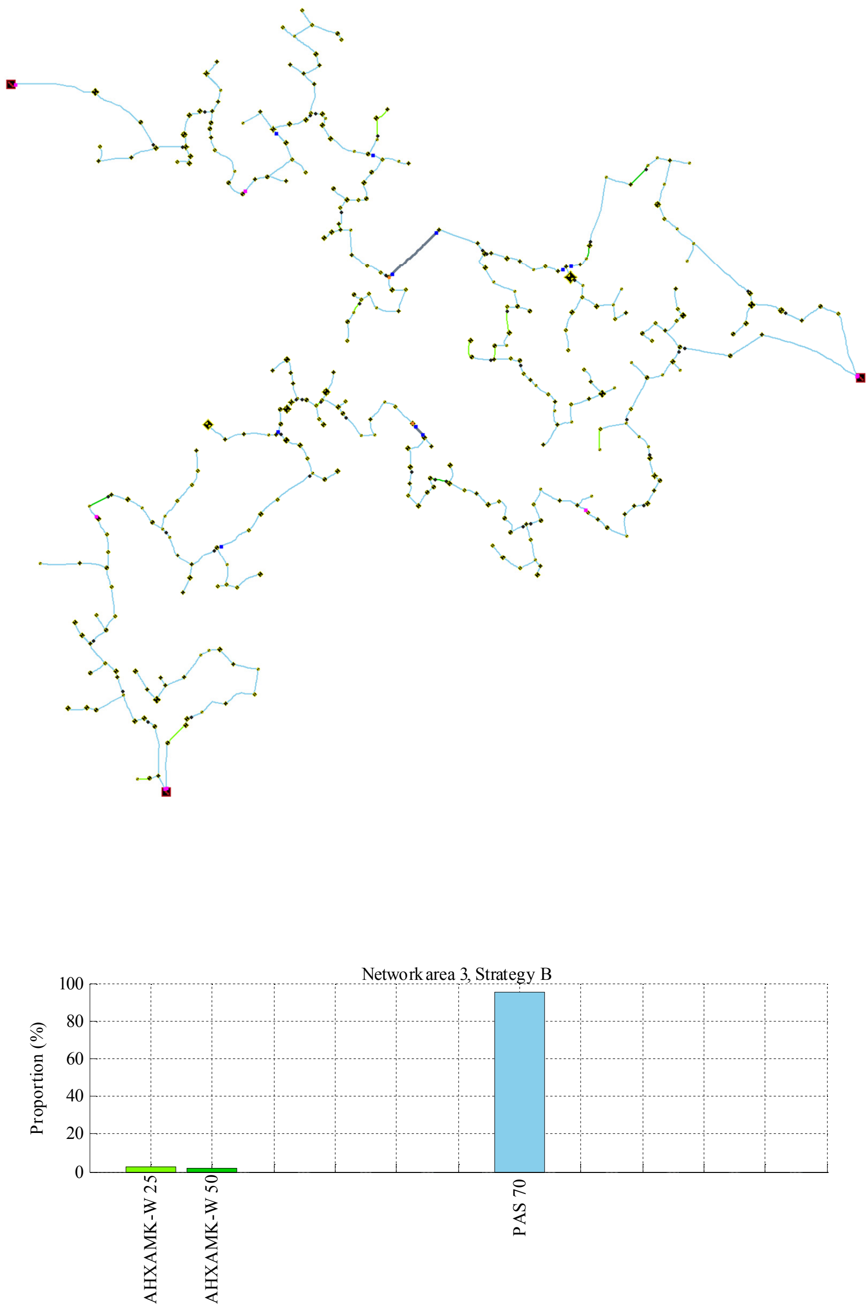
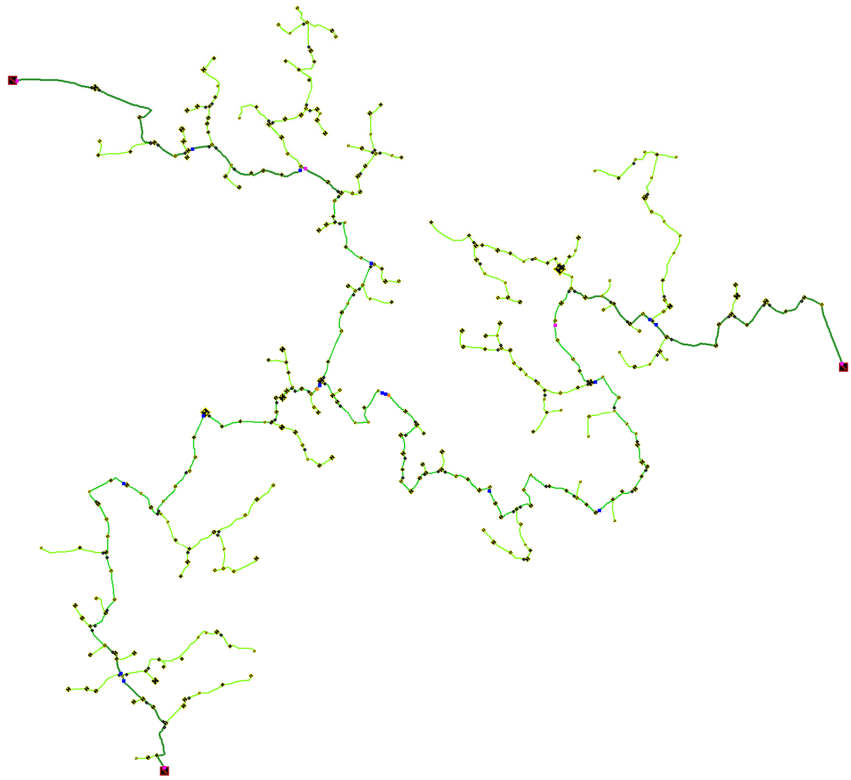


Figure A 4. Final network B: Topology and conductor sizing



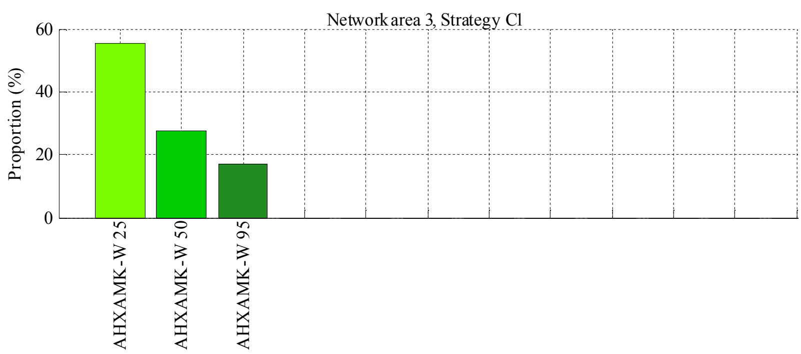
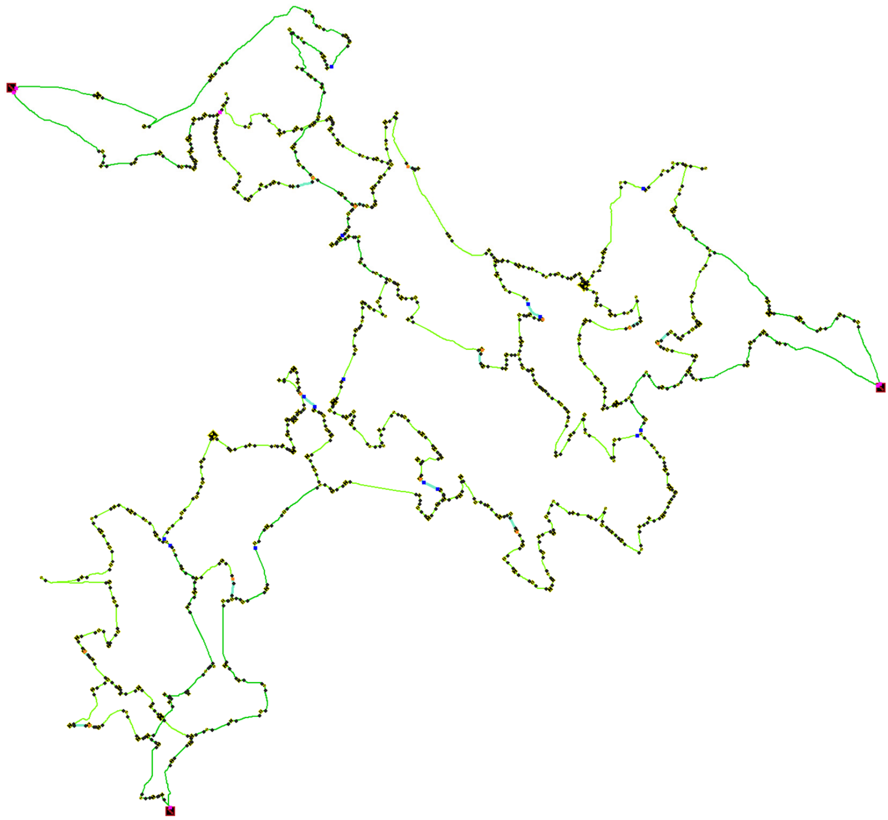


Figure A 5. Final network C1: Topology and conductor sizing



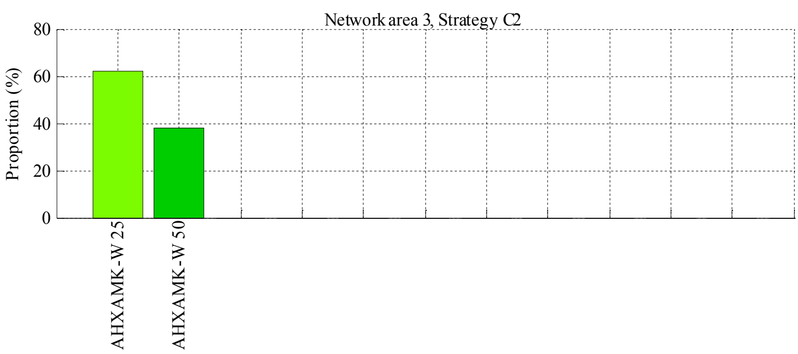
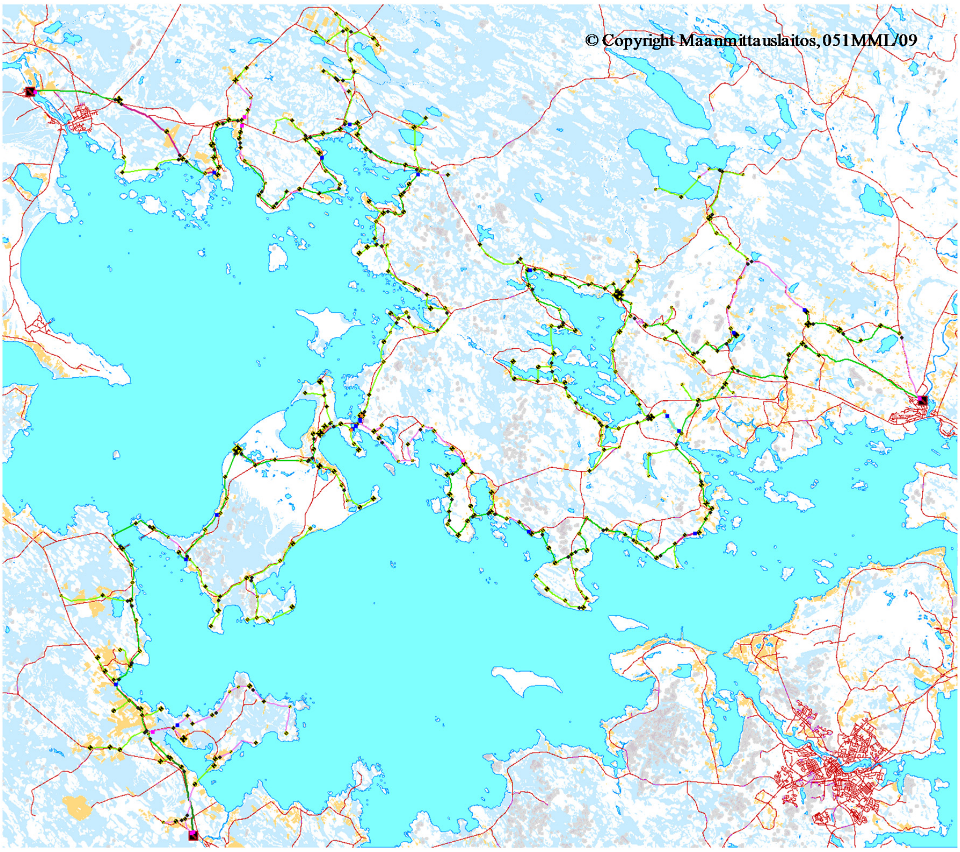


Figure A 6. Final network C2: Topology and conductor sizing



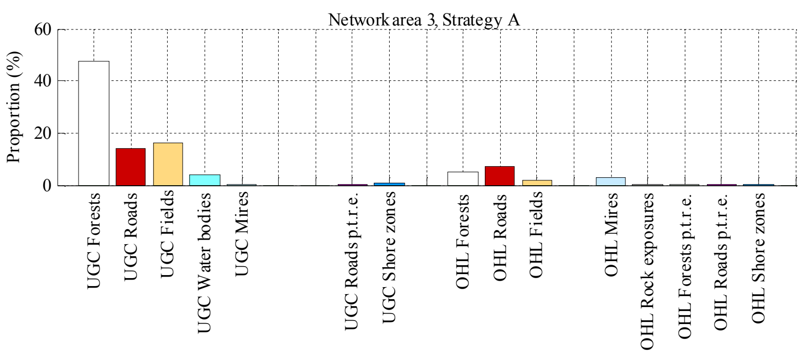
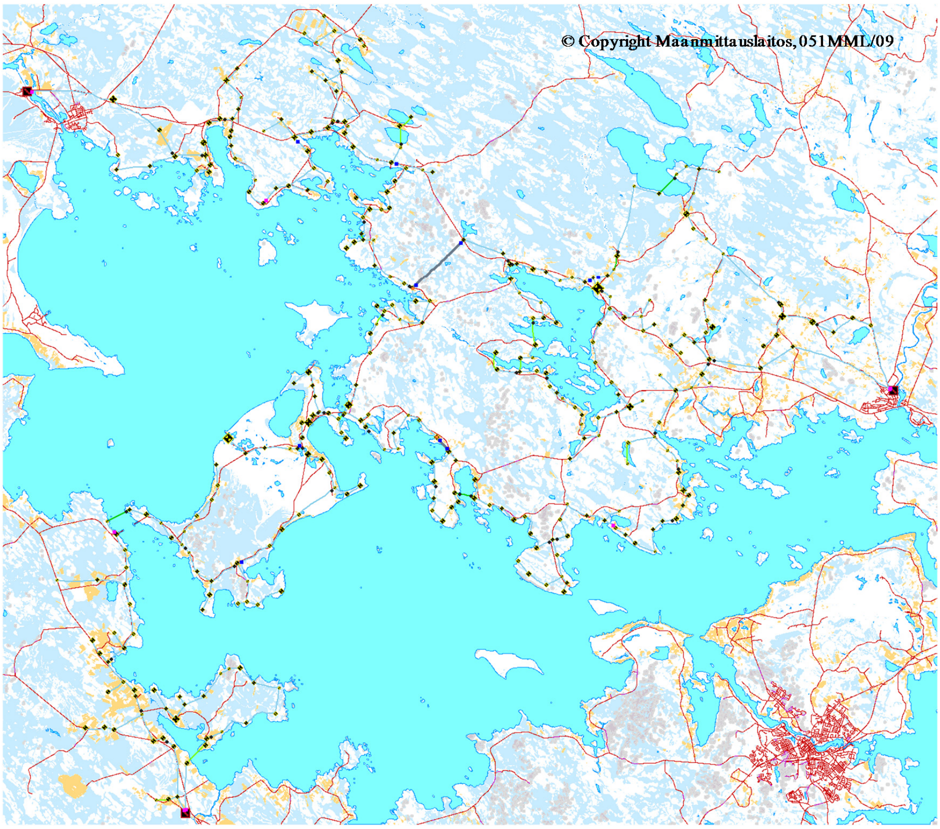


Figure A 7. Final network A: routing of the lines with regard the topography



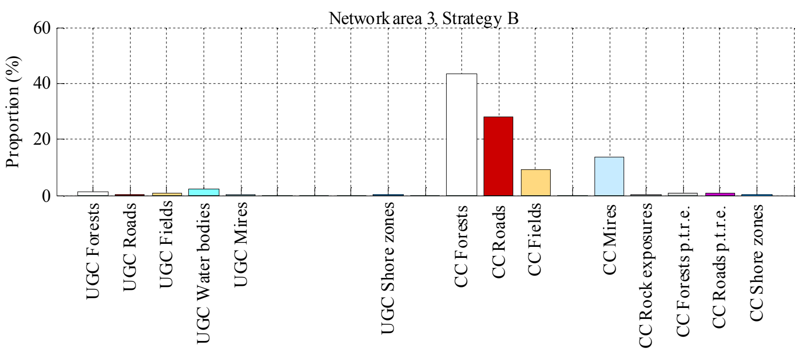
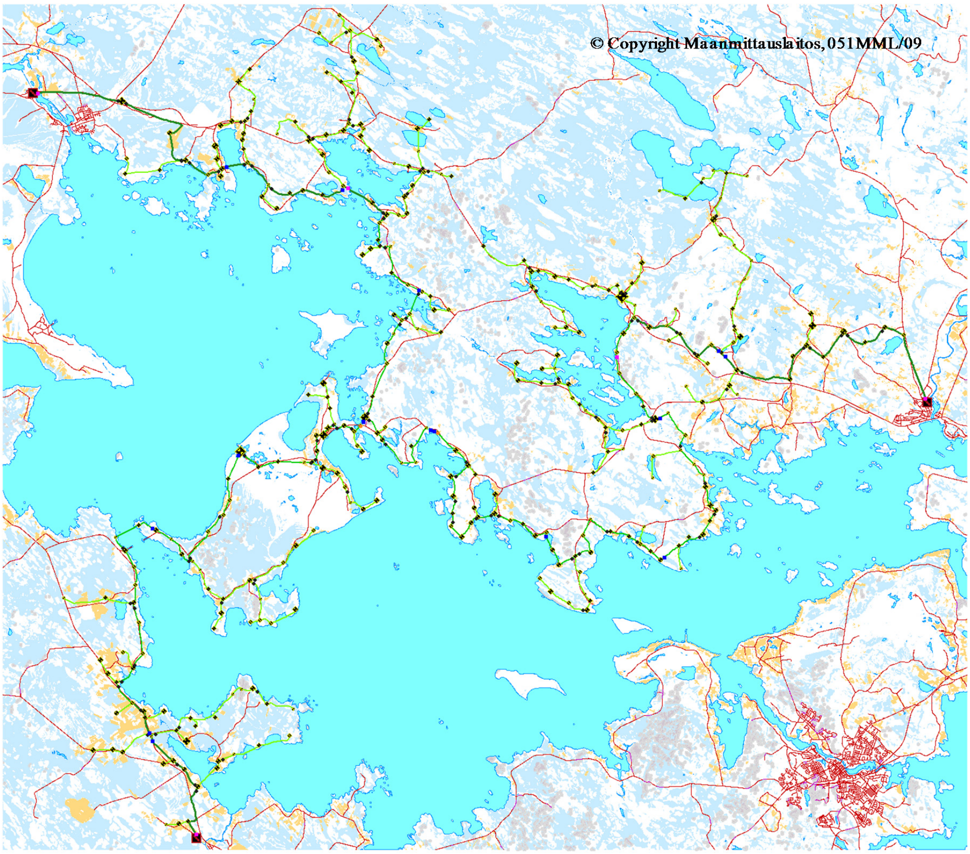


Figure A 8. Final network B: routing of the lines with regard the topography



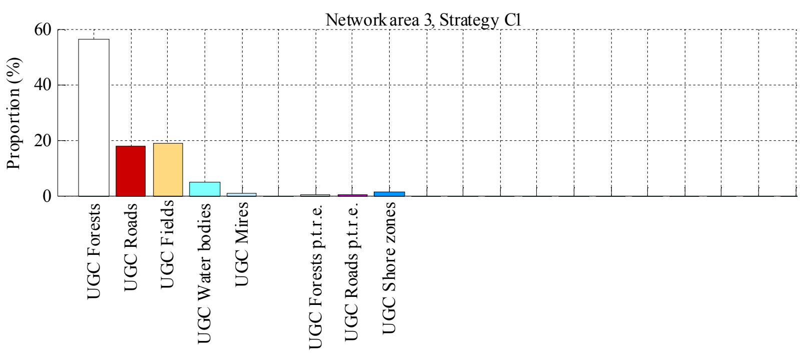
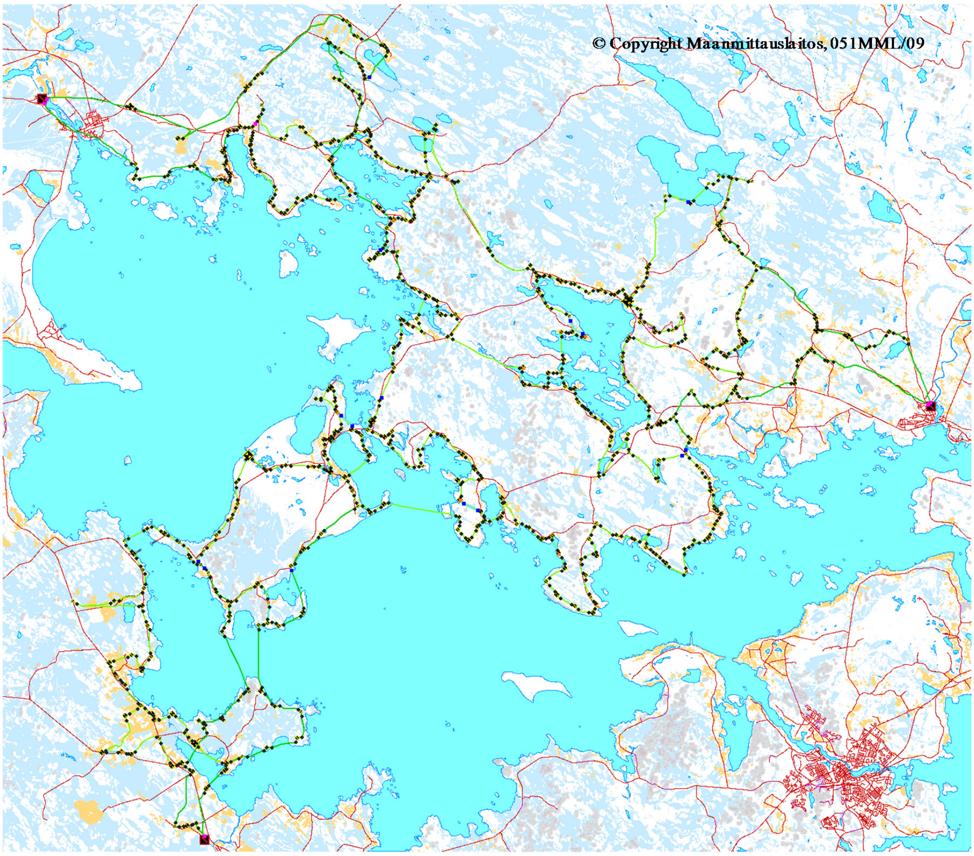


Figure A 9. Final network C1: routing of the lines with regard the topography



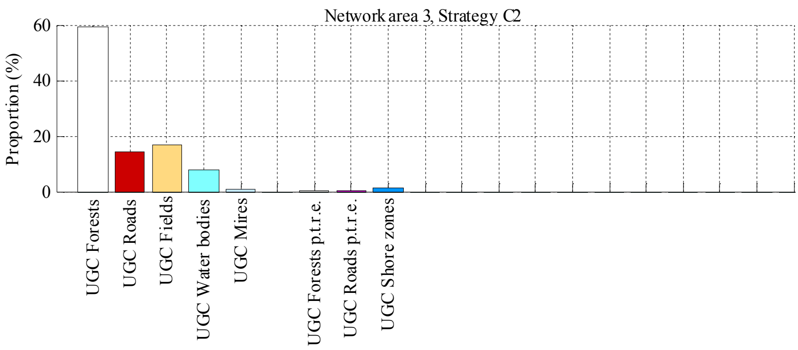


Figure A 10. Final network C2: routing of the lines with regard the topography

Appendix 4
Network area 4: Keimola

Table A 1. Network area: substations

Network area 4	
Secondary substations	186
Primary substations	3

Table A 2. Network area: terrain types

Terrain types (%)	
Forests	36.32
Roads	3.92
Fields	22.55
Water bodies	0.00
Mires	2.71
Rock exposures	3.16
Forests proximate to rock exposures	29.58
Roads proximate to rock exposures	1.35
Shore zones	0.42

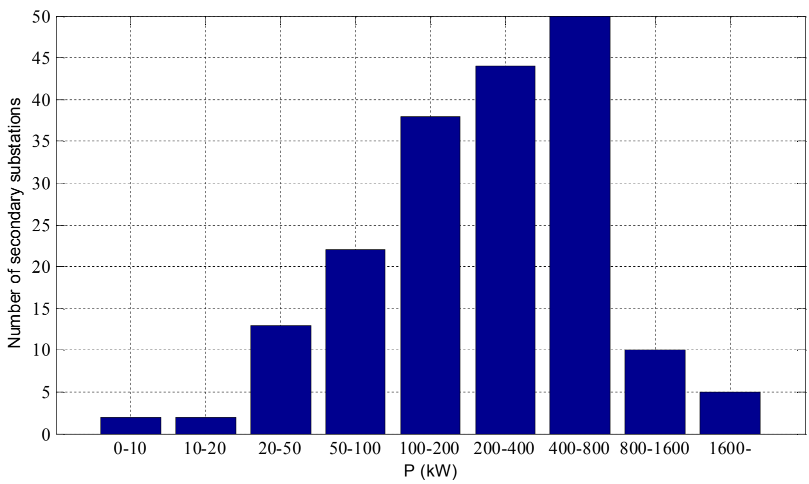


Figure A 1. Network area: secondary substations grouped by the maximum hourly demand

Table A 3. Final network: cost and length

Cost and length	A	B	C1	C2
Total length (km)	83.563	88.197	85.386	117.865
Length per shortest (p.u.)	1.00	1.06	1.02	1.41
Investment (M€)	5.495	4.087	5.767	7.874
Losses (M€)	0.821	0.797	0.763	0.568
Interruptions (M€)	1.017	1.025	0.885	0.474
Total cost (M€)	7.333	5.909	7.415	8.916
Cost per length (k€/km)	87.755	67.000	86.838	75.646
Cost per least cost (p.u.)	1.241	1.000	1.255	1.509
Extra cost per length (k€/km)	17.039	0.000	17.632	25.511

Table A 4. Final network: sectionalization

Sectionalization	A	B	C1	C2
Backed-up sec. substations (%)	46.24	41.40	52.69	100.00
Manual disconnectors	133	58	144	381
Remote disconnectors	20	1	13	0
Reclosers	4	3	1	1

Table A 5. Final network and route options: lengths

	A		B		C1	C2
General	UGC	OHL	UGC	CC	UGC	UGC
Internodal distance (avg., m)	402	760	689	452	442	581
Length (km)	69.87	13.69	4.13	84.06	85.39	117.86

Table A 6. Final network and route options: terrain types

	A		B		C1	C2
Terrain types (%)	UGC	OHL	UGC	CC	UGC	UGC
Forests	40.87	2.70	1.47	33.14	45.85	52.77
Roads	9.43	4.07	0.13	26.51	14.00	10.53
Fields	27.21	4.34	3.06	20.05	32.79	29.85
Water bodies	0.00	0.00	0.00	0.00	0.00	0.00
Mires	0.10	0.00	0.00	0.50	0.01	0.01
Rock exposures	0.08	0.00	0.00	0.35	0.04	0.02
Forests prox. to rock exposures	4.89	1.48	0.01	7.17	5.25	5.63
Roads prox. to rock exposures	1.02	3.79	0.00	7.56	2.02	1.10
Shore zones	0.02	0.00	0.02	0.04	0.04	0.09

Table A 7. Final network and route options: conductor sizes

	A		B		C1	C2
Conductor sizes (%)	UGC	OHL	UGC	CC	UGC	UGC
Conductor 1	39.21	4.90	3.80	49.54	41.59	0.43
Conductor 2	3.01	0.00	0.00	0.78	7.80	26.35
Conductor 3	6.59	6.74	0.00	37.66	5.63	9.11
Conductor 4	11.98	0.00	0.00	7.25	10.11	30.87
Conductor 5	3.25	3.45	0.00	0.00	11.92	25.07
Conductor 6	20.88	0.00	0.98	0.00	22.96	8.18

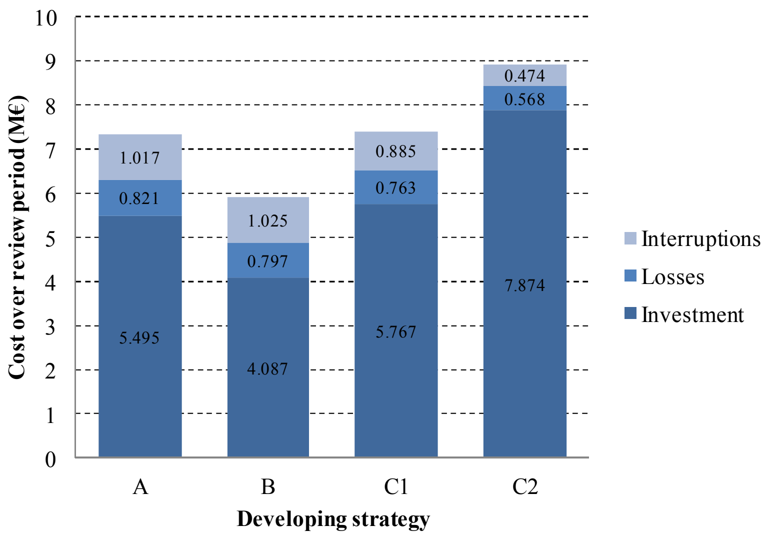


Figure A 2. Final network: cost

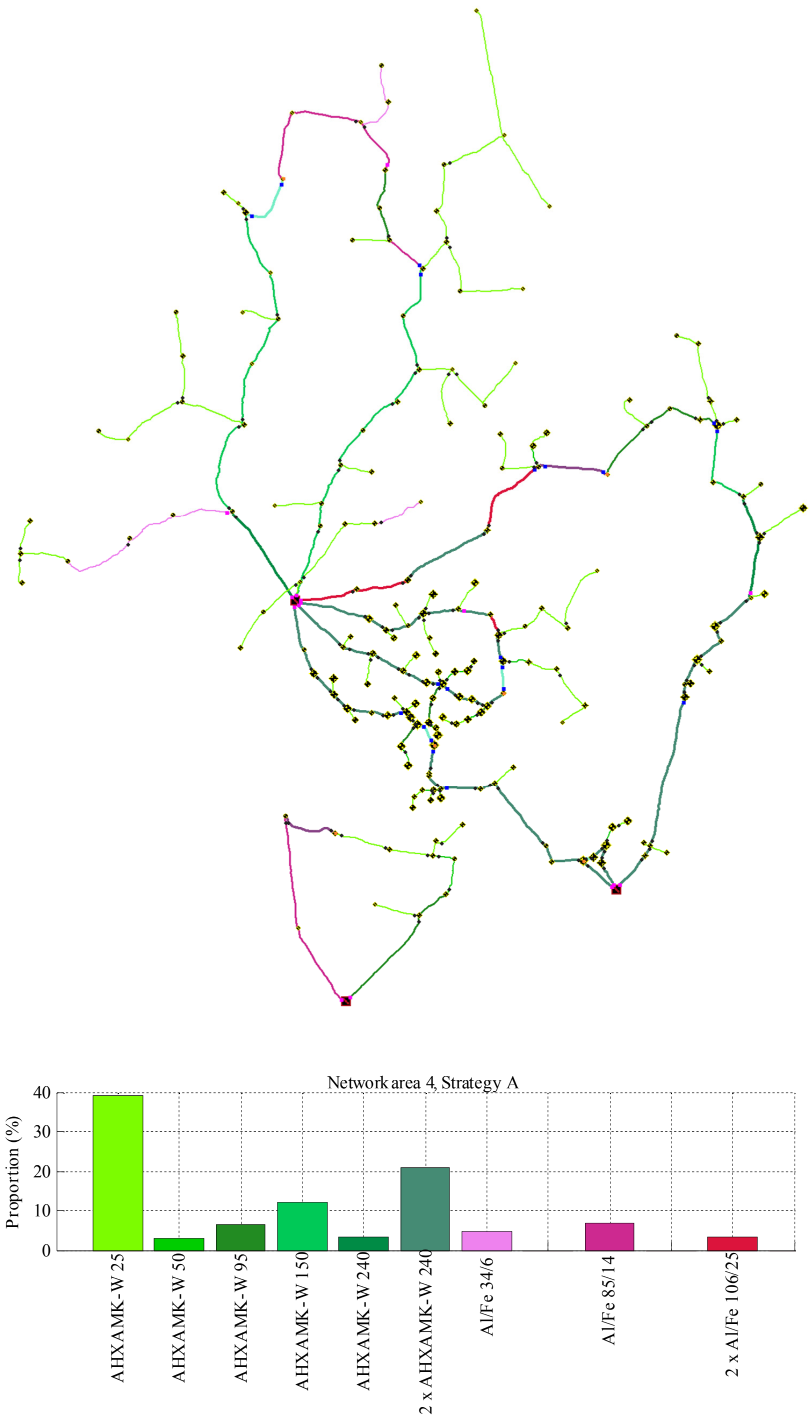


Figure A 3. Final network A: Topology and conductor sizing

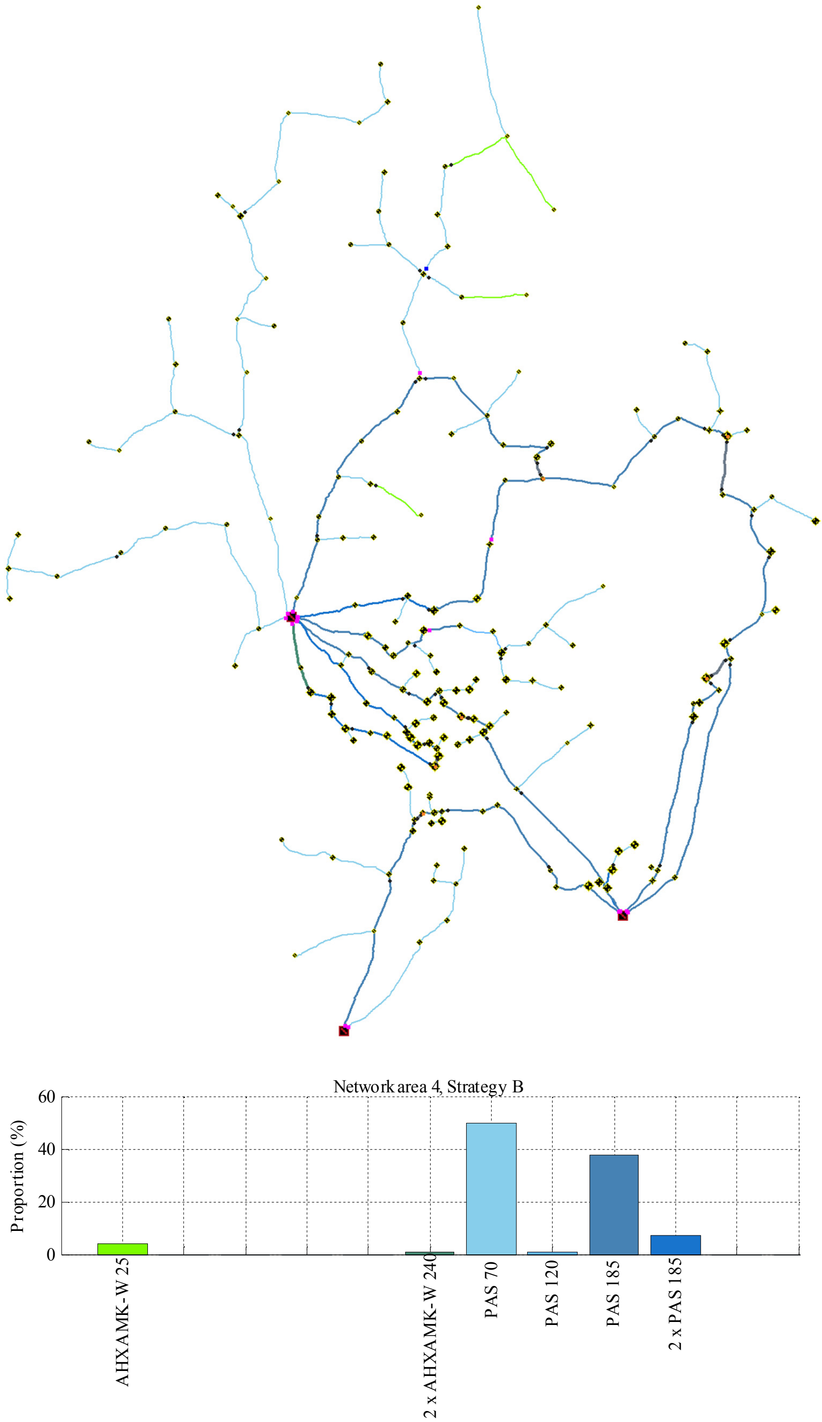
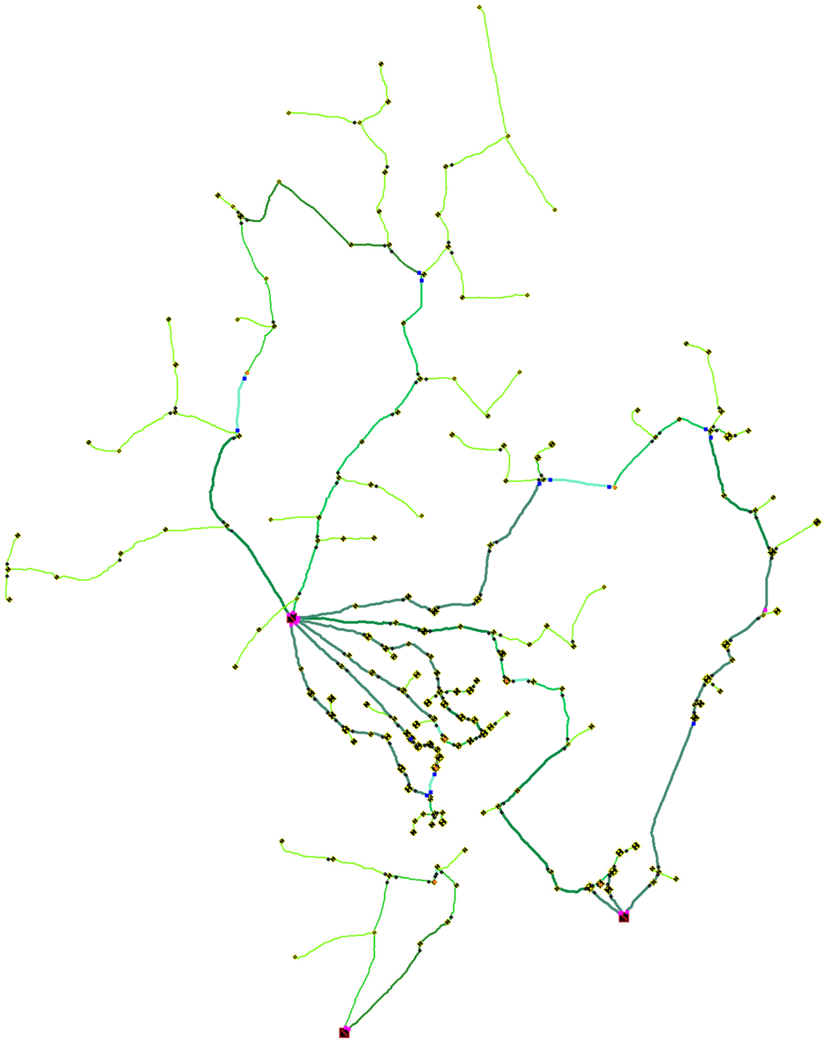


Figure A 4. Final network B: Topology and conductor sizing



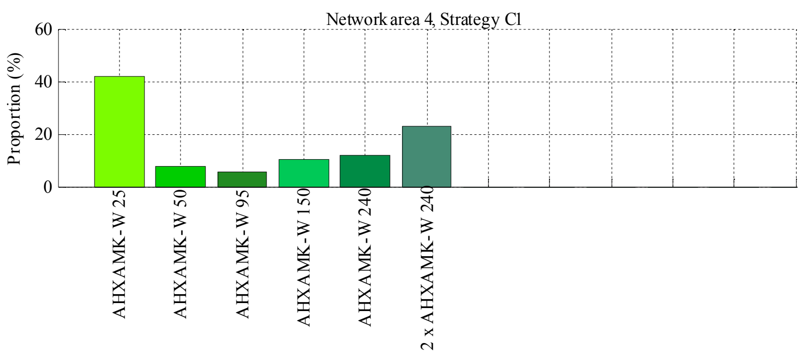
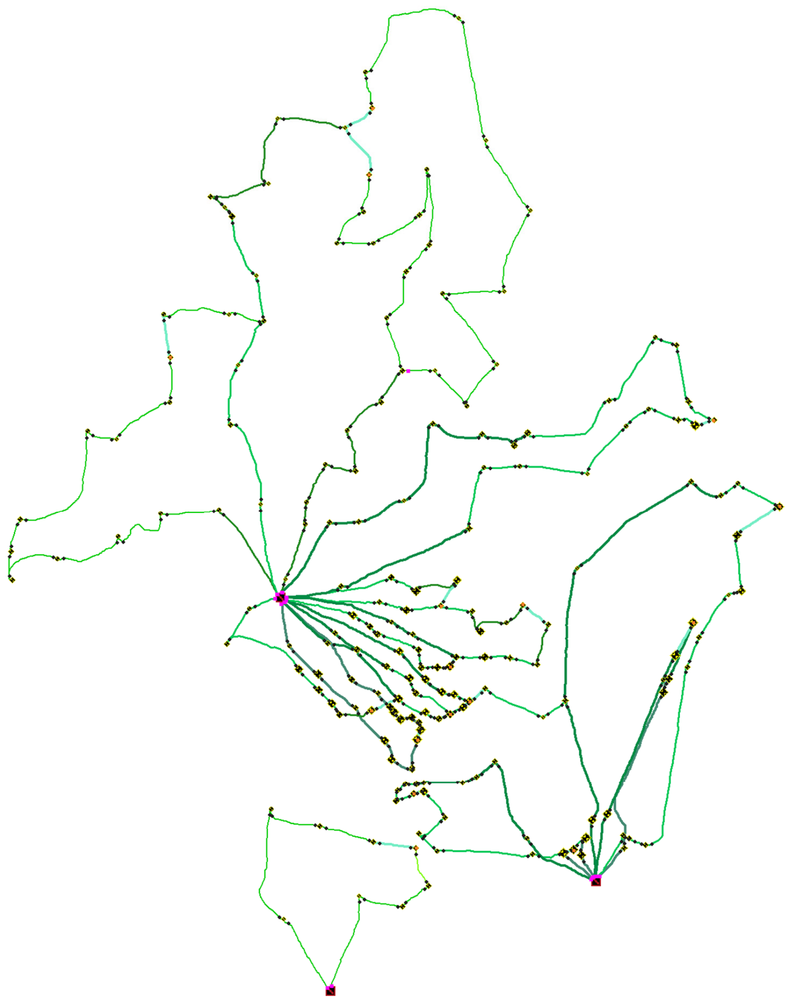


Figure A 5. Final network C1: Topology and conductor sizing



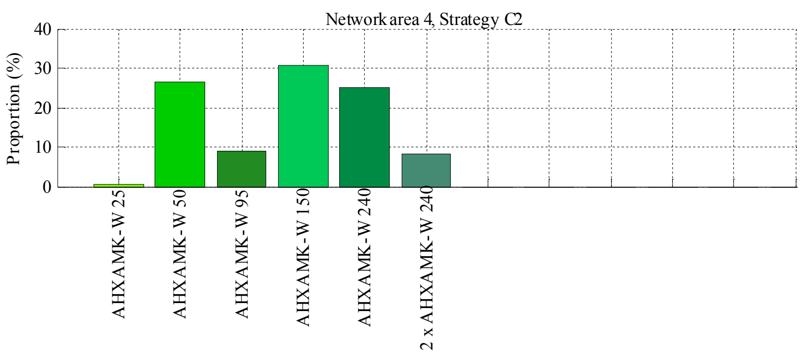
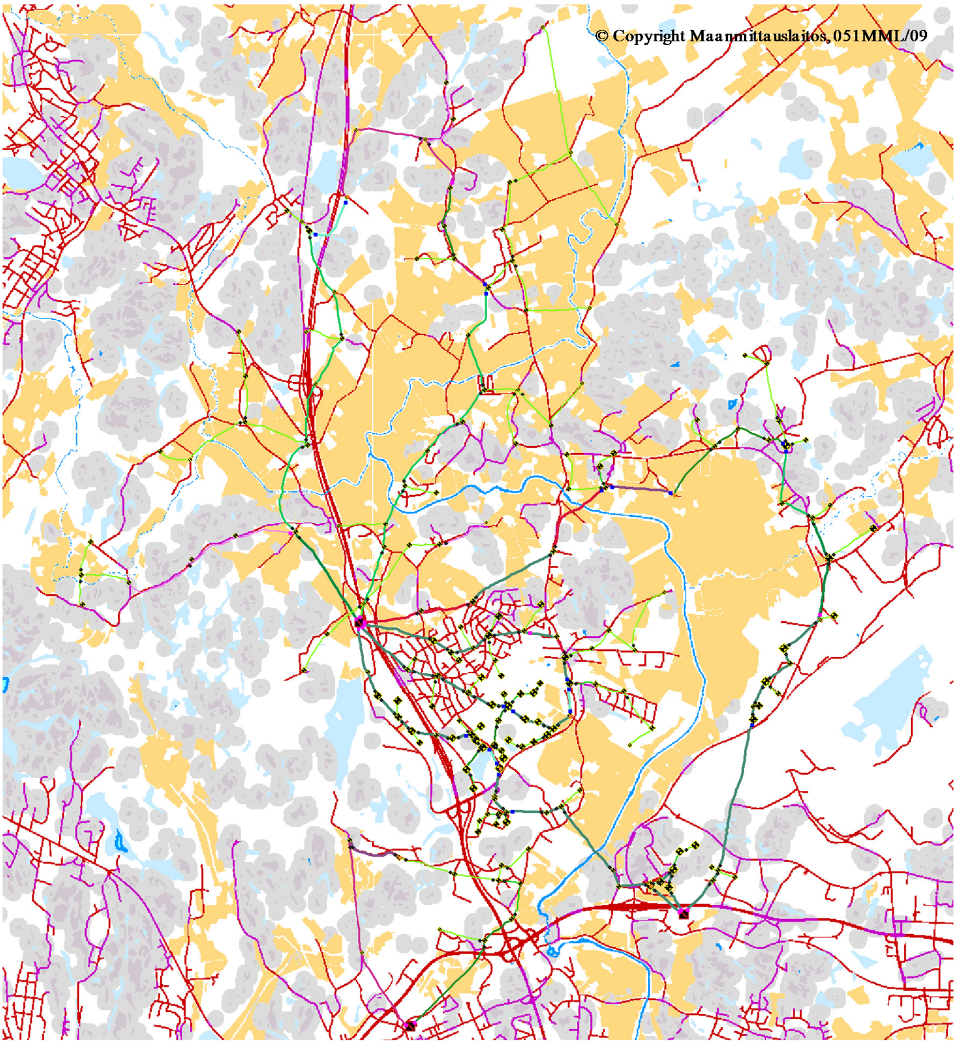


Figure A 6. Final network C2: Topology and conductor sizing



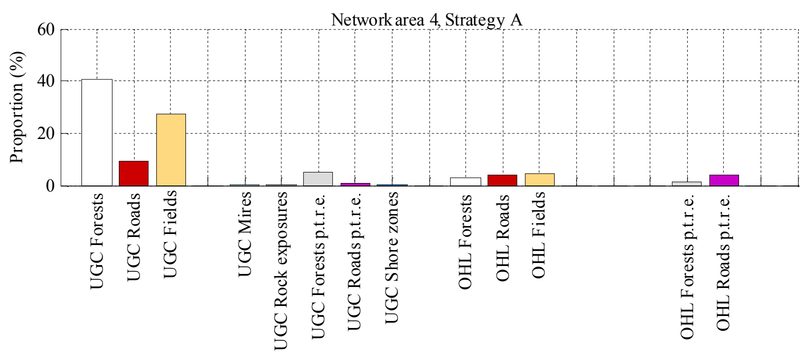
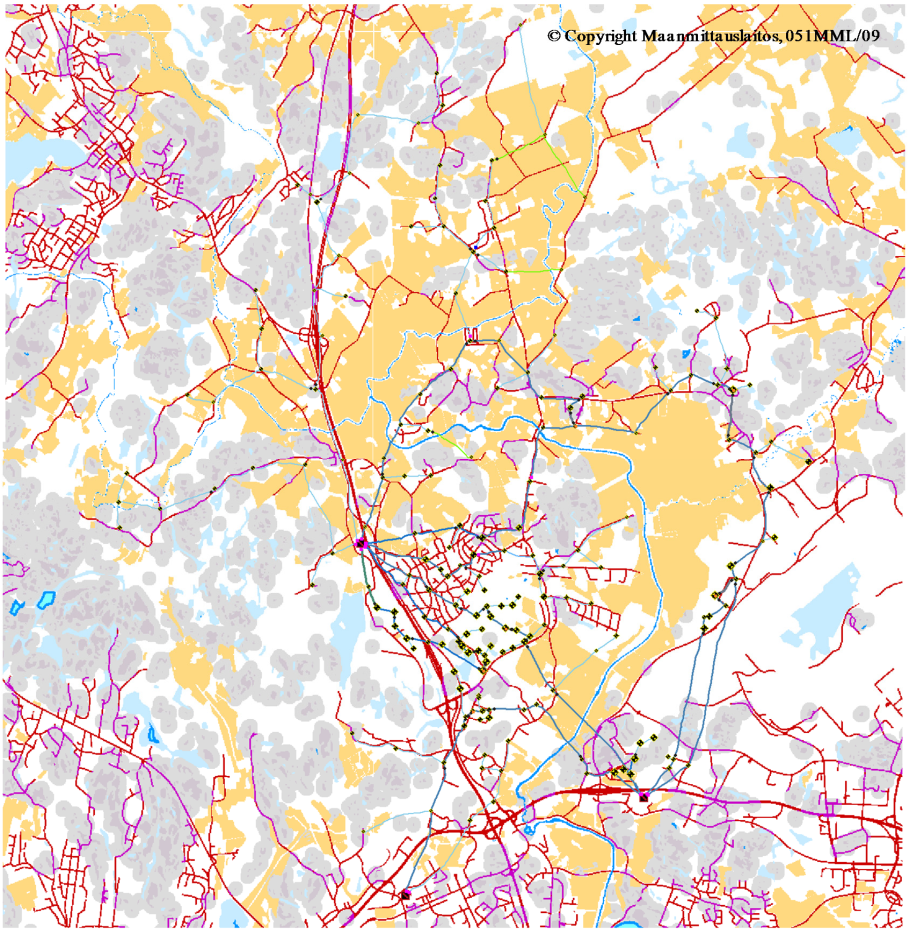


Figure A 7. Final network A: routing of the lines with regard the topography



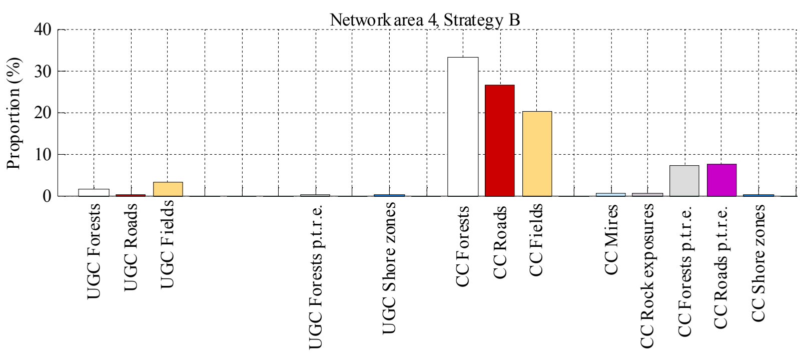
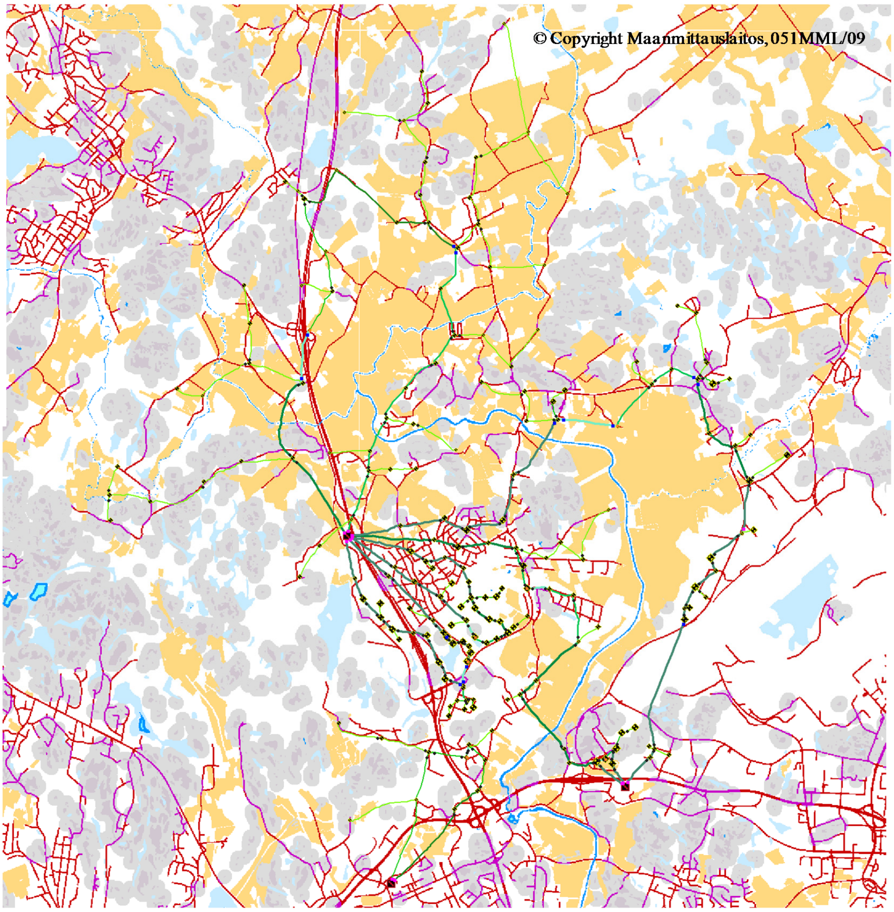


Figure A 8. Final network B: routing of the lines with regard the topography



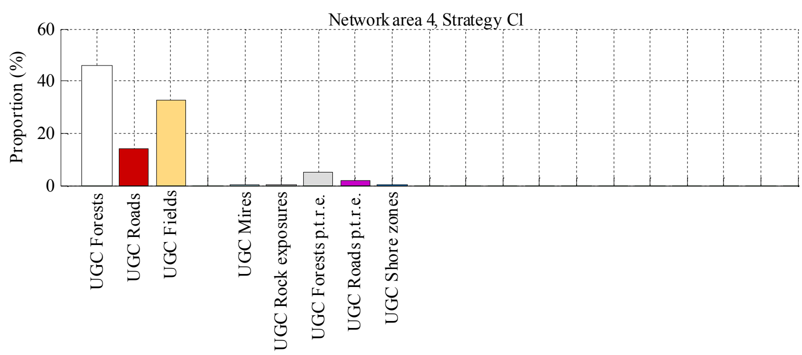
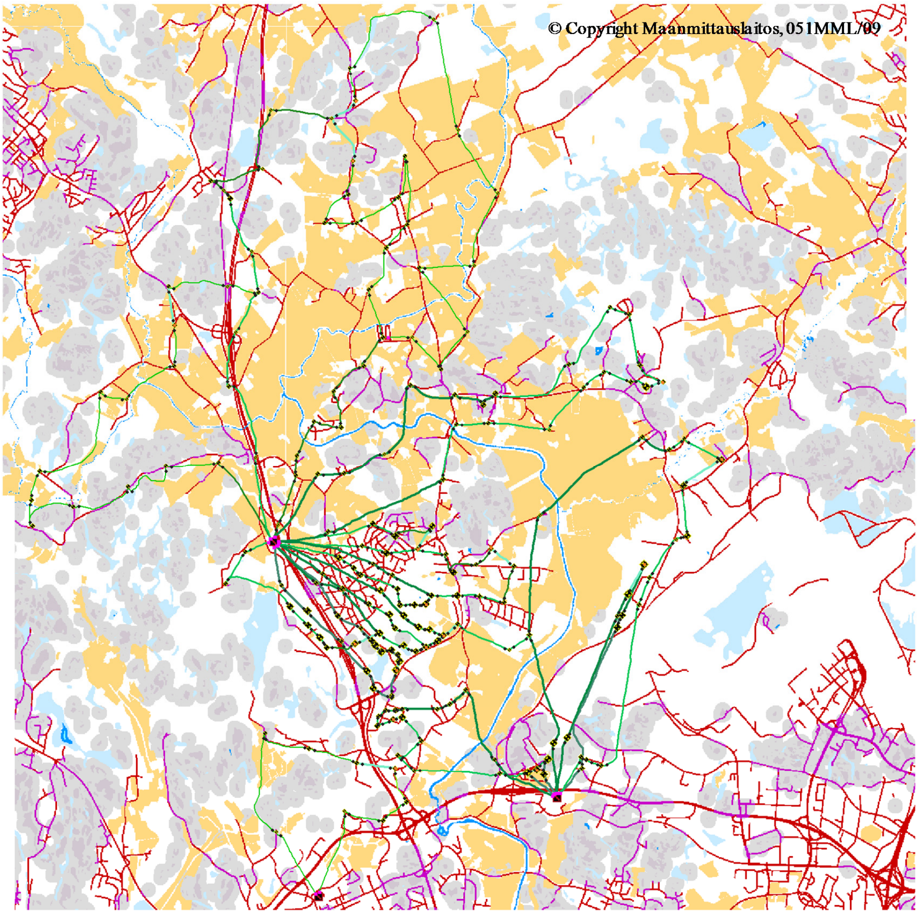


Figure A 9. Final network C1: routing of the lines with regard the topography



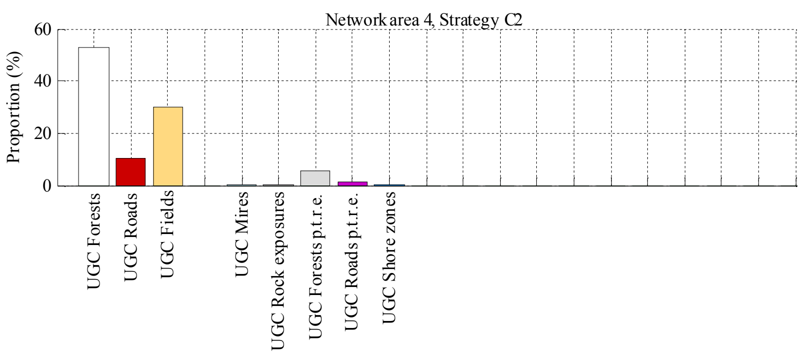


Figure A 10. Final network C2: routing of the lines with regard the topography

Appendix 5
Network area 6: Helsinki

Table A 1 presents the geographically referenced parameterization separately adjusted for the network area 6 Helsinki (others the parameterization is as presented in Chapter 7). In cities, parks are rather common, but often these are not considered possible places for constructing infrastructure. Roads are emphasized in the feasible places for routing, though the constructions costs are raised overall due to, e.g., traffic arrangements and street pavements, and buildings cover a great deal of the terrain type considered as forest (i.e., the areas that are not included to any other terrain type).

Table A 1. Geographically referenced parameters for network 6 for the line type of underground cable

	forests	roads	fields	water bodies	mires	rock exposures	forests proximate to rock exposures	roads proximate to rock exposures	Shore zones	Parks
C_{inst} (€/m)	200	21.36	2.78	14.99	200	200	100	100	24.35	200
λ (1/100km/a)	0.79	0.78	0.82	0.82	5	0.79	0.79	0.78	0.82	0.79
T_r (h)	17	12	12	24	17	17	17	12	24	12
λ_{re} (1/100km/a)	0	0	0	0	0	0	0	0	0	0
C_{maj} (€/m)	0	0	0	0	0	0	0	0	0	0
C_{rw} (€/m)	0.23	0.23	0.76	0	0.23	0.23	0.23	0.23	0	0

Table A 2. Network area: substations

Network area 6	
Secondary substations	314
Primary substations	2

Table A 3. Network area: terrain types

Terrain types (%)	
Forests	45.47
Roads	10.66
Fields	6.38
Water bodies	0.10
Mires	1.47
Rock exposures	2.51
Forests proximate to rock exposures	27.70
Roads proximate to rock exposures	3.67
Shore zones	0.41
Parks	1.62

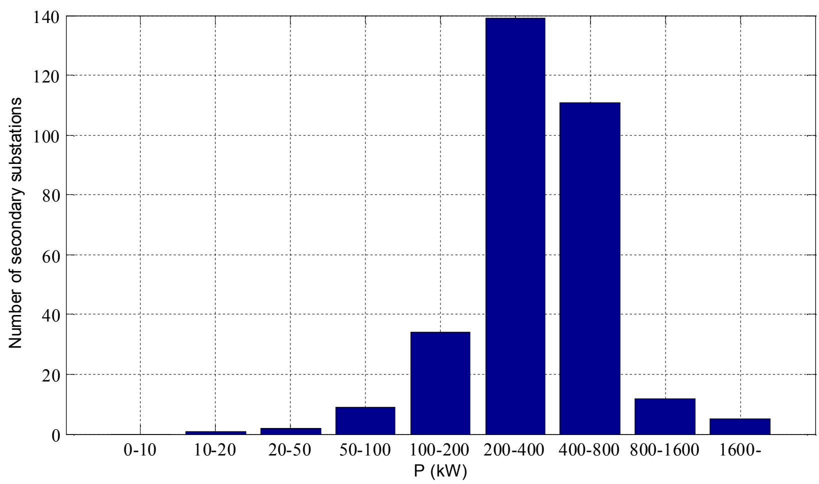


Figure A 1. Network area: secondary substations grouped by the maximum hourly demand

Table A 4. Final network: cost and length

Cost and length	A	B	C1	C2
Total length (km)	N/V	N/V	87.208	122.553
Length per shortest (p.u.)	N/V	N/V	1.00	1.41
Investment (M€)	N/V	N/V	10.813	15.504
Losses (M€)	N/V	N/V	0.757	0.587
Interruptions (M€)	N/V	N/V	1.790	0.750
Total cost (M€)	N/V	N/V	13.360	16.840
Cost per length (k€/km)	N/V	N/V	153.198	137.409
Cost per least cost (p.u.)	N/V	N/V	1.000	1.260
Extra cost per length (k€/km)	N/V	N/V	0.000	28.396

Table A 5. Final network: sectionalization

Sectionalization	A	B	C1	C2
Backed-up sec. substations (%)	N/V	N/V	34.71	100.00
Manual disconnectors	N/V	N/V	218	639
Remote disconnectors	N/V	N/V	22	0
Reclosers	N/V	N/V	6	2

Table A 6. Final network and route options: lengths

	A		B		C1	C2
General	UGC	OHL	UGC	CC	UGC	UGC
Internodal distance (avg., m)	N/V	N/V	N/V	N/V	271	367
Length (km)	N/V	N/V	N/V	N/V	87.21	122.55

Table A 7. Final network and route options: terrain types

	A		B		C1	C2
Terrain types (%)	UGC	OHL	UGC	CC	UGC	UGC
Forests	N/V	N/V	N/V	N/V	24.50	23.71
Roads	N/V	N/V	N/V	N/V	52.08	50.53
Fields	N/V	N/V	N/V	N/V	3.68	6.40
Water bodies	N/V	N/V	N/V	N/V	0.00	0.00
Mires	N/V	N/V	N/V	N/V	0.01	0.00
Rock exposures	N/V	N/V	N/V	N/V	0.14	0.11
Forests prox. to rock exposures	N/V	N/V	N/V	N/V	12.11	13.82
Roads prox. to rock exposures	N/V	N/V	N/V	N/V	7.42	5.29
Shore zones	N/V	N/V	N/V	N/V	0.05	0.13
Park	N/V	N/V	N/V	N/V	0.00	0.00

Table A 8. Final network and route options: conductor sizes

	A		B		C1	C2
Conductor sizes (%)	UGC	OHL	UGC	CC	UGC	UGC
Conductor 1	N/V	N/V	N/V	N/V	40.81	0.00
Conductor 2	N/V	N/V	N/V	N/V	12.71	0.58
Conductor 3	N/V	N/V	N/V	N/V	3.25	6.53
Conductor 4	N/V	N/V	N/V	N/V	1.95	34.67
Conductor 5	N/V	N/V	N/V	N/V	3.52	44.34
Conductor 6	N/V	N/V	N/V	N/V	37.76	13.89

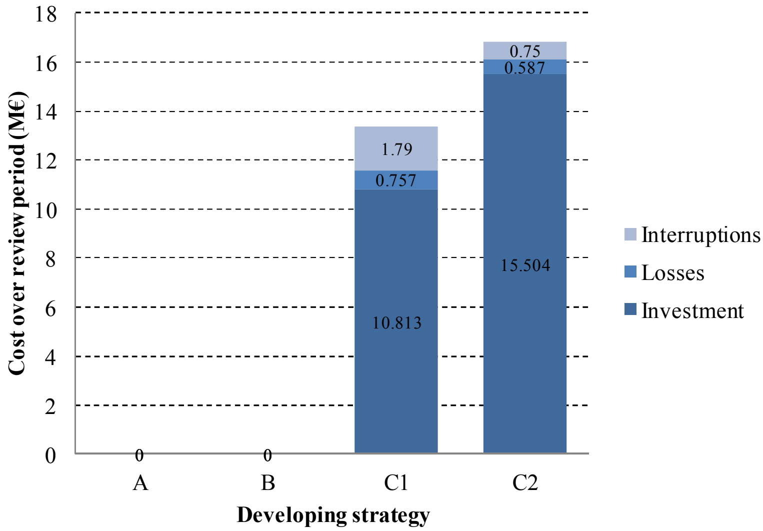
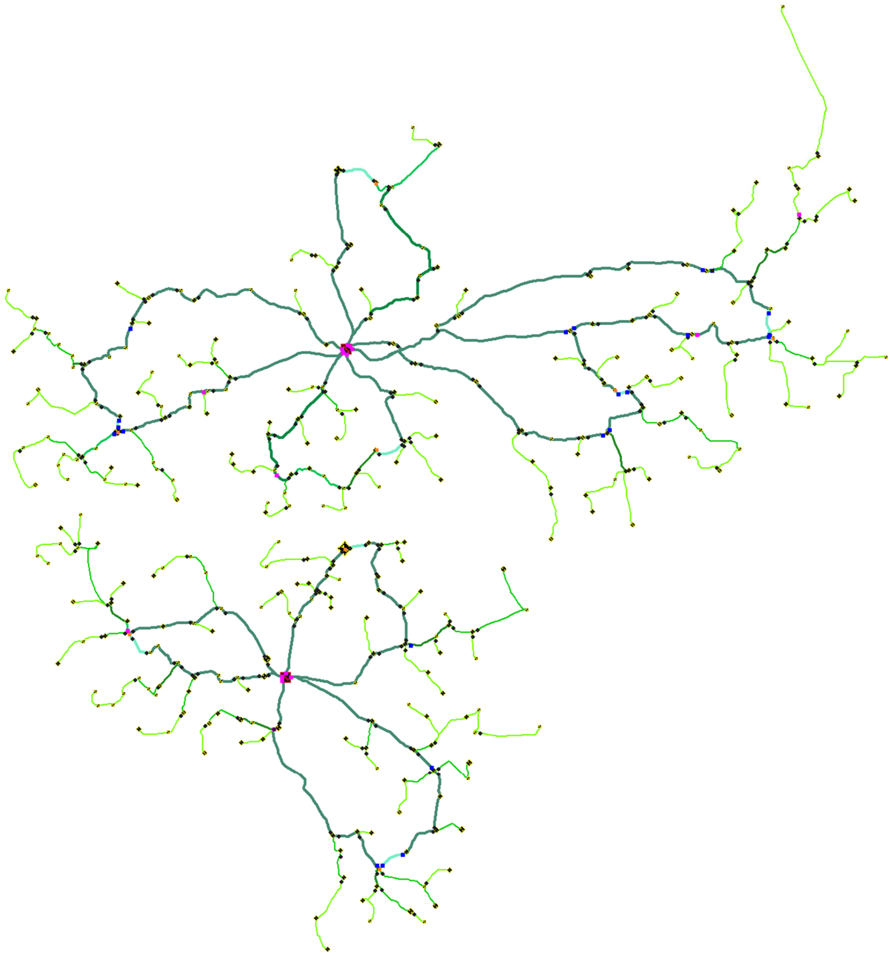


Figure A 2. Final network: cost



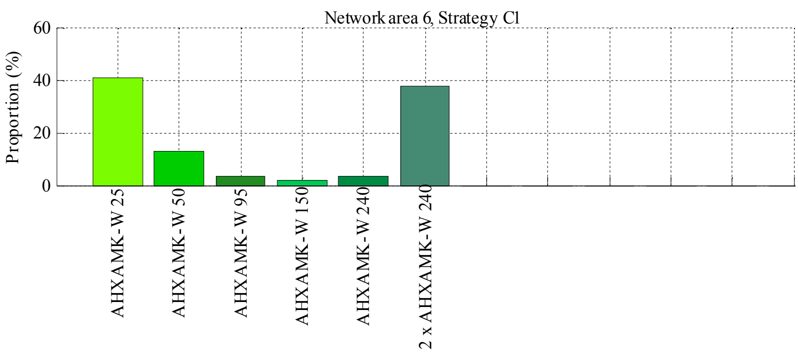


Figure A 3. Final network C1: Topology and conductor sizing

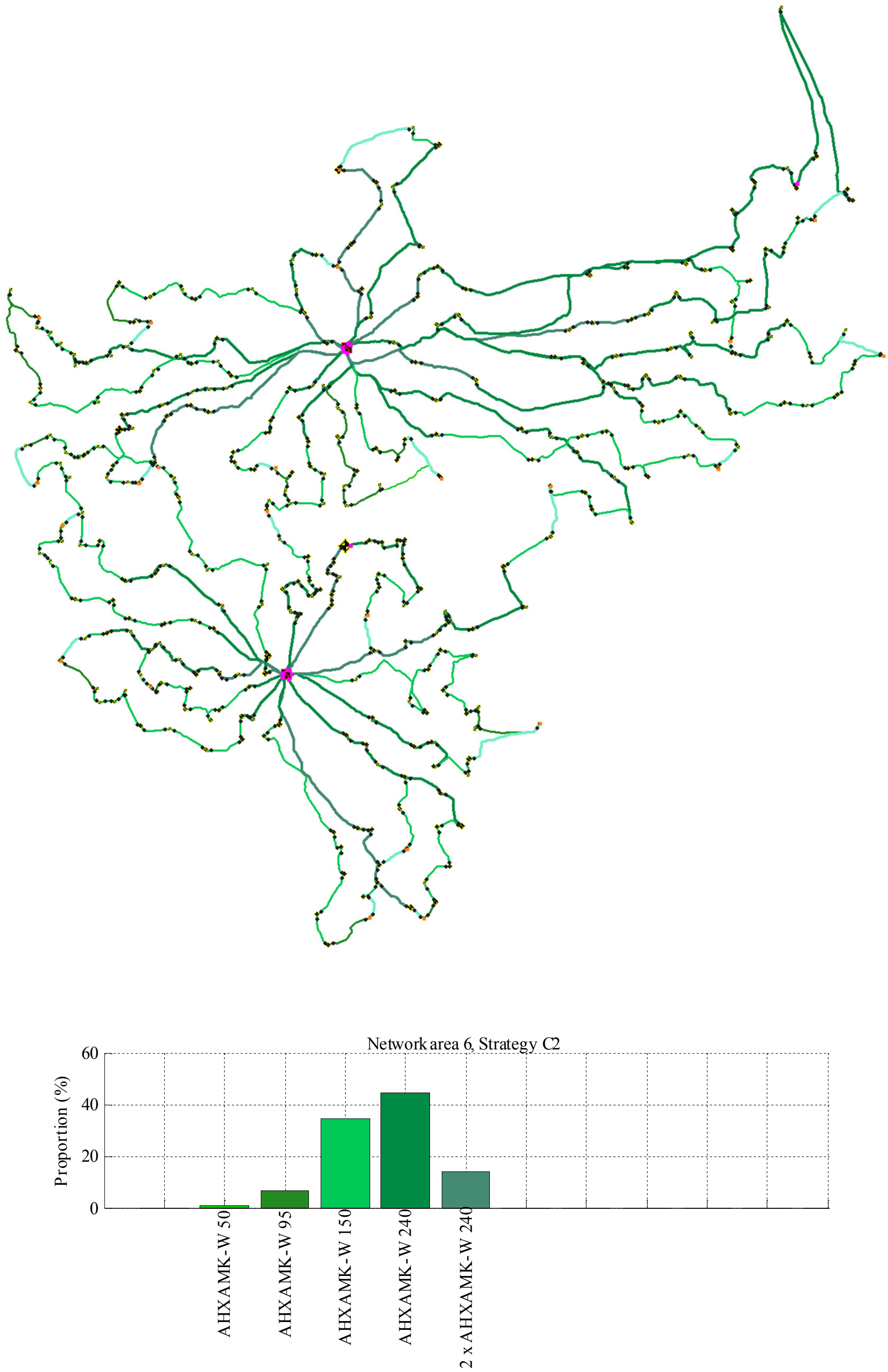
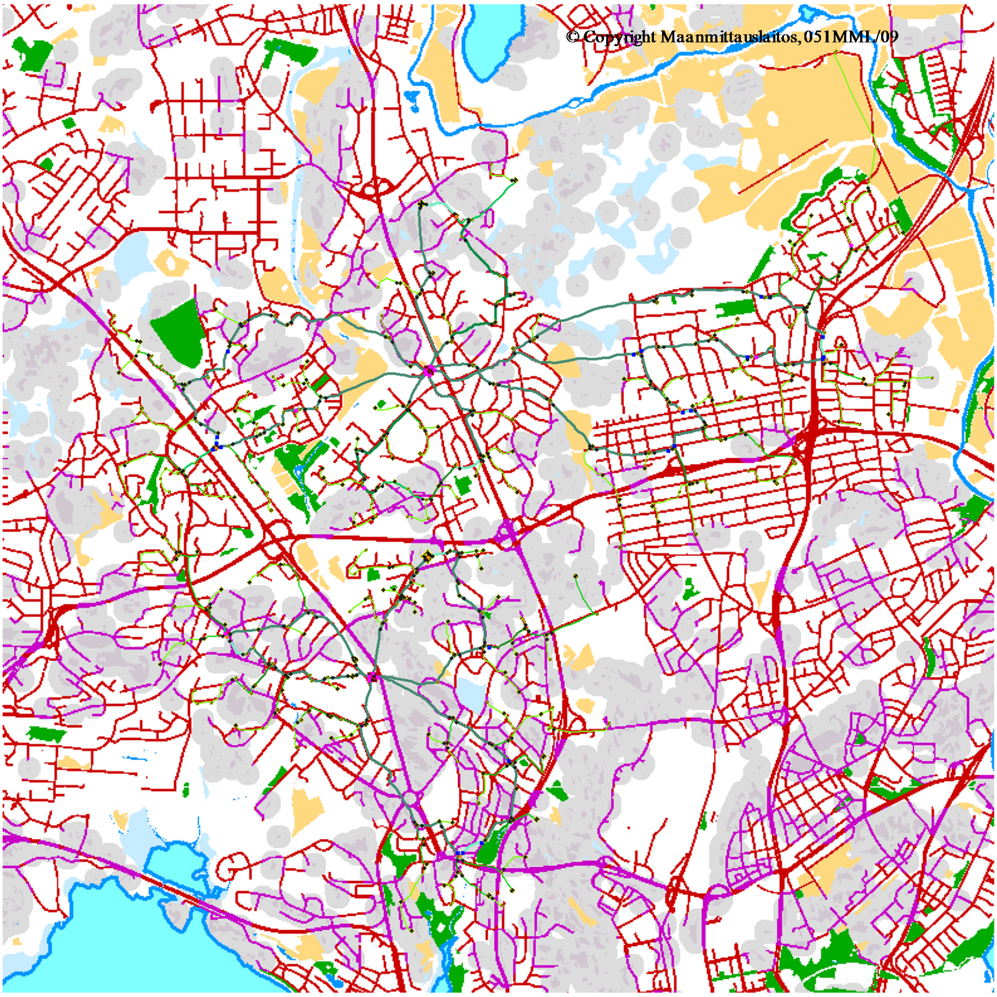


Figure A 4. Final network C2: Topology and conductor sizing



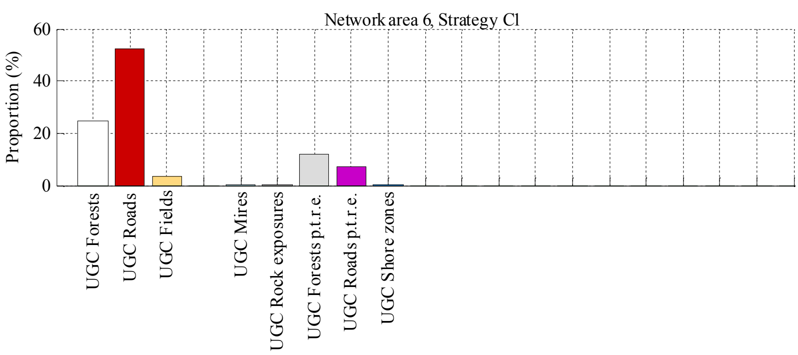
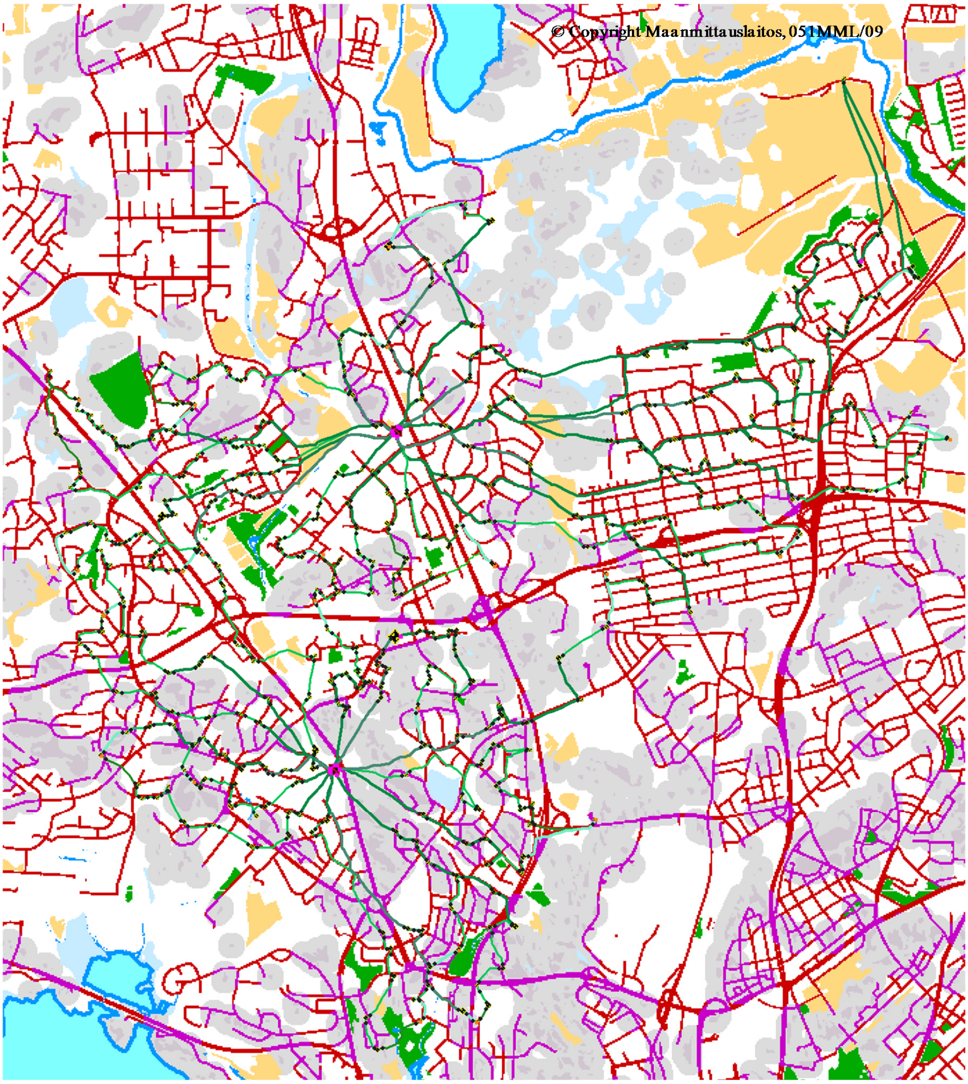


Figure A 5. Final network C1: routing of the lines with regard the topography



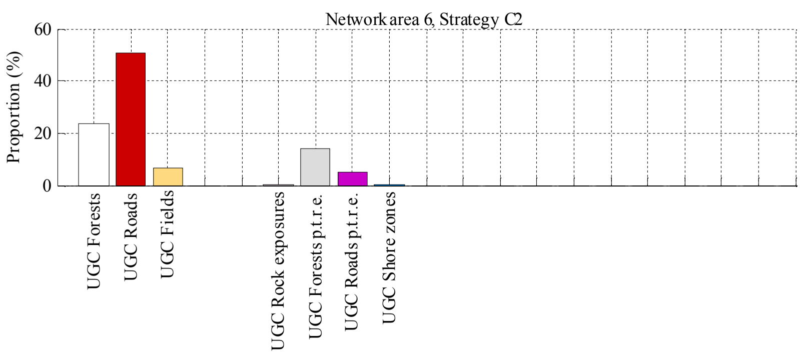


Figure A 6. Final network C2: routing of the lines with regard the topography

Appendix 6
VOH Network Topology Optimization Algorithm

Figure A1 presents the main sequence of the VOH network topology optimization algorithm [Mil09] [Mil12] [Mil12b] [Mil13]. The algorithm works by modifying an underlying radial network using a set of multi-layered branch exchange functions. At each stage the underlying radial network undergoes radial-to-full network conversion, in order to obtain a full network including optimal switching and reserve connections. In addition to sectionalization (manual and remote operable disconnectors and reclosers) and reserve connections, the optimal configuration for normal operation is given.

Reserve connections, sectionalization and configuration are considered with regard to the complete main objective of minimization of the life cycle cost, including the fixed as well as the variable cost components. The user of the algorithm has the means to overrule this basic principle when it comes to, e.g., preferences with reserve connections or sectionalization. For instance, demanding full back-up is a user heuristic which will result in a sub-optimum final network when it comes to the main objective of minimizing the life cycle cost.

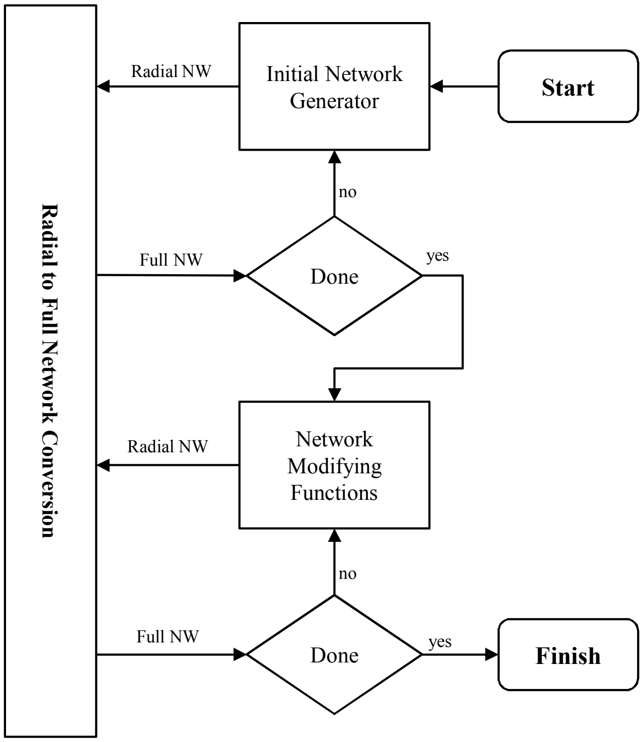


Figure A1. A simplified schematic of the VOH algorithm.

Once a radial network is brought into the radial-to-full conversion routines (Figure A2), the network is initially equipped with full switching (i.e., full penetration of default switches) unless the user prefers not to consider the outage costs, in which case there would be no incentive for improving the reliability and mitigation of the impact of interruptions. According to the user preferences, either optimal, full or no reserve connections are placed in order to maximize the savings on the costs related to reliability. Once the reserve connections are put in place, the switching is optimized. The default switching type may affect the placing of the reserve connections, and, will affect how the switch optimization proceeds. For instance, with manual default switches, the algorithm proceeds by removing the non-cost-effective manual switches and then upgrading the remaining switches to remote when that provides a net saving on the overall network life cycle cost. Following these upgrades, any further manual switches that have become non-cost-effective are removed. Finally, all switch positions are checked to ascertain whether there are feasible locations for reclosers.

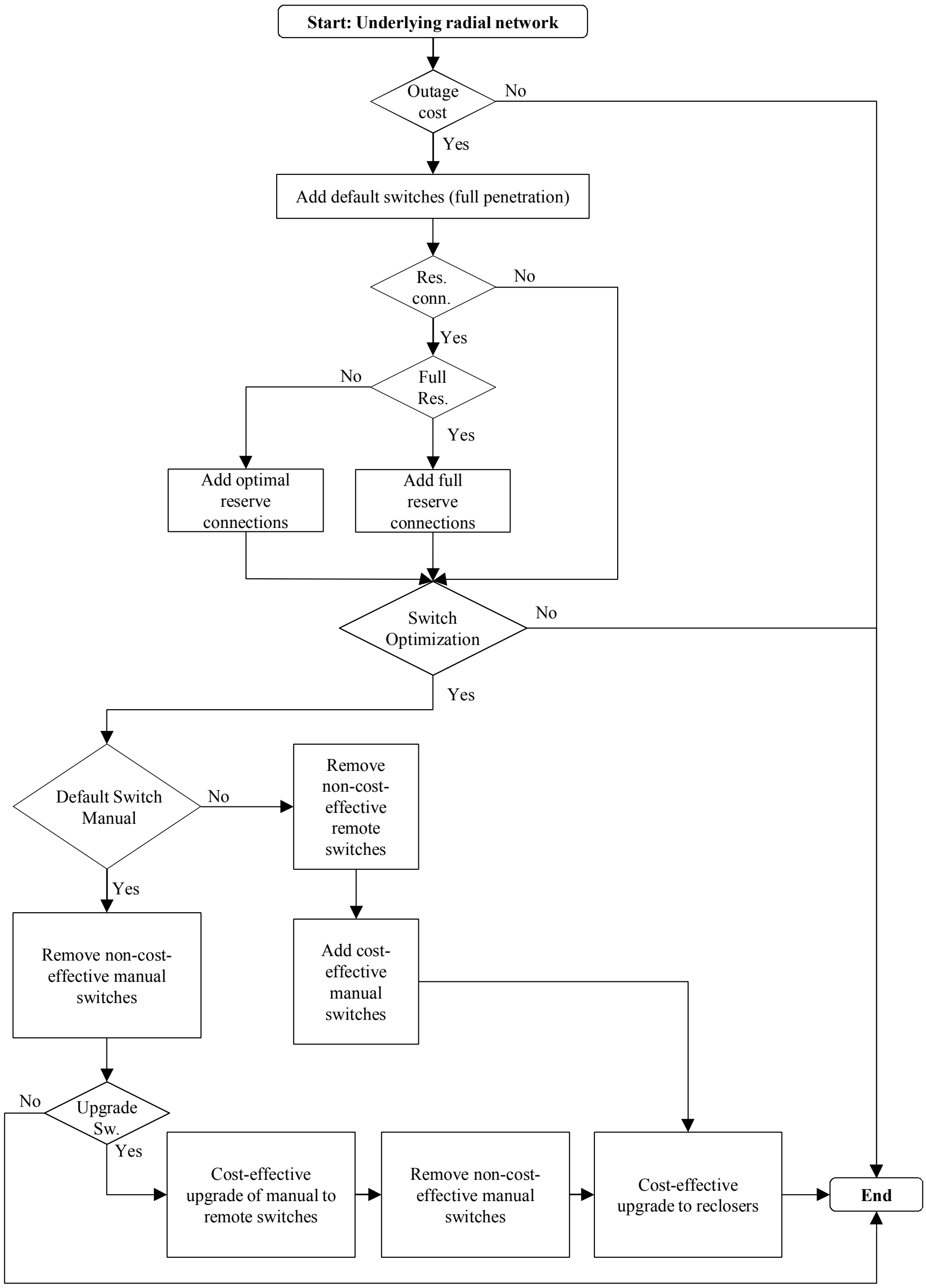


Figure A2. A simplified schematic of the VOH radial-to-full network conversion.

As was shown in Figure A1, the radial-to-full conversion is run as a sub-routine of the VOH algorithm, and is run several times in an iterative process that has the convergence of the life-cycle-cost as the decisive measure of whether to continue the iterations.

As mentioned earlier, Figures A1 and A2 must be seen as simplified schematics and do not present all the individual functions included in the VOH algorithm. For instance, route choices are checked every now and then. This is an important feature when considering the case studies in this thesis, where the different network development strategies including various line types are compared. Some of the branch exchanges are classic techniques that check single changes in upstream or downstream connections. However, several multi-layered branch exchanges have been developed in order to overcome the tendency of branch exchange routines to become caught in locally optimum solutions. In addition, the initial network generation takes into account sector-based and radial load distribution, and interruptions. This guides the network towards global optimality right from the start.

In this thesis, bringing accurate geographic data into the use of the VOH algorithm is in the core of the developed new methodology. This is done by using so called internodal matrices, as covered in Chapter 5. These internodal matrices form an essential part of the VOH algorithm input data, which also include nodal data (containing the node specific parameters, e.g., coordinates, power demand, load growth profiles and customer interruption costs), existing network data (e.g., the line data and remaining lifetimes of the existing line sections) and line data (i.e., the parameters for available line types and corresponding conductor families).

Appendix 7
Reactive Power in Extensive Cable Networks

The resistive line losses consist of losses due to active load current and losses due to the reactive current. Power losses due to active component of the load current depend on the magnitude and profile of the load (i.e., being quadratically dependent on the load current, here, simply the utilization time of the peak load and peak load are utilized). Reactive current losses, then again, depend highly on the used line type, but also on the consumption of reactive power on the customer side. Especially in extensive cable networks, distributed compensation reactors might be needed in order to be able to restrain the cost of the losses within reasonable limits. The dissipated active power P_h and reactive power Q_h on a line section are[11] presented as Equations (1)-(4),

$$P_h = \left(\frac{P}{U}\right)^2 R_j + \left(\frac{Q}{U}\right)^2 R_j \tag{1}$$

$$= 3R_j\left(I_r^{\,2} + I_q^{\,2}\right) \tag{2}$$

$$Q_h = \left(\frac{P}{U}\right)^2 X_j + \left(\frac{Q}{U}\right)^2 X_j \tag{3}$$

$$= 3X_j\left(I_r^{\,2} + I_q^{\,2}\right) \tag{4}$$

where

P_h	is the active power dissipated in the line resistance
Q_h	is the reactive power consumed by the line reactance
P	is the active power transferred through the line
Q	is the reactive power transferred through the line
U	is the phase-to-phase voltage
R_j	is the line resistance
X_j	is the line reactance
I_r	is the resistive component of current

---

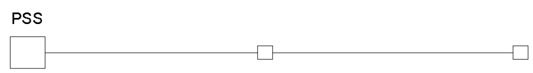
[11] $P_h = \left(\frac{P}{U}\right)^2 R_j + \left(\frac{Q}{U}\right)^2 R_j = 3I_r^{\,2}R_j + 3I_q^{\,2}R_j = 3R_j\left(I_r^{\,2} + I_q^{\,2}\right) = 3R_j\left(\sqrt{I_r^{\,2} + I_q^{\,2}}\right)^2 = 3R_jI^2 \;\big|\; I = I_r + iI_q$

$Q_h = \left(\frac{P}{U}\right)^2 X_j + \left(\frac{Q}{U}\right)^2 X_j = 3I_r^{\,2}X_j + 3I_q^{\,2}X_j = 3X_j\left(I_r^{\,2} + I_q^{\,2}\right) = 3X_j\left(I_r^{\,2} + I_q^{\,2}\right)$

I_q is the reactive component of current

In this study the losses in secondary substations are not considered. The losses of the transformers are assumed to be the same for the different line types and thereby do not affect line type selection, nor the strategic choices being made. Operational and maintenance costs consist of operation of the network, inspections of the network, maintenance and technical servicing, clearings (of the feeder corridor etc.) and operation- and communication system upkeep [Loh06][73]. An operating cost of 95 € per km per year for MV network was used in an earlier study [Loh06][76]. As this cost is small and is estimated to make no difference between the studied line types, it is not considered in the comparison.

Figure A1 illustrates the generation and consumption of reactive power on a simplified medium voltage feeder. When considering the balance $\sum Q$ between inductive loads ($S \cdot \sin(\varphi)$) and reactive power generation (Q_{lineC}) in present overhead distribution networks, generation is typically overweighed by the consumption. Example loads consuming reactive power include motor loads (e.g., increasing numbers of heat pumps in the future in comparison to conventional direct electric heating), fluorescent lamps and thyristor drives. Reactive power is also consumed in the distribution transformers (Q_{trafoL})[12] and in the medium voltage lines (Q_{lineL}). Especially with larger conductor sizes, the inductive reactance is rather close to the magnitude of the resistive component of the line impedance. The operating point where the reactive power generated by the line capacitance equals to the reactive power consumed by the line reactance is especially meaningful in transmission lines. For extensive medium voltage cable networks the ratio between consumption and generation of reactive power moves strongly towards surplus of generation.



$$\sum Q = \begin{matrix} -Q_{lineC} \\ +Q_{lineL} \end{matrix} \quad \begin{matrix} +S \cdot \sin(\varphi) \\ +Q_{trafoL} \end{matrix} \quad \begin{matrix} -Q_{lineC} \\ +Q_{lineL} \end{matrix} \quad \begin{matrix} +S \cdot \sin(\varphi) \\ +Q_{trafoL} \end{matrix}$$

Figure A1. Accumulation of reactive power on a simple radial feeder with two secondary substations

Reactive currents consume the economical (and technical) load capacity of the lines and therefore distributed compensation is feasible in the case of extensive cable networks. Also, the voltage rise might become an issue with long cables with no load (due to the Ferranti effect). For a 25 mm^2 AHXAMK cable, the reactive power generation is

[12] reactive power consumption of the no-load magnetization branch and of the serial component related to power flow through the transformer

approximately 16 kvar per km (or 0.47 A of reactive current per km per phase)[13], whereas for a 240 mm^2 AHXAMK cable the generation is 38 kvar per km. Ohmic losses of the line resistance are lower the closer to the point of generation the reactive power is consumed. Problems may arise as a consequence of resonating LC-circuits, where, e.g., harmonic currents might become significant.

Figure A2 presents two cases of capacitive reactive current distribution along a radial line section[14].

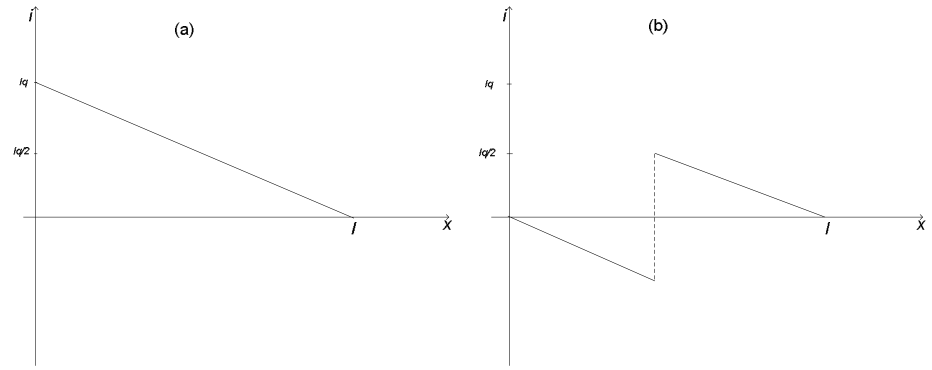


Figure A2. Reactive current accumulation on a non-compensated line (a) and on a line compensated with a reactor in the middle of the studied line section (b)

These alternative cases are (a) without compensation and (b) with a full-sized compensation unit (of the generated reactive power) half-way along the studied line section. Using the notations of Figure A2a, the reactive current *i* as a function of distance *x* can be expressed,

$$i(x) = I_q - \frac{I_q}{l} x \tag{5}$$

where

I_q is the total reactive current[15]
l is the length of the line section

The three-phase dissipation power dP_h in a differential element of distance dx caused by the reactive power flow[16] can now be expressed,

---

[13] [Lak08, p. 34] $Q = BU^2$, $B(25\ \text{mm}^2) = 40.841$ µS/km, $B(240\ \text{mm}^2) = 94.248$ µS/km, $U = 20$ kV, Q = reactive power

[14] Assuming a constant voltage and no consumption of reactive power over the studied line section.

[15] Not considering the reactive power consumed by the inductive serial reactance of the cable

$$dP_h = 3i^2(x)\cdot r\cdot dx\,. \tag{6}$$

Further, the three-phase dissipation power P_{ha} on the line in case (a) can be calculated[17],

$$P_{ha} = rl\cdot I_q^{\,2} \tag{7}$$

For the second alternative case with compensation (Figure A2b), the two halves, for which the amplitude of the current and integration interval are halved, can be calculated using the previous result. Now the dissipation power P_{hb} is

$$P_{hb} = 2\cdot\left[r\left(\frac{l}{2}\right)\cdot\left(\frac{I_q}{2}\right)^2\right] = \frac{1}{4}\cdot rl\cdot I_q^{\,2} = \frac{1}{4}P_{ha} \tag{8}$$

The present values for the two cases are[18]

$$cost_a = D\cdot h_h\cdot T_h\cdot rl\cdot I_q^{\,2} \tag{9}$$

$$cost_b = D\cdot h_h\cdot T_h\cdot\frac{1}{4}\cdot rl\cdot I_q^{\,2} \tag{10}$$

It is assumed that in rural areas networks load is mostly resistive[19] (heating load) and the reactive power consumption of small distribution transformers (typical sizes of 16 – 50 kVA) is small compared to the reactive power generated by the line capacitance. For the resistive load the maximum economical ampacity for each conductor size20 is used, refer to Table A1.

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[16] Only the right term ($3I_q^2R_j$) on the right side of Equation (4) is studied here as the left term ($3I_r^2R_j$) is not affected by the reactive current and is not of interest in this context

[17] $P_{ha} = 3\int_0^l i^2(x)\cdot r\cdot dx = 3r\int_0^l\left(I_q-\frac{I_q}{l}x\right)^2dx = 3r\int_0^l\left[I_q^{\,2}-2\frac{I_q^{\,2}}{l}x+\left(\frac{I_q}{l}x\right)^2\right]dx = 3r\left|\left[I_q^{\,2}x-\frac{2}{2}\frac{I_q^{\,2}}{l}x^2+\frac{1}{3}\left(\frac{I_q}{l}\right)^2x^3\right]\right|_0^l = rl\cdot I_q^{\,2}$

[18] The purchasing price of the compensation inductor is not considered at this point

[19] $\cos(\varphi)\approx 1 \Rightarrow \sin(\varphi)\approx 0$

[20] Considering the sum of purchasing price of cable (refer to Table 7.12 in Chapter 7 on page 86) and cost of losses (refer to Table 7.10 on page 85) individually for each conductor size and then selecting the conductor with lowest total cost as a function of power flow S: $K = H + D\cdot\frac{rT_hh_h}{U^2}S^2$

Table A1. Economical ampacity of cables

Conductor size	**Maximum economic load** (A)
25 mm^2	30.02
50 mm^2	58.89
95 mm^2	92.38
150 mm^2	134.67
240 mm^2	297.19
2 x 240 mm^2	N/V

For the reactive power consumed by the line reactance, a rough estimation using the current distribution of Figure A2b is used. The reactive power losses on the line reactance are calculated using Equation (11)[21].

$$\frac{Q_{lineL}(l)}{l} = \frac{X_j}{l}\left(3I_r^{\,2} + \frac{I_q(l)^2}{4}\right) \tag{11}$$

Figure A3 shows the line reactance (X_j) reactive power consumption per distance (Q_{lineL} per l) as a function of the compensation unit-to-unit distance l. It is shown, for the unit-to-unit distances less than 50 km, that the reactive power consumption is only weakly dependent on the distance l. For example, for 25 mm^2 cable the right term of Equation (11) inside the brackets equals the left term at a distance of approximately 100 km, after which it rapidly increases and overweighs the cost due to resistive load. With small conductor sizes, which often are sufficient to meet the economical ampacity in the rural feeders under study, the reactive power consumption is at least a decade smaller than the generation of the reactive power of the line capacitance (e.g. for 3 x 25 mm^2 with l = 10 km, Q_{lineL}/l = 0.434 kvar/km vs. Q_{lineC}/l = -16 kvar/km). Based on this, no further iterations or adjustments to the reactive current (I_q) values are made.

[21] Derived using Equations (9) and (8)

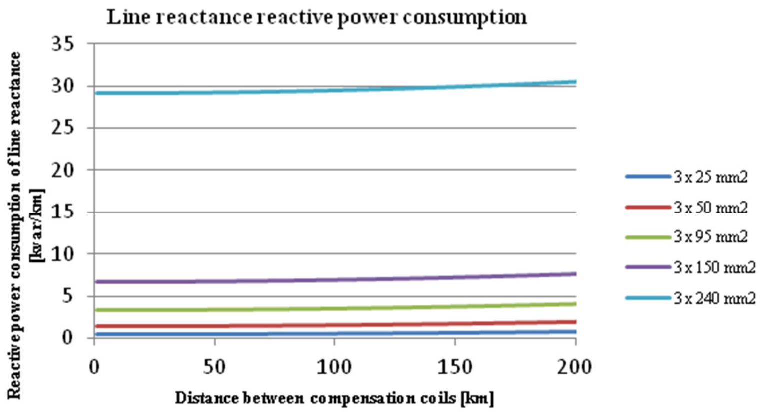

Figure A3. Reactive power consumption of line reactance at maximum economical ampacity as a function of reactive power compensation unit-to-unit distance

Figure A4 illustrates the quadratically increasing expenses of dissipated energy for different radial cable line lengths[22]. Only the losses occurring on the studied line section are taken into account. Calculations were carried out for the two alternatives shown in Figure A2a-b.

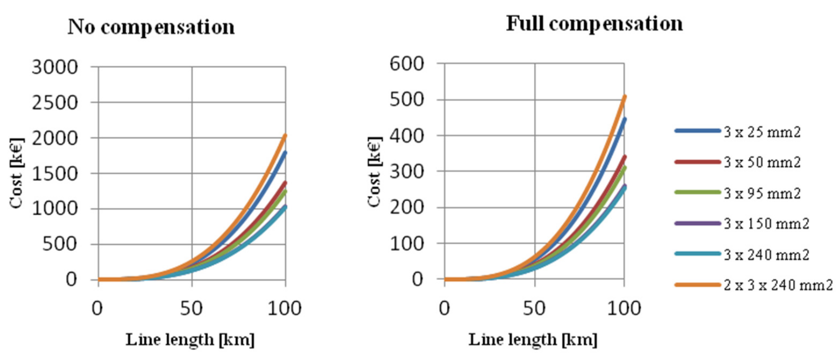

Figure A4. Dissipation energy cost of reactive current for different cable sizes as a function of the length of a radial line. Uncompensated case on the left ($cost_a$) and case with single compensation unit on the right ($cost_b$)

Figure A5 presents the costs per length for the case with no compensation (Figure A2a). Considering extensive cable networks, the accumulation of reactive power, especially at the feeder sections close to a primary substation, might easily become a significant cost

[22] Refer to Table 7.10 and Table 7.12 for details on parameters

driver. Extensive cable networks cannot be seen as a feasible alternative without considering distributed compensation of the generated reactive power.

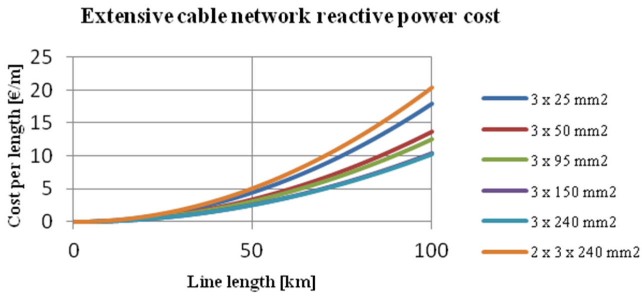

Figure A5. Dissipation energy cost of reactive current per length for different cable sizes on a branch line as a function of the length of a uncompensated line section

If it is assumed that compensation of this extra capacitive reactive power is carried out using iron-core reactors, for which the characteristics are rather close to those of distribution transformers of similar power rating, hence it is possible to approximate the dissipation energy costs due the reactive power and its compensation[23]. In fact, reactors modified from distribution transformers are known to be used in Finland. Table A2 lists the used parameters.

Table A2. Parameters used for costing coils[24]

Power rating (kVA)	Cost (k€)	P_0 (no load losses) (W)	P_k (load losses) (W)
30	3.11	103	585
50	3.17	140	885
160	4.55	220	1485
200	5.96	420	2295
315	7.33	600	4500
630	9.39	720	6600
800	13.33	1200	8500
1000	15.15	1450	10200
1250	18.04	1600	11500
2 x 1250	36.08	3200	23000
4 x 1250	72.16	6400	46000

The costs (per distance) include cost of the compensation device (coil), cost of losses on the compensation device and the losses on the lines (refer to Equation (10).

[23] Assuming that such coils would have similar structure: e.g. windings, iron core, oil, hermetic enclosure
[24] Purchasing prices from [Ene10:], technical parameters from [Abb90:]

$$\text{cost}(l) = \frac{1}{l}\left[H_{reactor} + DT_h h_h \left(P_0 + P_k + \frac{1}{4} r l I_q^{\ 2}\right)\right]$$

$$= \frac{H_{reactor}}{l} + DT_h h_h \left(\frac{P_0 + P_k}{l} + \frac{1}{4} r I_q^{\ 2}\right) \tag{12}$$

where:

cost	is the total cost per cable length
l	is the distance between compensation devices
$H_{reactor}$	is the purchasing cost for reactor
D	discounting factor
T_h	utilization time for losses
h_h	cost for dissipated energy
P_0	is the dissipation power of reactor with no load
P_k	is the dissipation power of reactor with nominal load
r	is the resistance (per cable length) of the line
I_q	is the reactive current (proportional to length)

The smallest reactor, which meets the demand (kvar), from the given set (Table A2) is always chosen. Utilization time for the losses is now full year (8760 h/a) as it is assumed that the device is always operating at nominal capacity when connected in parallel with the capacitance of the cable.

The total cost for different distances between the compensation coils (Equation (12)) is shown in Figure A6.

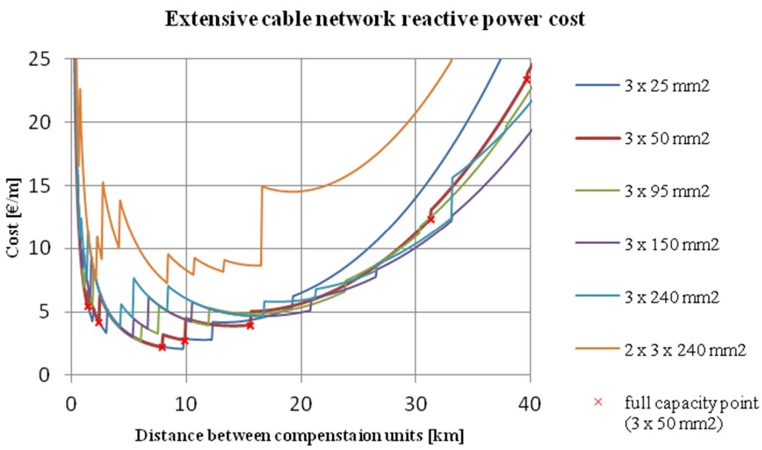

Figure A6. Total cost due to reactive power generation of extensive cable networks

Regardless of the conductor size, the lowest cost seems to occur with less than 20 km distances between the reactive current compensation devices. Strictly considering, only the points on the graph with distances right before shifting to larger compensation unit (step-like changes in the graph, refer to full capacity points shown for conductor size of 50 mm^2) are valid as for the region between these points Equation (12) pre-condition of sufficient compensation is no fulfilled. This study, however, is giving the minimum cost for each conductor size in the given conductor set and those are the values that are needed for quantifying the cost due to reactive power. Table A3 lists the minimum capacitive reactive power compensation costs for the set of studied conductor sizes. Extra space needed at secondary substations is not considered in these costs.

Table A3. Additional operating cost for the cable due to reactive power generation and compensation

Conductor size	**Minimum cost** (€/m)
3 x 25 mm^2	2.04
3 x 50 mm^2	2.17
3 x 95 mm^2	2.70
3 x 150 mm^2	3.02
3 x 240 mm^2	3.78
2 x 3 x 240 mm^2	7.24

In this thesis, the values shown in Table A3 are used for the cost due to reactive power and its compensation. Comparing these values with the values shown in Figure A5, the use of distributed compensation units is justified in extensive cable networks. If considering the use of air-core reactors, the cost due to iron-losses would be smaller. However the investment cost of such devices would be approximately ten times the purchasing prices used here for the iron-core reactors.

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