A Decision Support Tool for the Medium Voltage Networks Expansion Problem

Master Thesis

Stefan Jurriëns
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Master thesis
'A Decision Support Tool for the Medium Voltage Networks Expansion Problem'

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Management Summary

There is tremendous pressure on the energy infrastructure due to the rapid change towards a more sustainable energy system. The adoption of new technologies such as electrical vehicles and heat pumps is a substantial driver for an increasing power consumption. This requires an electrical network that can transport much more energy than we currently have in the Netherlands. Liander has to act quickly to prevent future capacity problems. Manually planning a large network far into the future is incredibly complex. Liander needs algorithms to determine the best expansion strategy. Therefore, the central research question of this thesis is:

'What is a model for generating adequate investment strategies to prevent capacity problems in medium voltage networks?'

The distribution network expansion planning problem can be formulated as a highly constrained, high-dimensional, mixed integer, non-linear combinatorial optimization problem (Scheidler, Thurner, & Braun, 2015). In order to obtain approximate solutions for this problem, we propose two simulated annealing (SA) algorithms in this thesis.

Two simulated annealing based algorithms proposed

The first algorithm aims to solve capacity problems by redirecting flow through different paths, using the switches in the network. This algorithm can be used for mitigating small capacity problems. A typical situation can be that a new substation will be completed within a few years that would solve a capacity problem. In this case, a temporary solution is required until the substation is operational. Expanding the current network with costly cables for a temporary capacity problem is not a viable option. Mitigating the capacity problems by using the switches is more cost efficient in such a case.

The second algorithm is designed for longer planning horizons, where the electricity demand growth is so large that the addition of cables is inevitable. It incorporates the parameter dependent penalization method in simulated annealing. It aims to solve all capacity- and voltage problems against the lowest possible investment costs. The planning options are the switches in the network and the addition of new cable connections. Expert knowledge of Grond (2016) is applied to prevent impractical solutions and to achieve shorter algorithm running times.

Case study

Both algorithms were tested in a challenging, real life case study involving a large-scale, highly meshed Medium Voltage (MV) network in *(confidential)*. The MV network has a large size of 358 MV stations and 394 MV cable sections. The network contains 36 Normally Open Points (NOPs), showing how meshed the network is. The forecasts of peak loads for the year 2040 were used as an input for the algorithm. In case no action is undertaken by 2040, the sum of overloads on the cables is expected to be 1245 A. Table 1 shows the results of the best solutions found by the algorithms. The algorithm that incorporates cables as a planning options is run with and without an n-1 check.

Surprisingly, the first algorithm shows that the sum of the overloads on the cables can be reduced by 76.14% by only changing the position of the NOPs. The second algorithm solves all capacity problems in normal state by adding only one cable to the network and switching 42 switches. The length of the proposed cable is 5,261 meter. The expected total cost is *(confidential)*.

	Optimization using the switches	Optimization using switches and cables	Optimization using switches and cables (including n-1 check)
Amount of added cable(s):	0	1	7
Sum of the overloads on the cables (A):	297.06	0	0
Voltage exceedances (V):	0	0	0
Length new cable(s) in meters:	0	5,260.99	27,946.64
Number of switches turned on/off:	22	42	76
Total expected investment costs:	*(confidential)*		
Algorithm running time (HH:MM:SS):	00:11:35	01:01:43	03:57:57

Table 0.1 - Overview of the best solutions in the case study.

One of the design criteria concerns the possibility to reconfigure the network in case of a cable outage, this is called the n-1 principle. An n-1 check is extremely computationally expensive to execute. Luckily, simplifications are proposed in literature which we used to maintain manageable computation times. To make sure that the n-1 principle holds in 2040, we have to expand the network with seven new cable connections that have an expected length of 27,947 meters. The total length of the cables needed is 531% more compared to the best solution in which the n-1 check is not included. The expected total investment costs are then *(confidential)*.

Within the ‘Waardegedreven Assetmanagement’ team, we designed an application such that end users can easily apply the algorithms proposed in this thesis. We call this application ‘Netuitbreidingstool’. Figure 1 presents the optimized network (including an n-1 check) from within the application. The blue colored lines are new cable connections proposed by the SA algorithm as the best solution.

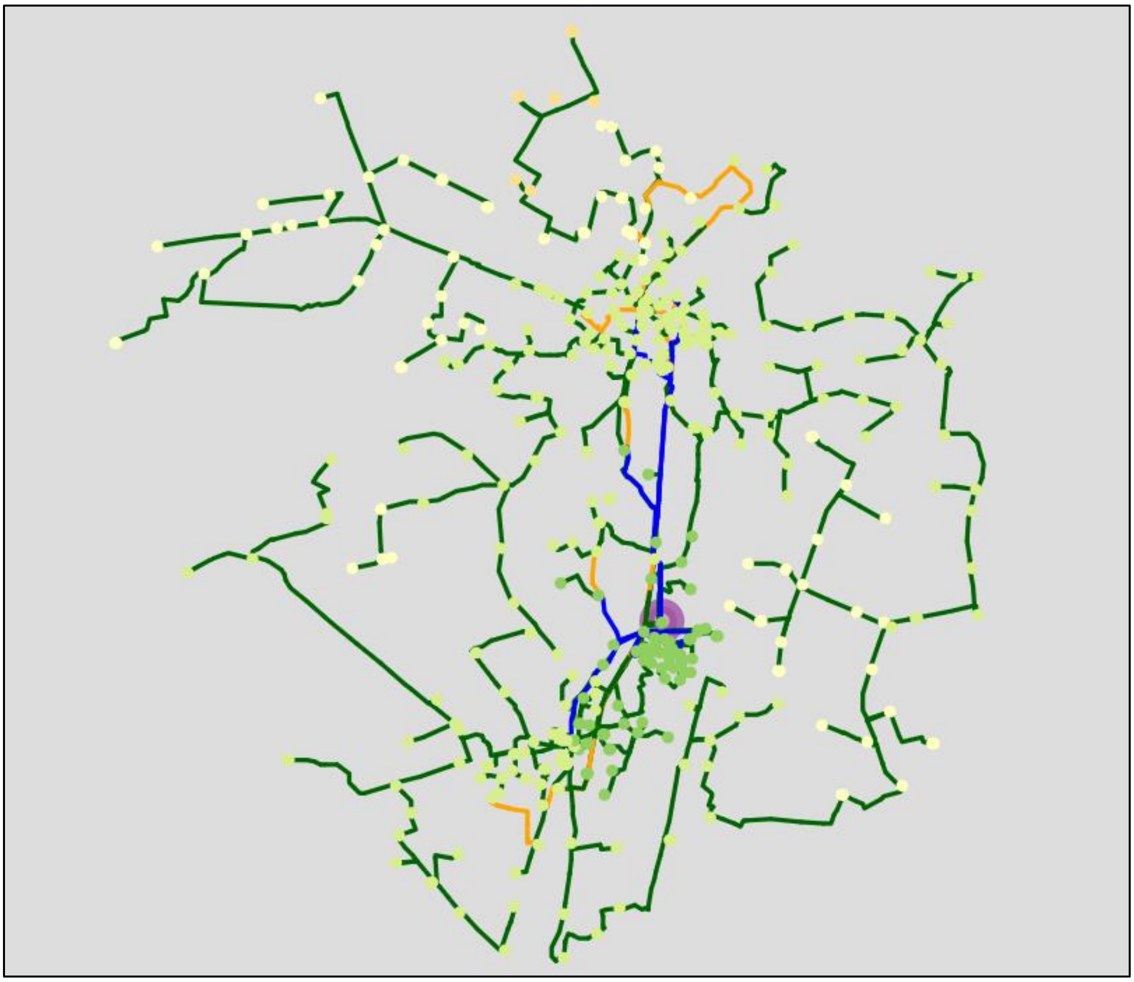

Figure 1 - Optimized network for the year of 2040, presented in the Netuitbreidingstool (anonymized).

Conclusions and contributions to practice and literature

We did experiments by running both algorithms multiple times. For the algorithm that only uses switches, 18 out of the 20 experiments came to similar solutions, while the other 2 deviated by a larger portion. The second algorithm that also considers cables was run ten times. 9 out of 10 experiments have similar results while 1 outlier was observed. Our experiments suggest that both SA algorithms find adequate solutions for large-scale, highly meshed MV networks in a reliable manner. Our contribution to literature is threefold. Firstly, we introduced a comprehensive and detailed solution approach to the distribution network expansion planning problem. Secondly, we employed the parameter penalization method in combination with SA for the first time to the distribution network expansion planning problem. Thirdly, we incorporated in our algorithm the fast load flow method recently developed by Van Westering, Droste & Hellendoorn (2019). As for the latter, note that the Newton-Raphson AC method is traditionally used to solve the load flow equations. This method is computationally expensive to apply within heuristic optimization methods.

Our contribution to practice at Liander is that we laid the foundation for an automated planning tool to solve distribution network expansion problems. Liander can use this to accelerate the process of finding alternative expansion strategies. We showed how the algorithms can be integrated in an application called 'Netuitbreidingstool' to make sure that the algorithms can be easily applied.

Future research

We recommend doing future research on the following topics:

- *n-1 principle:* We deem it worthwhile to conduct research into the approximation method by Grond (2016) for checking the n-1 principle to validate the results of Chapter 7. If the results are positive, the approximation can be applied in the second algorithm that uses cables as a planning option.
- *Consider larger parts of the network, with multiple feeder groups:* When considering multiple feeder groups at the same time, additional cable expansion options become available, such as connecting MV stations to neighboring networks.
- *Adding more planning options:* Research can be done to determine the benefits of incorporating future options such as storage systems.
- *Static versus dynamic models:* Consider the option to expand the models by adding a time dimension. The 'optimal' strategy can then be determined per time unit within the planning horizon. However, the trade-off is that the algorithm's running time will most likely rise.
- *incorporate power losses and breakdown time in the model:* Further research can be done to determine the benefit of extending the model by incorporating models for power losses and breakdown minutes.

Preface

This thesis is written in order to obtain my master's degree in Industrial Engineering and Management at the University of Twente. After an interesting period at Liander, I look back at a very pleasant time in which I learned a lot from many highly skilled professionals.

I want to thank my supervisor Peter Schuur who steered me in the right direction whenever it was necessary. I appreciate the meetings that we had in which you provided me with new input to continue the project, especially because this project has not always been easy. I would also like to thank Reinoud Joosten for his valuable feedback at a later stage of the project.

Furthermore, I would like to express my gratitude to my company supervisor Willem van Doesburg for giving me the opportunity to do a graduation project at Liander. I also appreciate our weekly meetings in which you gave me feedback that contributed to this thesis. Moreover, I would like to thank my colleagues of the 'Waardegedreven Assetmanagement' team for a very pleasant time and providing me with a lot of input for this project. I would also like to thank the other colleagues at Liander that contributed to this project in any way.

Last, I would like to thank my parents, girlfriend, brother, family and friends who all contributed in their own way. This thesis marks the end of a phase in my life and the beginning of another. As of September, I will continue working for Liander as a Data Scientist.

Stefan Jurriëns
Duiven, July 2019

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Glossary

Acronym	Explanation	Introduced on Page
DNO	Distribution Network Operator	1
HV	High Voltage	1
IV	Intermediate Voltage	1
MV	Medium Voltage	1
LV	Low Voltage	1
EV	Electrical Vehicle	2
PV	Photovoltaic	2
HP	Heat Pump	2
DG	Distributed Generation	2
PoC	Proof of Concept	6
AC	Alternating Current	7
DC	Direct Current	8
TSO	Transmission System Operator	10
NOP	Normally Open Points	15
GEP	Generation Expansion Planning	21
NEP	Network Expansion Planning	22
SEP	Substation Expansion Planning	22
RPP	Reactive Power Planning	22
SA	Simulated Annealing	23
TSP	Traveling Salesman Problem	24
GA	Genetic Algorithm	30
LODF	Load Outage Distribution Factors	30
MILP	Mixed Integer Linear Programming	33
KPI	Key Performance Indicator	61

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1 Introduction

This chapter introduces the research that was conducted in the framework of completing my master's study Industrial Engineering and Management. The purpose of this chapter is to introduce Liander, the challenges it faces and goal of this research.

Distribution Network Operators (DNO) are responsible for the operation and planning of a distribution network so that demand is continuously satisfied while meeting quality and security standards (Shahnia, Arefi, & Ledwich, 2018). DNOs in the Netherlands face challenging times as the current energy system is changing due to the energy transition (Nijhuis, Gibescu, & Cobben, 2015). As a DNO, Liander has to cope with these changes.

1.1 Liander

Liander manages the energy network that connects 3 million consumers and companies in the Netherlands. This energy network is used for the distribution of gas and electricity. As a DNO, Liander does not produce energy, energy producers do this. Liander operates in six defined regions: Amsterdam, Flevoland, Friesland, Gelderland, Noord-Holland and Zuid-Holland. Figure 1.1 visualizes the regions, where a distinction is made between 'Electricity and gas' areas and 'Electricity only' areas.

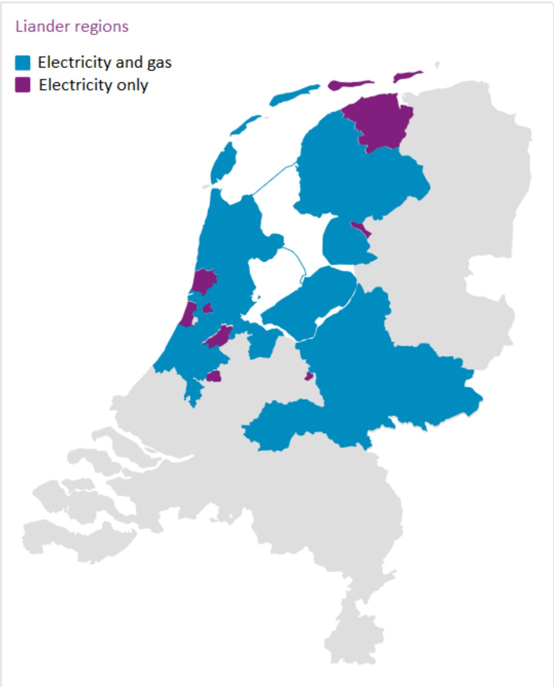

Figure 1.1 - Regions Liander.

In electricity networks, a distinction is made between High Voltage (HV), Intermediate Voltage (IV) Medium Voltage (MV) and low voltage (LV). HV and IV networks are used to transport electrical energy, while MV and LV networks are used to distribute electrical energy to customers. Liander is responsible for distributing electrical energy to customers, consequently its networks consist of MV and LV networks. Chapter 2.1 describes more about the structure of the electricity network.

Liander is part of Alliander that consists of a group of organizations. Their mission is to provide a reliable, affordable and sustainable energy supply that is accessible to everyone.

1.2 Problem description

The electrical network of Liander faces various changes, now and in the near future. On the demand side, a great increase of electrical power consumption is expected. On the supply side, sustainable power generation systems (distributed generation) are increasingly installed in the Liander region. Sustainable power generation is decentral and less controllable in comparison with classical energy generators (coal-fired power plants and nuclear power plants).

Demand side

The demand for electricity usually grows by a small percentage per year. Forecasting models show that this trend does not hold anymore in the near future. Liander has predicted the demand for electricity for the coming forty years. This includes the adoption of new technologies like Electrical Vehicles (EV), Photovoltaic (PV) and Heat Pumps (HP). A scenario forecasting approach is used to take into account uncertainties on the demand side. Three different scenarios are determined: low, basic and high scenario. Each scenario is equally likely to happen. These scenarios show a much higher increase in the demand for electricity than Liander is used to. The demand for electricity may rise by approximately two or three times the current demand in the coming forty years. The current system is unable to satisfy this growth.

The market for electrical vehicles is expected to increase, which has a major impact on the distribution network. In addition, the government of the Netherlands has the ambition that all households stop using natural gas by 2050 (Nieuwsuur, 2018). This shifts the demand from gas to electricity, because customers will likely purchase heat pumps instead of natural gas fired central heating. The adoption of these new technologies is a substantial driver for an increasing power consumption. This requires an electrical network that can transport much more energy than we currently have in the Netherlands.

To cope with the increasing demand for electricity, reinforcing the distribution network is inevitable. Options to improve the network capacity may consist of replacing cables, laying new cables, replacing transformers, installing new transformers. In addition, storage systems are planning options that may be used in the future, to level load on the networks. The expansion of the network require scarce resources. Liander is obligated by law to connect customers to the electricity network within a specific time limit. Because of this, the current workforce is forced to work on new connections at the expense of network reinforcements. The resource that is scarcest is therefore the availability of workforce. Given these limitations and a fast growing electricity consumption, Liander wants to ensure that the demand for electricity will be satisfied as much as possible.

Supply side

Other factors play a role such as the shift from centralized generation of electricity (e.g. coal-fired power stations) to distributed generation (e.g. solar panels and windmills). This changes the load profile on various parts of the electricity Network. Coal-fired power systems are controllable in the sense of meeting customer demand. When electricity consumption is high, more coal is burned to generate more electricity and vice versa. Distributed Generation (DG) such as solar- and wind parks are less controllable as the generation depends on weather conditions. When the supply of electricity is more than demanded, the voltage in a network may rise to levels that are undesirable. A goal of a DNO is to keep voltage between certain boundaries to ensure that connected devices are working properly. Wind- and solar parks are often connected to parts of the network that are sparsely populated. These networks often consist of cables with a smaller capacity, causing them to be overloaded rather quickly.

Problem cluster

Figure 1.2 presents a problem cluster to get a clear and structured view of the problems. The green box indicates the problem addressed in this study.

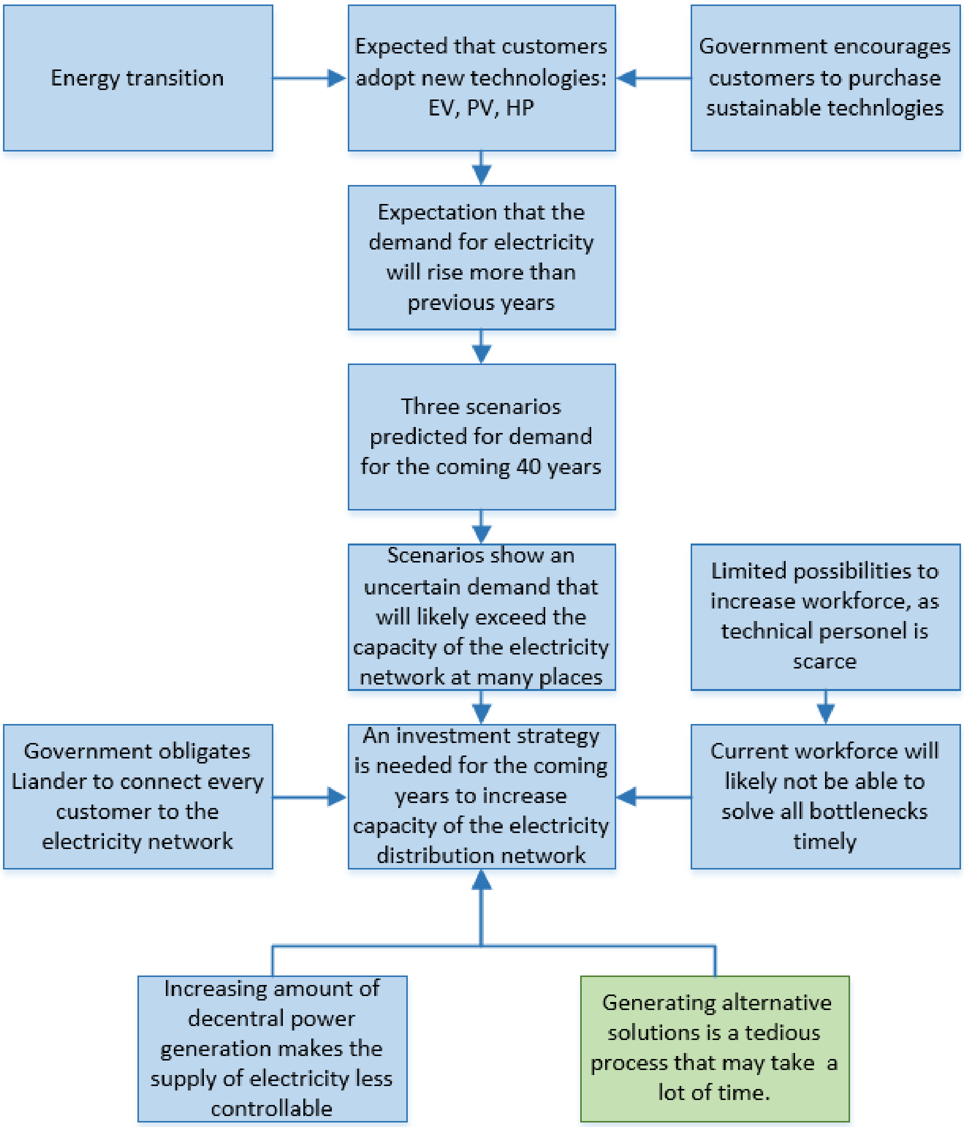

Figure 1.2 - Problem cluster.

An adequate investment strategy is needed to solve as many bottlenecks as possible with the resources that are available. The predicted demand for electricity is uncertain, decision makers should take this is into account.

In the current situation, network planners already identify and solve bottlenecks. The solutions are often custom-made and generated based on the experience of the network planner. This is often a time consuming process. The whole process of identifying a bottleneck to the decision to solve the bottleneck, may take up to half a year. Sometimes these solutions ask a lot of workforce capacity, which might not be available at the time. In this case, the project may be delayed. By the time that there is sufficient capacity, the situation may be different again. The rapid growth of electricity consumption requires a faster way of working.

The problem that we address in this study is the process of generating alternative solutions in an MV network. A decision support tool is needed to speed up this process.

1.3 Research design

This section discusses the goal of this study and the strategy to reach this goal. First, we describe the research goal and the research questions. After this, we describe the methodology and data collection methods per research question. Last, we describe an outline of this thesis.

1.3.1 Research goal

The goal of this research is to develop a model that supports Liander to make adequate decisions to the MV network expansion planning problem. The model should produce adequate investment decisions to solve bottlenecks in the MV electricity network. The model should also be tested on a real MV network.

1.3.2 Research questions

This section describes our strategy in solving the core problem. It contains the central research question and sub-questions that support this strategy.

Strategy

Our strategy is to first get acquainted with the problem by making an overview of different aspects of the problem. After this, we consult literature to find out what models can be used for this problem. Based on this, we develop models and try to implement it on a theoretical network. During this phase, we encounter knowledge problems of which most are answered using literature. When the results of the optimization model are positive, we implement it on a real MV network to see how it performs. In the end, we deliver a report with our findings and a proof of concept of the model that we develop.

Main research question

We formulate the following central research question:

'What is a model for generating adequate investment strategies to prevent capacity problems in medium voltage networks?'

Research questions

The following research questions help answering the central research question. The questions are explained in more detail. Section 1.3.3 describes the methodology and data collection methods for each sub question.

Sub question 1 – 'What is the context of the distribution network expansion planning?'

1.1 What are the basics of Alternating Current (AC) power networks?
1.2 How is the electricity grid structured?
1.3 How are capacity investments currently planned?
1.4 What are design criteria in distribution networks?
1.5 What planning options are available to increase capacity?
1.6 What are the objectives of distribution network planning?

The first sub-question is about gaining insight in the current situation. We start with some physical background in Alternating Current (AC) systems. After that, we examine the structure of the electricity network to become more knowledgeable about the subject. We will then look into the current planning process. Next, we discuss the design criteria of an MV-network. Last, we discuss the options that are available to increase capacity in the network, and the objectives in network expansion planning.

Sub question 2 – 'What approaches exist to distribution network expansion planning in literature?'

2.1 How can we categorize models for distribution network expansion?
2.2 What optimization models are generally used for distribution network planning?
2.3 How can we model a distribution network?
2.4 How can we evaluate the radial configuration constraint?
2.4 How are voltages on the buses and currents on the cables evaluated?
2.5 What is a good method to check the n-1 principle, such that we are able to use it in an optimization algorithm?

The main point of this question is to gather knowledge about the subject from literature. The categorization of choices that can be made in distribution network planning is first researched. After this, we look at the optimization models that can be used. Some design criteria are straightforward to check. Other criteria are more complex and need more considerations, especially when the goal is to check them in an optimization algorithm. The voltages on the buses should be within a specific width and the currents on the cables should be below a limit. We research methods in literature to check these constraints efficiently. One of the constraints concerns the possibility to reconfigure the network in case of an cable outage. This is called the n-1 principle, which we further discuss in Section 2.4.4. Checking the n-1 principle is a computationally expensive task and therefore more knowledge is needed on how to check this within optimization algorithms.

Sub question 3 – 'To what extent are metaheuristics, such as simulated annealing, able to be applied on the distribution network planning problem?'

3.1 To what extent can we solve bottlenecks by changing the configuration of the network?
3.2 To what extent can solve bottlenecks by adding cables as a planning option?

After consulting literature, we decide which optimization algorithm is used to optimize an MV network. This question is about implementing the chosen algorithm. This is done for two planning options; changing the configuration of a network and adding new cable connections.

Sub question 4 – 'How does the optimization model perform on a real MV-network?'

A case study will be performed where we look at a specific part of the electricity network that will have bottlenecks in the future without investments. The models that are developed are tested on this case by using the forecasts of future demand.

1.3.3 Methodology and data collection

This section discusses methodology and data collection methods to answer the aforementioned sub-questions.

Sub-question 1: *'What is the context of the distribution network planning?'*

Data about the current situation will be collected by interviews with experts. Other materials are available such as policy documents to expand distribution networks. A book 'Phase to Phase' by Van Oirsouw (2011) is available that describes how distribution networks are established in the Netherlands. Moreover, it describes the structure of the electricity network.

Sub question 2 – 'What approaches exist to distribution network expansion planning in literature?'

The data for this question will be collected by means of a literature study.

Sub question 3 – 'To what extent are metaheuristics, such as simulated annealing, able to be applied on the distribution network planning problem?'

To answer this question we use the input of the literature study to make decisions about how can model the problem. We start by modelling a small theoretical network in Rstudio. A metaheuristic approach is used to expand the overloaded theoretical network. From here, we expand the model by adding more complexity, such as evaluating more design criteria and adding expansion options to the model. To evaluate the design criteria, we also need the input of literature. When the models perform properly on the theoretical case, we move on to the next question, in which we test the models on a real network as a case study.

Sub question 4 – 'How does the optimization model perform on a real MV-network?'

Data should be collected of all variables that were used in the developed models. Interviews with data scientists will be held to find out which internal databases can be used. In case there are data missing, we make an estimate or a reasonable assumption. The data is then fitted into the theoretical models that we develop. The help of internal data scientists will be asked to develop an application, in which the proposed algorithms are running on a real case. The results are discussed with internal experts.

1.4 Scope

The following restrictions apply for this research:

- We restrict ourselves to MV networks.
- Demand forecasting is not the scope of this thesis. As explained in the problem description, another team works on demand forecasting. The focus will be on a tool to generate adequate (feasible) solutions to expand the MV network.
- The scope of this thesis is the network expansion problem. Station expansion is not part of this thesis.
- This research focusses on the expansion of existing MV networks. Greenfield planning is not the scope of this research.

1.5 Deliverables

The deliverables are:

- A Proof of Concept (PoC) that consists of the optimization method tested on a real case.
- A thesis that supports the decisions made in developing the PoC.
- An overview of the topics that can be further researched to expand the model.

1.6 Outline thesis

In Chapter 2, we give an overview of the basics for the expansion planning in medium voltage networks. In Chapter 3, we discuss the literature that was used to answer the knowledge problems that we encountered during this research. Next, we describe a 'mixed integer linear programming' approach that we initially started with in Chapter 4. Chapter 5 describes the selected local search method 'simulated annealing' as an optimization method. We expand the model in Chapter 6. In Chapter 7, checking the n-1 principle will be revisited. The algorithms developed in this thesis are tested on a real case in Chapter 8. Last, Chapter 9 discusses the conclusion and recommendations for future research.

2 Expansion planning in medium voltage networks

In this chapter, we explore the current situation to better understand the subject. In Section 2.1, we start with the physical background to get a basic introduction to electrical engineering aspects. Section 2.2 discusses the basic structure of the electricity network to obtain an overview of the whole system. After this, we discuss the current planning process to expand the MV network in Section 2.3. In Section 2.4, design criteria in MV networks are discussed. In Section 2.5, we discuss expansion options in an MV network. We discuss the objectives in distribution network expansion planning in Section 2.6. Last, a conclusion is given in Section 2.7.

2.1 Physical background

The aim of this section is to introduce a basic physical background to better understand the electrical distribution system. Most of the information can be found in the book '*Netten voor distributie van elektriciteit*' by Van Oirsouw (2011). We will describe some variables that are used in electrical engineering. In addition, equations for both voltage and current in Alternating Current (AC) systems are given. Last, we describe why we distinguish three different types of power in an AC system.

In an electrical distribution network, real power (P) is distributed from bus (node) to bus. The power flows through a cable that has a resistance (R). A current (I) flows through the cable that is caused by a voltage difference (ΔU). This gives us the variables listed in Table 2.1.

Quantity	**Unit**
Voltage (U)	Volt (V)
Current (I)	Ampère (A)
Resistance (R)	Ohm (Ω)
Real power (P)	Watt (W)

Table 2.1 - Basic variables in electrical engineering.

Two basic principles are Ohm's law and Joule's law, which are represented by the following equations:

Ohm's law: $\Delta U = I * R$ (2.1) Joule's law: $P = \Delta U * I$ (2.2)

Alternating Current

The electrical distribution system is a three-phase network that uses Alternating Current (AC). AC is an electrical current that periodically changes direction. The voltage and current can be described by a function of time. The voltage can be described using the following equations:

$U(t) = \hat{u} * \cos(\omega t + \psi_u)$

in which:

$\hat{u}$ is the maximum of the voltage

$\omega = 2\pi f$, which is the angular velocity in (rad/s) (2.3)

f is frequency in Hz

ψ_u is the voltage phase angle (rad)

t, time (s)

The equations for the current in AC systems is described similarly:

$I(t) = \hat{\imath} * \cos(\omega t + \psi_i)$

in which:

$\hat{\imath}$, the maximum of the current

$\omega = 2\pi f$, the angular velocity in (rad/s) $\quad (2.4)$

f, frequency in Hz

ψ_i is the current phase angle (rad)

t, time (s)

When a voltage difference exist between two connected buses, a current flows from one bus to another. The voltage difference triggers a current to flow. In Direct Current (DC) systems where voltages and currents are constant, real power (p) can be easily calculated by applying Joule's formula.

This is different for AC systems. It takes a fraction of a second for a current to flow from a bus to another. This is caused by an impedance Z in the cable. The current follows the constantly changing voltage with a small delay, also referred to as a phase difference. Note that instead of the resistance, we are interested in the impedance of the cable. In AC systems, the resistance has an additional component called the reactance (X). The reactance is caused by a changing magnetic field in AC systems.

To illustrate this effect, consider Figure 2.1 and Figure 2.2. Both figures show a voltage and a current in an AC system (which can be described by equations 2.3 and 2.4). Figure 2.1 considers the power through a system with a pure resistance, meaning that there is no phase difference. The current immediately follows the voltage and therefore real power can be calculated using Joule's law at each moment in time. In MV networks, we are most of the time interested in the average real power.

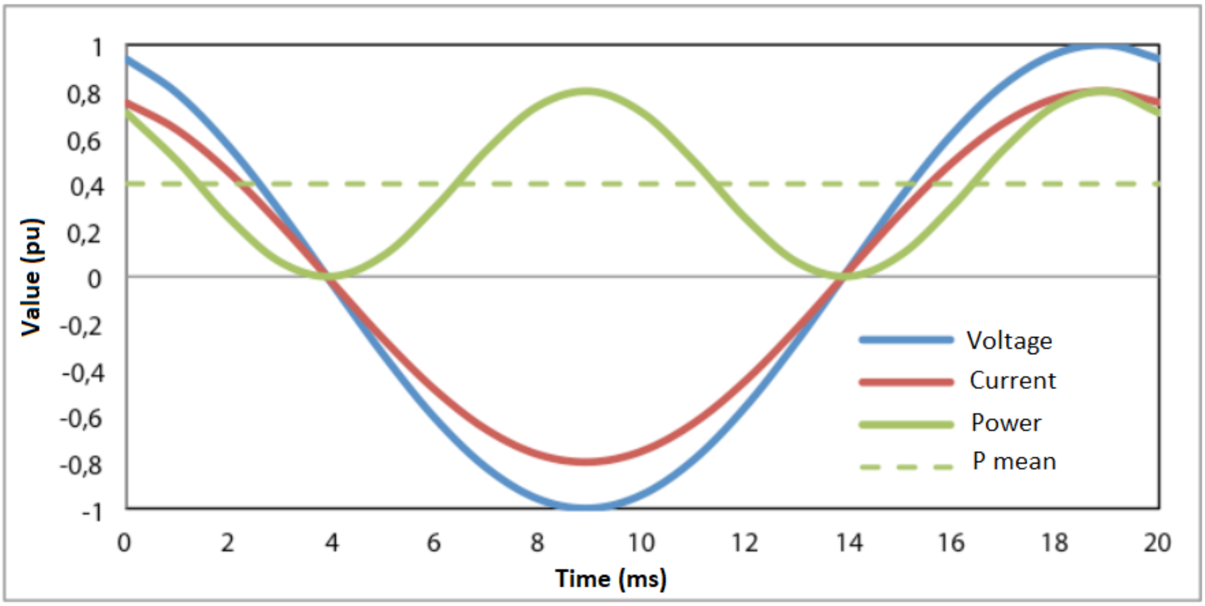

Figure 2.1 - Voltage and current without a phase difference, adapted from Van Oirsouw, (2011).

Figure 2.2 assumes an impedance that causes a phase difference with a phase angle of 45 degrees. Comparing this to the current in Figure 2.1, we see that the current is lagging behind the voltage.

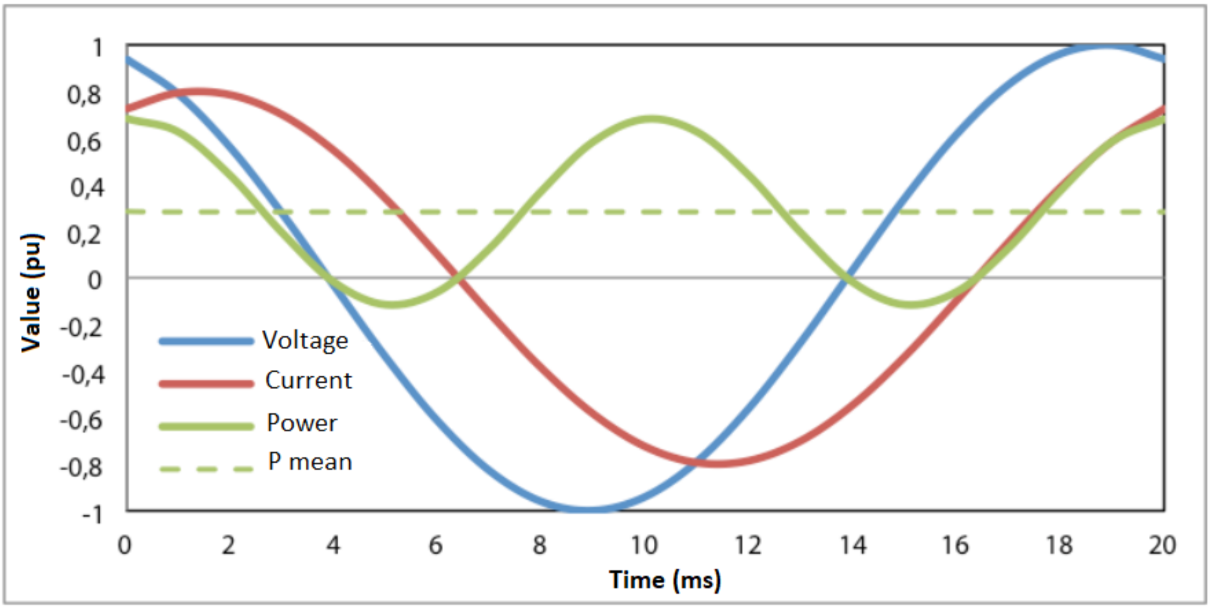

Figure 2.2 - Voltage and current with a phase difference, adapted from Van Oirsouw, (2011)..

Due to this phase difference, the average real power is lower than in the situation without the phase difference. The mean power is the average of the real power over time, measured in Watt (W). It can be calculated using the following equation:

$$P = U_{eff} * I_{eff} * \cos(\varphi) \tag{2.5}$$

in which φ is the phase of voltage relative to the current. The effective value for both the voltage and current can be calculated using the root mean square. For a sine wave this means that the effective value is $\sqrt{2} * maximum\ value$.

The product of the effective value of the current and voltage is called the complex power and measured in Volt-Ampere (VA). This is the following equation:

$$S = U_{eff} * I_{eff} \tag{2.6}$$

We can also calculate the reactive power (Q), the part of the power that cannot be used to deliver power to customers. This is the following equation:

$$Q = U_{eff} * I_{eff} * \sin(\varphi) \tag{2.7}$$

Often, real power (P), reactive power (Q) and complex power (S) are presented in a complex plane. This is shown in Figure 2.3.

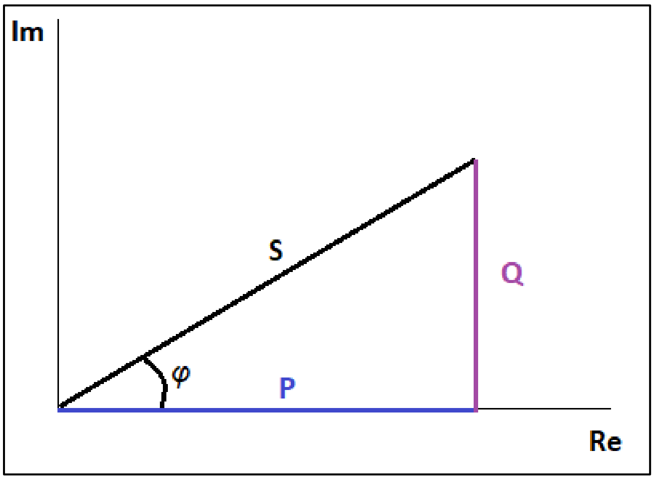

Figure 2.3 - Real power (P), reactive power (Q) and complex power (S) in a complex plane.

The plane describes a real part (x-axis) and an imaginary part (y-axis). The real power is presented on the x-axis, while the reactive power is parallel to the y-axis. The diagonal between the two is the complex power. The angle between S and P is φ.

Some additional variables were introduced and are summarized in the following table:

Quantity	Unit
Reactive Power (Q)	Volt Ampère reactive (var)
Complex power (S)	Volt Ampère (VA)
Phase of voltage relative to the current	φ
Impedance (Z)	Ohm (Ω)
Reactance (X)	Ohm (Ω)

Table 2.2 - Additional variables.

In this section, we discussed concepts that are used in AC systems. In the next section, we consider the structure of the electricity network in the Netherlands.

2.2 Structure of the electricity network in the Netherlands

The network in the Netherlands can be divided into two parts: a transmission network and a distribution network. A graphical representation of both networks is shown in Figure 2.4. Electricity is generated at central power stations such as coal-fired power stations or decentral by for example solar- and wind parks. The electricity is transported over longer distances by the transmission network. The transmission network in the Netherlands is managed by Transmission System Operator (TSO) TenneT. The distribution network is managed by several Distribution Network Operators (DNOs), of which Liander is one. The main difference of both networks is the goal they aim to achieve. Transmission networks have the goal to transport electricity over longer distances as opposed to the distribution network. The distribution network has the goal to distribute electricity to customers. The green dotted line in Figure 2.4 shows were the network is divided into the transmission- and distribution network.

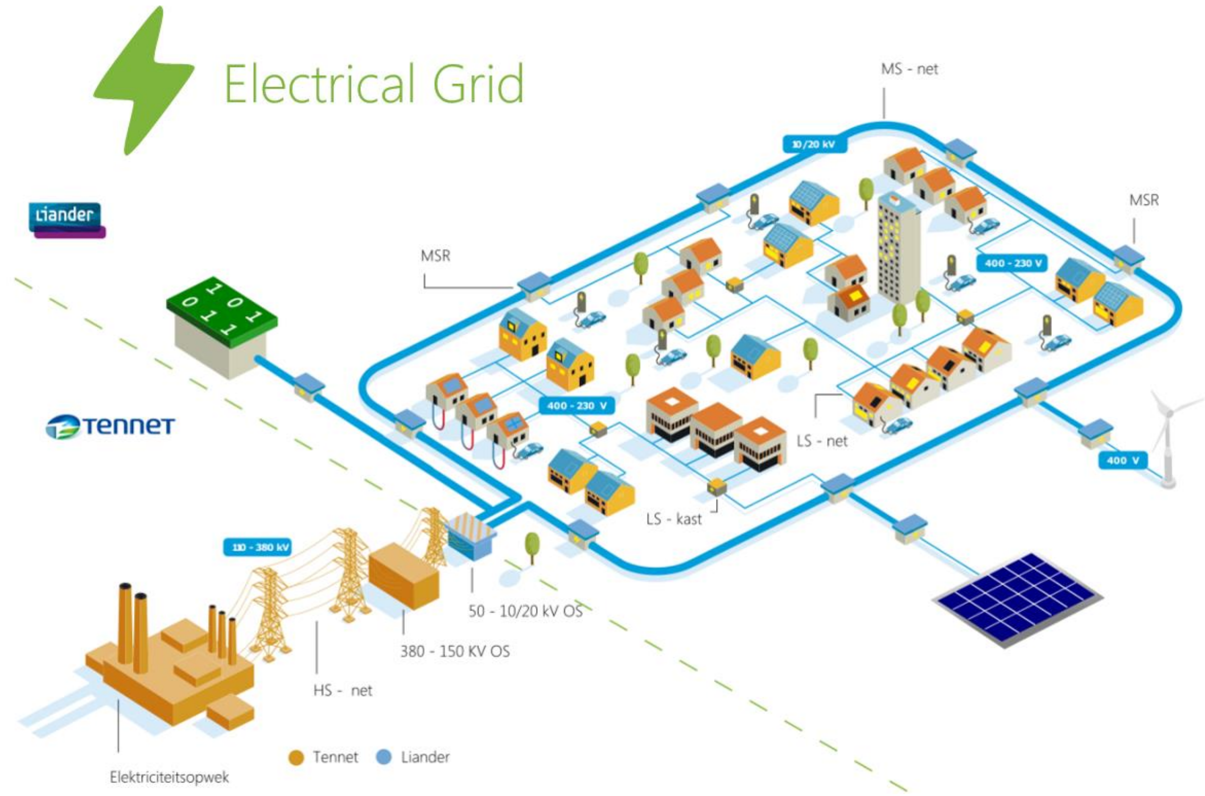

Figure 2.4 - Graphical representation of the electricity network (internal source).

From the coal-fired power stations to the households, different levels of voltages are used. In general, the higher the voltage, the more electricity that can be transported through the network. Along the way to the customers, voltages are transformed into lower levels of voltages. This is done by transformers, which are placed at stations. The green dotted line in Figure 2.4 has a substation that connects the transmission network to the distrbution network. At a substation, electricity is transformed from High Voltage (HV) or Intermediate Voltage (IV) to Medium Voltage (MV). Some customers that have a large power consumption or generation are directly connected to the MV network. Examples are data centres, large industries and winds/solar parks. Other customers, such as households, need lower levels of voltages. The MV network contains MV/LV substations that contain transformers to transform the MV into Low Voltage (LV). From here we will abbrevitate MV/LV substation to MV station.

Four categories of voltages exists, which are presented in Table 2.3.

Category	**Voltage level**	**Managed by (in the Netherlands):**
High Voltage (HV)	kV ≥ 110	TSO TenneT
Intermediate Voltage (IV)	20 < kV < 110	TSO TenneT
Medium Voltage (MV)	10 ≤ kV ≤ 20	DNOs, such as Liander
Low Voltage (LV)	230 ≤ V ≤ 500	DNOs, such as Liander

Table 2.3 - Voltage categories.

A schematic overview is presented in Figure 2.5. The interlocking rings represent the transformers.

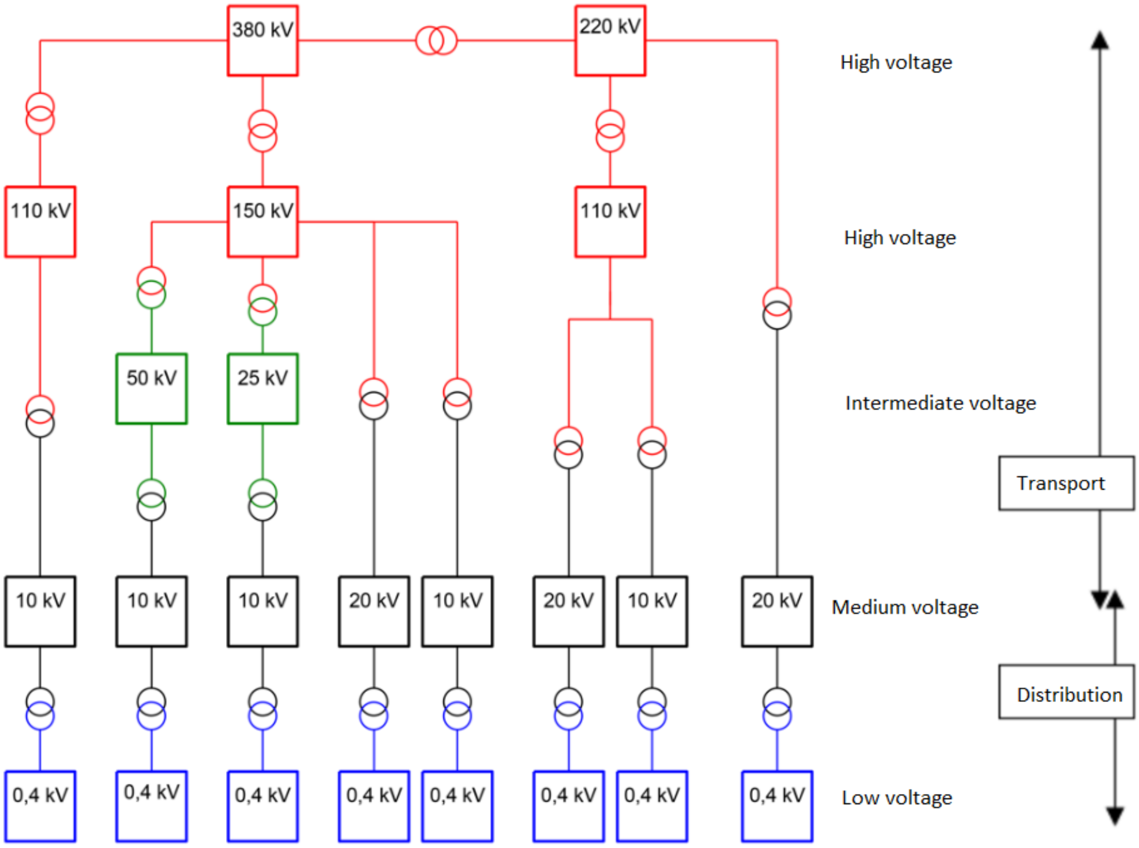

Figure 2.5 - Schematic structure of the electricity network (Van Oirsouw, 2011).

Control station (regelstation in Dutch)

When electricity travels over longer distances, around 10km or more, the voltage of the electricity drops below a minimum required level. A control station is a station that is able increase the voltage level to the required level.

In this research, we focus on the MV network. Besides substation, control stations and MV station, other net components may be present in a MV network. Some are not directly relevant for this thesis, while others will be discussed when they are relevant.

Connection categories

The different types of customers are categorized based on the expected power that they are planning to use. Liander classifies the customers in categories AC1 to AC7, as shown in Table 2.4. Based on the categories, the type of connection is determined.

Category	Capacity	Network	Type of connection
AC1-OV	1x6 A	LV	Branch of the switched LV network.
AC1	3x25 A	LV	Branch of the LV network.
AC2a	35 - 50 A	LV	Branch of the LV network.
AC2b	63 - 80 A	LV	Branch of the LV network.
AC4a	>80 - 100 kVA	MV/LV	Separate connection from a feeding point
AC4b	>100 - 160 kVA	MV/LV	Separate connection from a feeding point
AC5a	160 - 630 kVA	MV	Connection to the MV network without transformer.
AC5b	630kVA - 1 MVA	MV	Connection to the MV network without transformer.

AC5	1MVA - 2 MVA	MV	Connection in the MV network without transformer.
AC6a	2 MVA - 5 MVA	IV- or HV/MV	Separate connection from a substation.
AC6b	5 MVA - 10 MVA	IV- or HV/MV	Separate connection from a substation.
AC6c	> 10 MVA	IV- or HV/MV	Separate connection from a substation.
AC7	> 10 MVA	IV	Separate connection from a substation (50kV).

Table 2.4 - Connection types (internal source).

2.3 Current planning process

This section describes the current planning process that is used by Liander. The process consist of the following primary processes:

1. Identifying bottlenecks.
2. Determine the risks and opportunities.
3. Generate alternative solutions.
4. Construct portfolio.
5. Portfolio realization.

The current asset management process that is used by Liander is visualized in Figure 2.6.

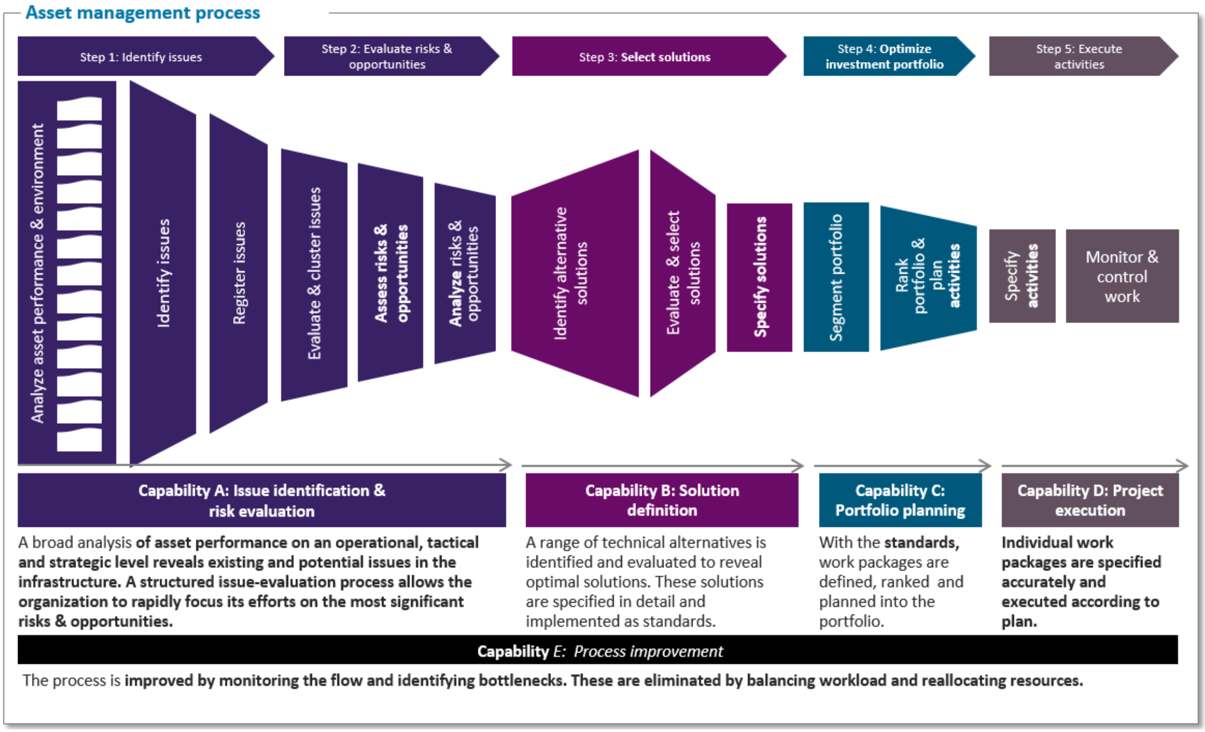

Figure 2.6 - Asset management process (internal source).

The primary steps are briefly described.

Step 1: Identifying bottlenecks

Multiple sources of information are used as input for identifying bottlenecks. A proactive approach is used by forecasting demand. New technologies like EV, HP and PV are included in the forecast. The future state of the assets are determined by solving load flow equations, which will be described more in Section 3.5. When solving the load flow equations, the voltages and currents in a network can be estimated. This is needed to determine the future bottlenecks. When the bottlenecks have been identified, the risks and opportunities are described.

Step 2: Determine the risks and opportunities
The goal of this step is to uniformly estimate the risk of bottlenecks. First, the bottlenecks are validated and checked whether the bottlenecks are asset related. When possible, the bottlenecks are clustered with bottlenecks that are similar. When the information is complete, the risk is estimated by a Risk Expert Panel (REP) and registered in a bottleneck register. A risk-owner will be appointed that is responsible for taking actions.

Step 3: Generate alternative solutions
Network planners generate solutions to solve the bottlenecks. While generating solutions certain technical constrains must be taken into account as well as standardized design choices. Standardized design choices may consist of the use of only 10/20 kV assets (e.g. cables). These rules are described in a policy document. Technical constraints such as voltage drops and capacity bottlenecks can be calculated in a software package called Vision. This program can also check whether the n-1 principle still holds in the new situation. More about these design criteria in Section 2.4. Once a number of possible solutions are generated, they are judged by four criteria:

1 To what extent risk is reduced.
2 Robustness of the solution given the uncertainty of the load forecast.
3 How future proof the applied technology is.
4 Optimal social cost development.

Currently this process step takes a while because the alternatives are generated manually. Generating alternatives is a complex and tedious for DNOs, especially when there are multiple bottlenecks and long planning horizons (Grond, 2016).

Step 4: Construct portfolio
In this step, the goal is to generate an overview of all bottlenecks and risk mitigating actions. The actions are then prioritized and a plan is made for executing the project.

Step 5: Portfolio realization
This step is about the realization of the mitigating actions. The service providers should be managed such that projects are executed timely and within budget

2.4 Design criteria in medium voltage networks

Liander uses guidelines to design MV networks that are described in a policy document. Grond (2016) describes design criteria based on the international standards. We use these criteria. In addition, we consulted internal experts, which resulted into one additional Liander specific design criterion. Below an overview of the criteria is given. Criteria 1, 2, 4 and 5 are from Grond (2016), while criterion 3 is Liander specific.

First, we give an overview of the design criteria. Next, we explain each criterion in more detail. We have the following criteria:

1. Voltage constraint: At each bus, the voltages should be within specific boundaries.
2. Current on the cables: The currents on the cables should not exceed a specified limit.
3. ΔU constraint: DNOs often design a network based on a high- and low load in case of a network with distributed generation. The voltages on the nodes should not be apart more than 7% between the two situations.
4. Radial operation: The network should be operated radially. This means that each bus is fed by only one cable.
5. The n-1 principle: The cables should have sufficient capacity to carry additional loads in case a cable breaks. This is also referred to as the n-1 principle, see Section 2.4.4.

2.4.1 Voltages and currents

Devices connected to the electricity network are designed to function under specified voltages and currents. When voltages and currents are not within the specified limits, devices connected to the grid will age faster (Van Oirsouw, 2011). This is also true for the network components. When designing a network, we are interested in the currents on the cables and the voltages on the buses. When the current on a cable is too high, it heats up due to the resistance of the cable. The cable's temperature is linked to its lifetime. Higher cable loading leads to a faster deterioration of the cable. Therefore, a limit is used that determines the loading of cables in currents. This may be different for different types of cables. The voltages are measured on the endpoints of the cables. In 10 kV networks, voltages at the buses should remain between 9.7 – 11.1 kV.

2.4.2 ΔU criterion

In network expansion planning, the peak loads are often of most interest, as the network should be able to handle the worst-case scenario. In networks with distributed generation, two scenarios have to be considered. The two scenarios are called the high load and low load. The scenarios consists of the following composition of load and generation.

High load: 100% load, 0% generation.
Low Load: 25% load, 100% generation.

When the voltages are measured under both scenarios. The voltage difference for each bus should not deviate more than 7%. The following equation should therefore hold:

$$\frac{U_{high} - U_{low}}{U_{nom}} \leq 0.07, for\ each\ bus, \tag{2.8}$$

where U_{high} is the voltage under high load, U_{low} is the voltage under low load and U_{nom} is the nominal voltage of the network.

2.4.3 Meshed structure, operated radially

MV networks can have different structures. An MV network can have a meshed, a radial structure or both. Figure 2.7 presents the structures. The purple dot in the middle represents a substation that feeds the networks. It delivers electricity to MV stations in these examples. The flags represent Normally Open Points (NOPs), which we explain below.

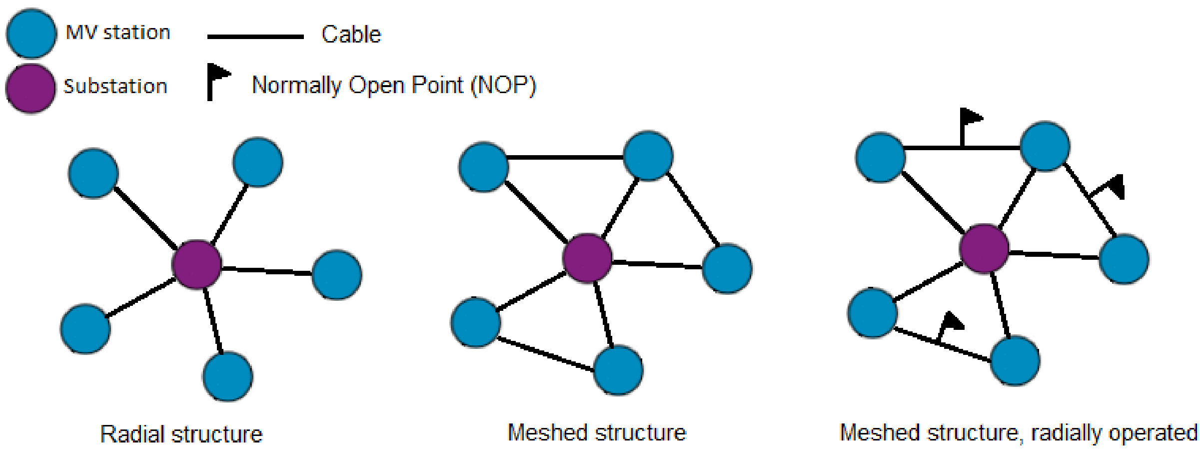

Figure 2.7 - Radial and meshed structure.

In a radial structure, every MV/LV transformer is fed by only one connection. Contrary to this, an MV/LV transformer can be fed by multiple connections in a meshed structure. In case a cable breaks, a radial structure is more fragile as there is no other cable connection that can feed the MV/LV transformer. The underlying MV/LV transformer will not have power until the cable is replaced/repaired. Meshed networks do not have this problem, but it is harder to identify which cable is broken in case of an outage.

Liander designed their network in such a way that it has a meshed structure, but it is operated radially. This is achieved by creating Normally Open Points (NOP) in the network. A NOP is a cable that is disconnected by a switch in a normal situation such that every MV/LV transformer is fed by only one connection. This makes sure that the meshed network is operated radially. This also creates the possibility to reconfigure the network. The network that results from a set of open and closed switches is called a *configuration*.

The reason why Liander designed their MV network this way is that the advantages of both structures are utilized. The failure of a cable is identified faster due to the radially operated network. In addition, in case a cable failure occurs, a different configuration can be used in which the broken cable is not included. To open or close a switch, a technician drives to the MV station to manually open or close the switch. A disturbance can therefore be solved relatively quickly. Solving disturbances in a radial network tend to take much more time to solve, as the underlying MV/LV transformer is only operational after the cable is repaired or replaced.

2.4.4 The n-1 principle

The medium voltage network has to satisfy the n-1 principle. Fritschy (2018) defines the n-1 principle as following:

‘*If an outage in a cable in the MV network appears, the MV network can be switched into another configuration not using the damaged cable in such a way that every customer can be provided electricity*’

To this, we add that the same holds for transformers at substations. In a substation, additional HV/MV transformers are placed to satisfy demand when another transformer fails.

To demonstrate the principle, consider Figure 2.8 below. An MV network with three MV stations is connected by two transformers to the HV network. The two transformers are both located at a substation. Three MV stations with MV/LV transformers (numbered 1 to 3) are connected in a meshed way. Each MV station has an underlying LV network, which we left out as we only consider the MV network. The diamond shaped icons are switches that can be opened or closed. If a switch is open, no electricity can flow through the cable that attaches to the switch. If a switch is closed, electricity can flow through the cable.

The flag between MV station 1 and 2 represents a NOP, which disconnects the cable in the normal configuration between MV station 1 and 2. Power flows from the transformers to MV station 1 and 3. It also flows through MV station 3, to supply MV station 2.

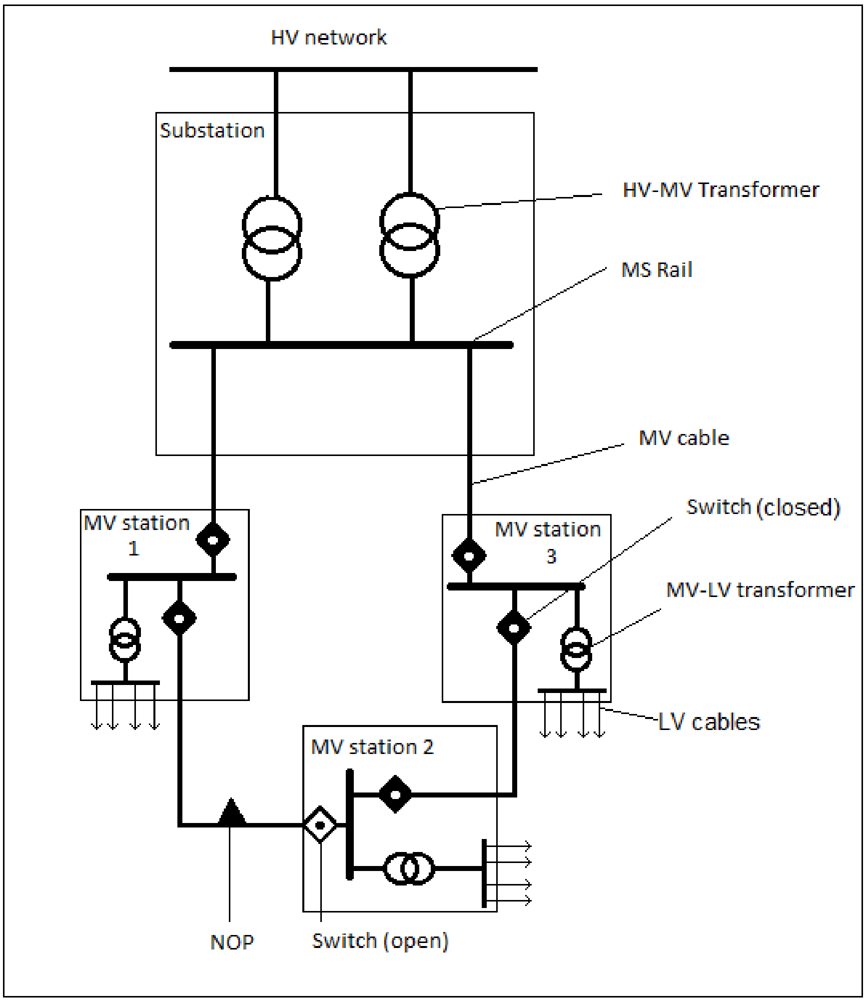

Figure 2.8 - The n-1 principle in an MV-network.

This situation satisfies the n-1 principle. When one transformer fails, the other transformer at the substation is able to take over the load, preventing major disturbances in the MV stations underneath. When the cable between the transformers and MV station 1 breaks, the switch at MV station 2 will be closed. This creates a new configuration in which power flows through MV station 3 and MV station 2 to supply area 1. The cables between the substation, MV station 3 and MV station 2 should have enough capacity to also supply MV station 1 in an n-1 situation. The same principle holds for all other cables in the MV network.

2.5 Objectives of the network expansion problem

This thesis focusses on solving capacity problems against the lowest possible investment costs. In practice however, there are more reasons to expand the network. Besides the investment costs of adding new assets to the network, we have operational costs. Operational costs consist of maintenance, management, failure and power losses costs. Power losses are a substantial part of the operational costs (Van Oirsouw, 2011).

2.6 Expansion options to solve bottlenecks

This section describes the expansion options that we identify to mitigate the effects of increasing peak loads through the distribution system. A strategy can be to increase the grid capacity by adding components such as transformers or cables. A different strategy can be to place storage systems in the network that can reduce peak loads through the system.

Adding transformers to the network
When transformers are overloaded, we can choose to install a new transformer. The transformers Liander uses in MV networks are standardized and have capacities of 250, 400, 630 or 1000 kVA. In practice, an MV station is installed in such a way that the transformer is able to be replaced by a transformer that is one tier higher in capacity than the current one. The process of transformer expansion is straightforward (Grond, 2016). In case a transformer has reached its capacity, it can be replaced by a transformer with a higher capacity once. The used transformer can be used elsewhere. If the option to replace the transformer is not available, a new MV station has to be installed. Note that the expansion of transformers is not the scope this thesis.

Adding cables to the network
In Table 2.5, the standard types of cables that are used when expanding the MV network are presented. The first cable is used for 10kV MV networks while the other cables are used for both 10 kV and 20kV networks. Each type has a different capacity that is measured in amperes. Each cable has a variable price per meter that is used for estimating the total cost of new cables. In addition, the cables have an assumed constant resistance (R) and constant reactance (X), measured in Ω/km. The reactance is an additional component to the resistance that are present in AC systems. The resistances are important to take into account when determining the voltages and currents in an electrical distribution system.

Cable type	Capacity (A)	Costs per meter (€)	R (Ω/km)	X (Ω/km)
10 kV 3 x 95 mm^2 Al rm + as 50 mm^2 Cu	215	*(confidential)*	0.411	0.102
20 kV 3 x 240 mm^2 Al rm + as 50 mm^2 Cu	360		0.162	0.098
20 kV 3 x 1 x 630 mm^2 Al rm + as 50 mm^2 Cu	575		0.063	0.1

Table 2.5 - Capacities of standardized cables in an MV-network.

Note that all three types of cables are actually three cables combined, as electrical distribution systems are three phase AC systems. The first two types are three cables combined to one cable, while the last type are three separate cables that are parallel to each other.

We also note that the capacity constraints are guidelines and a cable does not instantly break when exposed to a small exceedance of capacity for a short period. Sometimes a different capacity is chosen for n-1 situations. One could decide for what period of time an exceedance is accepted. A factor that should be taken into account is the effect of warm cables heating up the sand around it. If the sand is heated up for longer periods, it dries up, and dry sand heats up faster.

Expanding the network by adding cables and transformer expansion can be seen as two isolated problems (Grond, 2016). Transformer expansion is straightforward in practice and the number of standardized transformers is limited.

Practical cable expansion options are visualized in Figure 2.9. More about why these options are practical in Section 3.7. The following practical options are available:

1. In general, the first option generates a lot of capacity. A cable is added from the substation to an MV station. NOPs have to be added to make the configuration radial again (Option 1 in Figure 2.9).
2. The second option is to replace a current cable by a cable that has more capacity (Option 2 in Figure 2.9).
3. The third option is to connect one or more MV stations to a neighboring substation. New NOPs have to be placed to make the solution radial again (Option 3 in Figure 2.9).

4. The fourth option is to transfer MV stations to a neighboring feeder group by connecting them with a new cable. NOPs are placed to create a radial configuration. This option is applied only in specific cases (Grond, 2016). This is Option 4 in Figure 2.9.

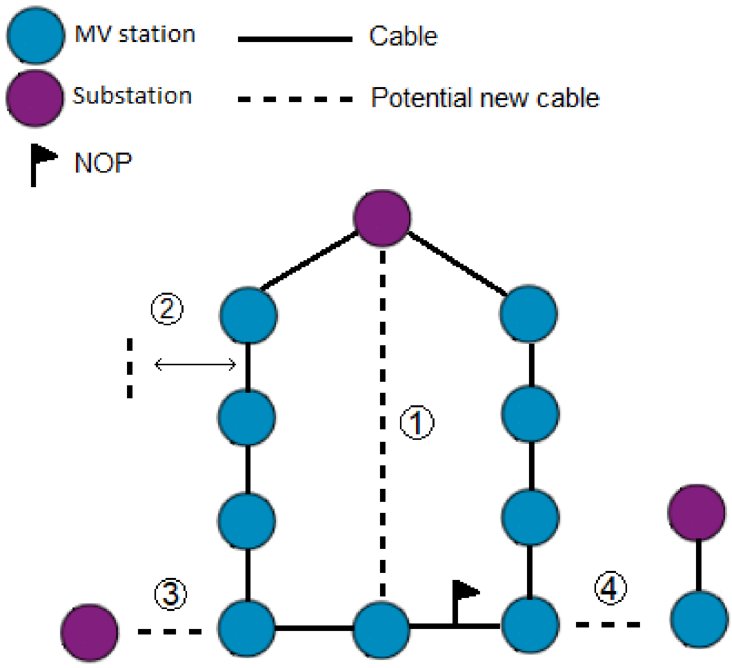

Figure 2.9 - Practical expansion options (adapted from Grond (2016)).

Switch to another configuration
We have discussed how NOPs are placed in the network to create a radial configuration of the network (in Section 2.4.3). Using a different set of NOPs, we can try to redirect power flow through cables that have enough capacity left.

Future options
Adding transformers and cables are both options that increase capacity of the network. As noted in the introduction of this chapter we could also apply a different strategy which aims to better match supply and demand. An option could be to install storage systems which reduce the variability of power flow through the system. When electricity usage is low and generation is high, a storage system can be used to store the excess power from the network and reduce voltage problems.

2.7 Conclusion
In this chapter we described the fundamentals of the MV network expansion planning problem. We discussed the physics in AC systems, the structure of the electricity network in the Netherlands and the current planning process to solve bottlenecks. We also discussed the design criteria of an MV network and the objectives of expansion planning in MV networks. Last, we discussed the expansion options that are available to expand the current network.

In the next chapter, we examine literature to answer the knowledge problems that we encountered during the development of our models.

3 Literature review

In this chapter, literature is gathered to answer knowledge problems. First, we aim to create a better understanding of network expansion problems by categorizing the models in literature. We will then research what optimization models can be used and describe Simulated Annealing (SA) in greater detail in Section 3.2 and 3.3. After this, we search for literature that can assist us modelling a network and checking the design criteria of MV networks. This consists of graph theory, power flow methods and checking the n-1 principle. This will cover Sections 3.4, 3.5 and 3.6. An overview of applied expert knowledge to prevent impractical solutions is discussed in Section 3.7. Last, the conclusion is given in Section 3.8.

3.1 Categorization of distribution network expansion planning models

This section provides an overview of the choices that can be made in power system planning and is based on the work of Grond (2016). Grond (2016) presents an overview of the scope of power system planning models, which is shown in Figure 3.1. The figure describes three different categories in which a decision can be made in power system planning models. This is about system level, sub system and the planning period. In addition, sometimes a distinction is made between greenfield planning and expansion planning. We will now describe the choices that can be made.

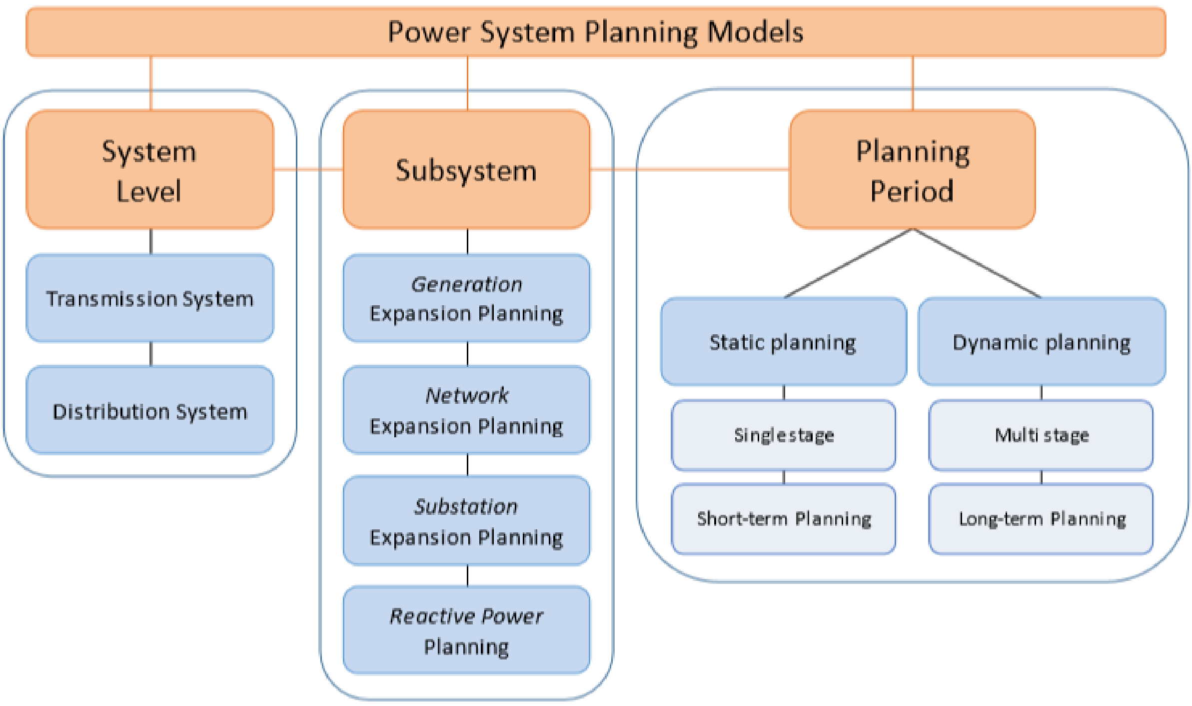

Figure 3.1 - Overview scope of power system planning models (Grond, 2016).

Greenfield vs expansion planning

In power system planning models a distinction is made between greenfield planning and expansion planning. Greenfield planning is about the deployment of a network at a location where none existed before, while expansion planning is about expanding a currently existing network.

System level

On system level a distinction is made between transmission and distribution systems. We have discussed this topic in Section 2.2. Sometimes both systems are considered together.

Subsystem level

The next distinction is made on subsystem level. The system can be expanded by four subsystem levels:

- *Generation Expansion Planning (GEP)*: planning (GEP) is necessary to ensure that the future demand for electricity is met by future generation power. GEP determines what type of generation units at which times and what places should become operational.
- *Network Expansion Planning (NEP)*: Network Expansion Planning (NEP) is about preventing future network congestion and to maintain a reliable network. The planning options that are uses are cables.
- *Substation Expansion Planning (SEP)*: The goal is the same as NEP, but the planning option is different. SEP is about placing new stations as well as expanding the capacity of current stations. For new stations the locations have to be determined.
- *Reactive Power Planning (RPP)*: RPP is about the optimal placement of reactive power sources and is needed to prevent voltage stability issues and to limit power losses.

Planning period

There are different approaches regarding the time dimension of the models. A common approach is to determine the optimal solution at the end of the planning horizon. These are known as static planning models. On the other hand, we have dynamic planning models, which consider the optimal solution over the entire planning horizon. These models also tell when a cable should be laid. An additional dimension time is introduced in these models. In general, static models are used for short term planning and dynamic models are used for long term planning.

3.2 An overview of optimization models

In this section, we discuss the different classes of optimization models and our motivation for choosing the SA algorithm. We can divide the optimization models in the categories as presented in Table 3.1.

Models	Example(s)
Mathematical models	Linear programming, mixed integer linear programming
Simulation models	Agent based modeling
Exact optimization algorithms	Complete enumeration
Approximation algorithms	Local search, tabu search, simulated annealing and neural networks.

Table 3.1 - Overview of optimization models (adapted from (Grond, 2016)).

Optimization models in distribution network expansion planning

The network planning problem can be formulated as a highly constrained, high-dimensional, mixed integer, non-linear combinatorial optimization problem (Scheidler, Thurner, & Braun, 2015). An approach is to simplify the problem and use deterministic algorithms such as linear programming. The advantage is that they are guaranteed to find the global optimum. However, they require many simplifications in constraints, solution space or a linearization of the problem (Franco, Rider, & Romero, 2014). Metaheuristics neither require differentiability, continuity, nor convexity of objective functions and they are therefore very popular in solving distribution system planning problems (Scheidler et al., 2015). According to Escobar, Gallego and Romero (2004), the mathematical models for transmission network expansion planning problems are NP-hard, which mean that no method exists that solves it in polynomial time. The number of solutions grows exponentially as the network size increases. The problem also presents a large number of local optimal solutions (Escobar et al., 2004).

Motivation for simulated annealing

In this research we first decided to use Mixed Integer Linear Programming (MILP) as an optimization model of which the results are presented in Chapter 4. However, we recognized the limitations and decided to use a different approach. We decided to use the metaheuristic method Simulated Annealing (SA). As discussed above, metaheuristics are very popular in literature for distribution network expansion planning. SA is a metaheuristic that is able to escape from local optimal solutions. SA seems therefore suitable for our problem as the problem contains many locally optimal solutions. In addition, SA allows the use of parameter dependent penalization. This could be useful as the problem is also highly constrained. We will describe SA and parameter dependent penalization in the next section.

To the best of our knowledge, an SA algorithm using the parameter dependent penalization method has never been used before in MV network expansion planning. This could be a promising method for solving this problem.

3.3 Optimization using simulated annealing

Combinatorial optimization problems are about finding the optimal solution from a finite set S consisting of all system configurations. An objective function f assigns a real number to each configuration $i \in S$. The goal can be either to find the minimum or the maximum of the objective function. A combinatorial optimization problem can be NP-hard, which means that we cannot find the optimal solution in polynomial time. Heuristic methods such as the local search algorithm Simulated Annealing (SA) can be used to find good solutions efficiently. The advantage of SA is that it is able to escape from local optima.

Outline of the algorithm

This outline is based on the work of (Kirkpatrick, Gelatt, & Vecchi, 1983). The origin of SA lies in solid-state physics. Annealing is the thermal process to get low energy solid states of a substance in a heat bath. This can be achieved by raising the temperature of a substance until it melts. The temperature of the substance is then lowered carefully so that the parts order themselves in ground state. This is the equilibrium state of a substance.

The algorithm starts with an initial random solution. An initial temperature c_{start} has to be chosen. In every step, a neighbor solution is generated and measured by an objective function. The objective value of the neighbor solution is defined as B and the objective value of the current solution is defined as A. Both values are compared with each other to determine whether the neighbor solution is accepted as the new current solution. Assuming a minimization problem, the probability of accepting a transition to neighbor with value B with regard to solution with value A is:

$$P_{AB}(c) = \begin{cases} 1, & if\ B \leq A \\ e^{\frac{A-B}{c}}, & otherwise \end{cases} \tag{3.1}$$

This means that a better solution is always accepted, while a worse neighbor solution is accepted with a certain probability. In case of a worse solution, the probability dependents on the difference between A and B and the temperature c. As the algorithm progresses, c decreases and the probability of accepting a worse solution becomes smaller. The start of the algorithm acts like a 'random search' method, while it ends as a 'local search' method. Initially almost all transitions are accepted, because the temperature is high. As temperature goes down, the algorithm tends to only accept improvements. After a certain amount of transitions, the temperature is lowered by a decreasing factor α. The number of transitions before the temperature decreases is called the Markov chain length k. The algorithm stops when a stop temperature c_{stop} is reached or when the algorithm does not find a better solution for a predetermined number of iterations. We can summarize the algorithm in the following pseudo code:

```
c = c_0
S_current = create_random_solution()
S_best = S_current
while c > c_stop do
        for (i = 1 to k)
                S_neighbor = generate_neighbor(S_current)
                if f(S_neighbor) < f(S_current) then
                        S_current = S_neighbor
                        if f(S_current) < f(S_best) then
                                S_best = S_current
                        end if
                elseif exp((f(S_current) - f(S_neighbor)) / c) > rand() then
                        S_current = S_neighbor
                end if
        end for
        c = c * α
end while
```

Note that in our problem, the neighbor has to be created before we can determine the objective value of the neighbor. In other problems, such as the Traveling Salesman Problem (TSP), the objective value of a neighbor can be determined without actually 'creating' the neighbor.

The way neighbor solutions are created is also called the generation mechanism. When choosing a generation mechanism it is important that every solution is reachable, in as few transitions as possible.

Cooling scheme

At the beginning of the algorithm a cooling scheme has to be determined that consists of the following parameters:

- Initial temperature c_0.
- Stopping temperature c_{stop}.
- Decreasing factor α.
- Markov chain length k.

Those parameters have to be chosen carefully as they influence the quality of the solution. There are some ways to determine these parameters. The initial and stopping temperatures can be determined by means of the acceptance ratio. The acceptance ratio is calculated using:

$$\chi(c) = \frac{number\ of\ accepted\ transitions}{number\ of\ proposed\ transitions} \tag{3.2}$$

The initial temperature is chosen such that the acceptance ratios at the beginning of the algorithm are close to one. The stopping temperature is chosen such that the algorithm ends when the acceptance ratios are close to zero. A rule of thumb is that the Markov chain length is chosen by the number of neighbor solutions.

The penalization method
The (parameter dependent) penalization method is described in the paper by Schuur (1989). The theory about this topic is based on this paper.

In practice it frequently appears that it is difficult to define a generation mechanism on the set S that is compatible with a set of restrictions. However, there exists a finite set $\overline{S}$ in which S is contained for which a simple generation mechanism exists. We relax some of the constraints that define the solution space S to such an extent that we have a manageable set of restrictions. SA is now applied to the solution space $\overline{S}$. The solutions $\overline{S} \setminus S$ are penalized in the objective function as we extend the objective function f to $\overline{f}$. It is sometimes possible to find an extension $\overline{f}$ of f satisfying:

$$\forall j \in \overline{S} \setminus S: \quad f(i_0) < \overline{f}(j), \tag{3.3}$$

Where i_0 is some element of S. In such a case, the combinatorial optimization problems associated with (S, f) and $(\overline{S}, \overline{f})$ have the same set of optimal solutions.

The parameter dependent penalization method
We call $\overline{f_c}$ the parameter dependent penalization of f with respect to the solution space $\overline{S}$. The extension $\overline{f_c}$ of f has the property that the elements of $\overline{S}$, that do not belong in the S, are penalized more heavily as c tends to zero. A real number (penalty) is added to f. We then divide the penalty by c, causing the penalty to increase as c decreases. In addition, the following property holds: $\overline{f}_c(i) = f(i)\ for\ i \in$ S. This means that the outcome of $\overline{f}_c(i)$ equals $f(i)$ when none of restrictions are violated.

3.4 Background in graph theory

Graph theory can be used to model networks. In Section 2.4 we also specified that a design criterion is to have a radially operated network. To check whether this constraint holds, we can use graph theory. In addition, graph theory can be used for load flow calculations, which is discussed in Section 3.5. In Section 3.4.1 we consider some concepts in graph theory and in Section 3.4.2 we discuss how we check the radial configuration constraint in an MV network.

3.4.1 Concepts in graph theory

This section is based on the work of Fritschy (2018) and Bondy & Murty (1976). In graph theory a graph is denoted as $G(V, E)$, Where V is a set of nodes and E a set the edges as shown below.

$$V = \{v_1, v_2, \dots, v_n\}, E = \{e_1, e_2, \dots, e_m\} \tag{3.4}$$

Figure 3.2 shows an example of an undirected graph $G(\{v_1, v_2, \dots, v_5\},\ \{e_1, e_2, \dots, e_6\})$.

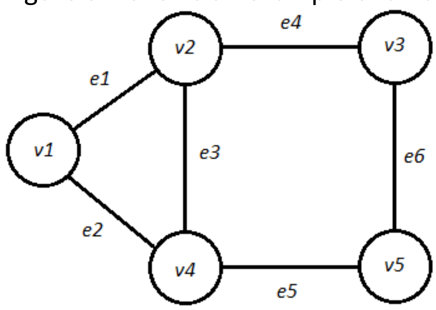

Figure 3.2 - Example of an undirected graph.

This graph can be described using an adjacency matrix, which is a symmetrical matrix with dimensions $(n * n)$. It describes which nodes are directly connected by edges. The adjacency A matrix of the example above looks as following:

$$A(\mathrm{G}) = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix} \quad A(\mathrm{G})_{ij} = \begin{cases} 1, & if\ node\ i\ is\ directly\ connected\ to\ node\ j \\ 0, & otherwise \end{cases} \tag{3.5}$$

The graph has a one-on-one connection with its (undirected) incidence matrix $C(G)$. The incidence matrix shows which node is connected to which edge. Usually, the incidence matrix is denoted by I, but later we use I for a vector of currents, which is why we use C instead. The dimensions are $(n * m)$, where n is the total number of nodes and m the total number of edges. The following matrix is the incidence matrix of the example:

$$C(\mathrm{G}) = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \quad C(\mathrm{G})_{ij} = \begin{cases} 1, & if\ node\ i\ is\ directly\ connected\ to\ edge\ j \\ 0, & otherwise \end{cases} \tag{3.6}$$

The graph and incidence can be either a directed or an undirected graph. If the graph is directed, the direction of an edge is expressed by denoting:

$$C(\mathrm{G})_{ij} = \begin{cases} 1, & if\ edge\ j\ starts\ in\ v_i \\ -1, & if\ edge\ j\ ends\ in\ v_i \\ 0, & otherwise \end{cases} \tag{3.7}$$

Connectivity
A graph is connected if and only if for each pair $(v, w) \in V$ there exists a path (Fritschy, 2018). A *vertex cut* of G is a subset V' of V such that G(V') is disconnected. A *k-vertex cut* is a vertex cut of k elements. The connectivity $K(G)$ is the minimum k for which G has a k-vertex cut, otherwise it is $n - 1$. The connectivity of a graph $K(G) = 0$ if the graph is either trivial or disconnected. A graph is said to be k-connected if $K(G) \geq k$.

Degree
The degree of a node is the number of edges that are connected to the node. If there is a node with a degree of 0, we know that this node is unconnected to the graph.

Cycles
A cycle is a (sub)graph whose nodes can be arranged in a cyclic sequence such that two nodes are adjacent if and only if they are consecutive in the sequence (Fritschy, 2018).

3.4.2 Checking the radial configuration criterion

In graph theory a radial configuration of a network is also referred to as a *spanning tree* or just a *tree*. (Fritschy, 2018) formulated four properties of a spanning tree. When G is a graph with n nodes, the following properties are equivalent:

1. G is a tree.
2. G is connected and has $n - 1$ edges.
3. G has no cycles and has $n - 1$ edges.
4. There is a unique path in G between any two nodes.

We can see the configuration as a subset of edges from the whole network. We know that we need a subset of in total $n-1$ edges from the original network to have a possibility of being a radial configuration. In addition, the graph should be connected, such that we meet the second property. These characteristics are easily checked for a network and seem a logical way to check the radial configuration constraint. Rstudio offers a package 'igraph' in which a function 'vertex.connectivity' determines the connectivity of a graph.

We can also calculate the number of open edges that are present in a network that is radially operated. The following equation holds (Andrei & Chicco, 2008):

$$number\ of\ NOPs = q = m - n + s \tag{3.8}$$

Where s is the number of nodes that supply the network, which relate to the number of substations in our problem. The s is added to the equation, because we would need one less edge to be able to have separate unconnected networks. Note that two substations should not be in direct contact with each other, otherwise we create a loop in the network and violate the radial operation constraint.

The fact that we need separate unconnected networks in case of multiple substation is counteracting our strategy in checking the radial configuration criterion, as we stated that we check the connectivity of the graph in combination with the $n-1$ edges. A way to solve this, is to aggregate all substations to one substation. When doing this, the property should hold again on the network that we create by doing this.

3.5 Load flow methods

In Section 2.4, we have discussed the design criteria of MV networks. The voltages on the buses and the currents on the cable should be within certain limits. An increasing demand for electricity may cause voltages and currents to exceed those criteria. We try to find adequate investments to solve these problems and therefore we need to check the effects of an investments on both the voltages and currents.

Load flow methods are used to calculate the voltages and currents in a network to check whether they meet the design criteria (Van Oirsouw, 2011). They aim to solve load flow equations. The load flow problem is widely discussed in literature (Grond, 2016). Detailed information can be found in the book '*Netten voor distributie van elektriciteit*' by Van Oirsouw (2011) and Van der Meulen (2015). The load flow problem is the computation of the voltage magnitude and angle at each nodes. This can be described as a set of non-linear equations (Grond, 2016):

$$P_i = \sum_{j=1}^{n} |Voltage_i||Voltage_j|\left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right] \tag{3.9}$$

$$Q_i = \sum_{j=1}^{n} |Voltage_i||Voltage_j|\left[G_{ij}\sin(\delta_i - \delta_j) + B_{ij}\cos(\delta_i - \delta_j)\right] \tag{3.10}$$

in which,

$P_i = injected\ active\ power\ at\ node\ i$
$Q_i = injected\ reactive\ power\ at\ node\ i$
$G_{ij} = real\ part\ of\ the\ admittance\ matrix\ element\ Y_{ij}$
$B_{ij} = imaginary\ part\ of\ the\ admittance\ matrix\ element\ Y_{ij}$
$Voltage_i = voltage\ level\ at\ node\ i$
$|Voltage_i|, |Voltage_j| = voltage\ magnitude\ at\ nodes\ i\ and\ j, respectively$
$\delta_i, \delta_j = voltage\ phase\ angle\ at\ nodes\ i\ and\ j, respectively$
$n = the\ number\ of\ nodes$

3.5.1 Newton-Raphson AC method

A commonly used technique to solve the load flow equations is the Newton-Raphson AC method. It is the preferred algorithm for solving the load flow problem (Le Nguyen, 1997). This is an iterative approach that relies on linearizing the non-linear power flow equations. The method is accepted as the most accurate, but it has some disadvantages (Grond, 2016). The first disadvantage is that convergence is not guaranteed. Second, the method is also relatively computationally expensive to use when they have to be evaluated many times.

Heuristics like simulated annealing rely on evaluating different alternatives many times, a faster load flow method is desirable to be able run simulated annealing within reasonable algorithm running times. Fortunately, a faster load flow method is proposed in a recent paper which we discuss in the next section.

3.5.2 Linear load flow assuming only a constant impedance

A method that was designed to be fast, is the linear load flow method proposed by Van Westering, Droste, & Hellendoorn (2019). They tested this method on an MV and LV network with 24 million cable segments and could solve the load flow problem in under a minute. We will the describe the method that is proposed by Van Westering et al. (2019) below.

First, a network is modelled as a graph $G(V, E)$, where V are the nodes and E are the edges. In this case, buses are nodes and cables are edges. The goal is to find the voltages on the nodes denoted by U_V and the currents on the cables I_E. We first have to derive the admittance matrix $\overline{Y}$. Admittance is a measure of how easily a circuit allows a current to flow. We obtain the admittance matrix using the following formula:

$$\overline{Y} = C\, Z_E^{-1} C' \tag{3.11}$$

Where C is a directional incidence matrix, as described in Section 3.4.1. C' is the transpose of the C matrix and Z_E is a square matrix containing the corresponding impedances of each cable on its diagonal. Recall from Section 2.1 that the impedance is the resistance in AC systems.

The voltages and currents in a network can be calculated using Ohm's law:

$$I_V = \overline{Y} U_V \tag{3.12}$$

To create the 'constant impedance' model, the power consumption of customers is converted to an equivalent resistance Z_{eq} by using the following formula:

$$Z_{eq} = \frac{U_{v,ref}^2}{P_{user}} \; \forall\, v \in V \tag{3.13}$$

P_{user} is the power consumption of the customer and v represents a customer connection. $U_{v,ref}$ is the reference voltage at customer location v. The voltage at the customer is usually not known and therefore the nominal voltage of the network is assumed.

Equation 3.12 cannot be directly solved, because both I_V and U_V have elements that are unknown. The matrices are sorted first and then solved as two separate equations. The matrices are sorted as follows:

$$I_V = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \overline{Y} = \begin{bmatrix} K & L \\ L' & M \end{bmatrix}, U_V = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{3.14}$$

At all nodes, no power leaves the network and therefore $I_2 = \overline{0}$. The voltages on the end nodes U_1 are known, which are 0 for all nodes except for the transformer at the substation. This results the following load flow equations:

$$\begin{bmatrix} I_1 \\ \overline{0} \end{bmatrix} = \begin{bmatrix} K & L \\ L' & M \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{3.15}$$

To solve for U_2, the following equation has to be solved:

$$L'U_1 = -MU_2 \tag{3.16}$$

This can be solved in practical ways as it is in the form $Ax = B$. After computing the voltages on the nodes, the currents on the cable can be directly calculated by:

$$I_E = Z_E C' U_V \tag{3.17}$$

In comparison to other load flow methods, this method is not prone to unfeasible solutions and numerical difficulties. This makes the method more stable.

Adding reactive power
To add the reactive power to the load flow calculations, we add the cable reactances to Z_E. This results in imaginary elements of Z_E, Y, U and $I \in \mathbb{C}$. The subscripts $\mathbb{C}$, $\mathbb{R}$ denote the imaginary and real part, respectively. To add this to Equation 3.12, it is expanded to:

$$\begin{bmatrix} I_{\mathbb{R}} \\ I_{\mathbb{C}} \end{bmatrix} = \begin{bmatrix} Y_{\mathbb{R}} & -Y_{\mathbb{C}} \\ Y_{\mathbb{C}} & Y_{\mathbb{R}} \end{bmatrix} \begin{bmatrix} U_{\mathbb{R}} \\ U_{\mathbb{C}} \end{bmatrix} \tag{3.18}$$

This can be simplified to:

$$\begin{bmatrix} M_{\mathbb{R}} & -M_{\mathbb{C}} \\ M_{\mathbb{C}} & M_{\mathbb{R}} \end{bmatrix} \begin{bmatrix} U_{\mathbb{R},2} \\ U_{\mathbb{C},2} \end{bmatrix} = -\begin{bmatrix} L_{\mathbb{R}} & -L_{\mathbb{C}} \\ L_{\mathbb{C}} & L_{\mathbb{R}} \end{bmatrix} \begin{bmatrix} U_{\mathbb{R},1} \\ U_{\mathbb{C},1} \end{bmatrix} \tag{3.19}$$

This is a complex form of the equation $MU_2 = LU_1$. By solving Equation 3.19, the voltages are determined. Equation 3.18 can be used to find the current through the cable segments. The voltages on the nodes can then be determined by:

$$U_V = \sqrt{U_{\mathbb{R}}^2 + U_{\mathbb{C}}^2} \tag{3.20}$$

3.6 Checking the n-1 principle in an MS network

Evaluation of the n-1 principle comes down to the evaluation of many load flow calculations per alternative solution. A breakdown for every cable in the network has to be simulated. For each cable, the possible reconfigurations are then identified. Often k, the number of switches that are allowed to be switched, is limited (i.e. $k = 3$). For each cable, the voltages and currents of all radial reconfigurations are checked by performing a load flow calculation, one by one, until a feasible solution is found. If for any cable, no feasible reconfiguration is found, the n-1 principle does not hold. We are then interested in the n-1 reconfiguration that exceeds the capacity constraints the least, such that we can measure the performance of the reconfiguration in terms of overload. In this case, we have to check all possible reconfigurations, for all cables, for each alternative solution.

An exact method for checking the n-1 principle in MV networks is proposed by Fritschy (2018). The goal of Fritschy (2018) was to find an algorithm that is fast and exact. The algorithm returns whether a feasible reconfiguration exists or not. In case a feasible reconfiguration exists, the switches that need to be switched are also returned. Note that this is not exactly what we are looking for as we are interested in the reconfiguration that deteriorates the constraints the least. Fritschy (2018) performed some test to check the n-1 principle using the algorithm. A network of around 410 nodes took 40,8 seconds to check when $k = 3$. The whole MV network of Liander took around 110 minutes to compute when $k = 6$. This method was based on the linear load flow calculations by Van Westering et al. (2019).

Such algorithm running times are undesirable for heuristic approaches in network expansion planning, as they often rely on the evolution of thousands of alternatives. Even if the algorithm is applied on a small network, it could be running for days before it finds an adequate solution. An approximation that is faster is desired. The following approximations were found in literature:

Genetic algorithm
Given an outage situation, the choice of open and closed switches is a combinatorial optimization problem with a solution space of 2^k, where k is the number of switches (Mendes, Boland, Guiney, & Riveros, Nov. 2010). Because of the exponential complexity, metaheuristics such as Genetic Algorithms (GA) are proposed (Mendes et al., 2010). The GA algorithm was tested on a 96 buses, 97 branches, 16 switches and 2 generators network. The algorithm ran in 30 seconds and is expected to increase by $O(N^3)$ for larger networks.

Simplification 1: Only check the n-1 principle on the outgoing cables from a substation
Other researchers that used a heuristic approach for the network expansion planning problem also had to check the n-1 principle. Two simplifications were found in literature. The first simplification is to not check the n-1 principle for all the cables, but only the cables that are connected to the substation. This is applied by Luong, Grond, Bosman & La Poutré (2013). The failure of a cable that is connected to the substation is often seen as the worst-case scenario, as all underlying nodes are then to be fed by other paths in an n-1 situation.

Simplification 2: Close all NOPs and perform a simulation of a cable failure, for each cable.
The second simplification is to ignore the radial configuration constraint in n-1 principles, which is applied by Grond (2016). By closing all switches in the network, the network is operated in its meshed form. This simplifies the method as we do not have to have to find reconfigurations, as we assume one reconfiguration that closes all switches. This results in one load flow calculation per cable. This is then further simplified by using Line Outage Distribution Factors (LODF). LODF are a sensitivity measure of how much a change in flow of a cable changes the flows on other cables in the network. By first determining these factors, the flow does not have to be recalculated by means of a load flow calculation, as long as the topology stays the same (Grond, 2016). It also should be noted that LODF introduce a certain error as it is an approximation method. Ignoring the radial configuration criterion also introduces an error, as this is not allowed in reality. We think that this underestimates the n-1 principle, as the meshed configuration is able to use more cables than allowed in a radial configuration.

The GA algorithm still has computation times much higher than we desire. Two simplifications of the n-1 check are proposed in literature. However, the accuracy is unknown. We will revisit this subject in Chapter 7.

3.7 Expert knowledge to reduce the solution space

A recent research on this topic by Grond (2016) uses expert knowledge to discard cable options that are impractical. These are classified as topological, geographical and bottleneck specific constraints. By applying such constraints we can reduce the solution space and prevent solutions that impractical. The decision rules are listed in Table 3.2. Decision Rules 1-4 are topological constrains, Decision Rules 5-7 are geographical constraints and Decision Rule 8 is a bottleneck specific constraint.

Decision rules	**Explanation**
1. If bus i and bus j of branch k_{ij} are part of the same existing feeder group, then discard this expansion option (i.e. branch k_{ij}).	It is not allowed to create subrings (due to protection reasons).
2. If there is already a cable installed at branch k_{ij}, then discard this expansion option, unless the existing cable has a small cross-sectional area (≤ 35 mm2).	Cables have a long lifetime and therefore it is in most cases inefficient to remove cables (i.e. capacity) from the network.
3. If bus i or bus j of branch k_{ij} already has the maximum allowed number of connections (4 MV cable connections), then discard this expansion option.	Ring main units and switch gear have a physical limit for the number of cable connections.
4. If bus i of branch k_{ij} is an MV-T or HV/MV substation, and bus j is an MV-T or HV/MV substation, then discard this expansion option.	This would resemble a cable expansion in the MV transmission network which does not directly solve bottlenecks in the MV-D network.
5. If the buses of branch k_{ij} are an MV/LV transformer substation and an MV-T substation, and a shorter cable connection exists between this MV/LV transformer substation and another MV-T substation, then discard this expansion option.	In most cases a connection to the nearest MV-T substation is the cheapest option and connections to distant MV-T substations can be discarded.
6. If the buses of branch k_{ij} are both MV/LV transformer substations and both buses have a possible connection to an MV-T substation that is shorter than the cable length of branch k_{ij}, then discard this expansion option.	A shorter connection to a MV-T substation is preferred as this option has generally lower cable costs and increases the capacity of the network substantial.
7. If the estimated cable route of branch k_{ij} is longer than a maximum distance, then discard this expansion option.	To discard unrealistic long cable connections in MV-D networks, which are topologically possible, but economically irrelevant.
8. If bus i and bus j of branch k_{ij} are not part of the feeder group with the (greatest) bottleneck, then discard this expansion option.	Expansions in other feeder groups, which are not related to the feeder group with the bottleneck, will not affect or solve the (greatest) bottleneck.

Table 3.2 - Decision rules proposed by Grond (2016) based on expert knowledge.

Note that when applying Decision Rule 1 on a system with only one substation, the only new connection that are possible are new cables between a substation and an MV station. In addition, the current cable connections can be replaced. If Decision Rule 2 is also applied, then most of the replacing cables are blocked. Because of the long lifetime of the cables, it is often not justifiable to replace cables to add more capacity.

3.8 Conclusion

We consulted literature to answer our knowledge problems. We discussed an overview of model choices, the optimization models we can use and the way we can check the design criteria in an MV network.

The distribution network expansion planning problem can be formulated as a highly constrained, high-dimensional, mixed integer, non-linear combinatorial optimization problem (Scheidler et al., 2015). SA is a metaheuristic that is able to escape from local optimal solutions. SA seems therefore suitable for our problem as the problem formulation contains many locally optimal solutions. In addition, SA allows the use of parameter dependent penalization. This could be useful as the problem is also highly constrained.

We need to model MV networks such that we can apply SA. For this purpose, we can use graph theory to model an MV network as a graph. Furthermore, we researched how we can efficiently check the design criteria of an MV network in a model.

The first design criterion we discussed is that an MV network should be radially operated. To check whether this criterion holds, we can also use graph theory. If the configuration of the network represents a connected graph and the number of edges are equal to n-1, where n are the number of nodes, we know that the configuration is radial. By exploiting this characteristic, we can check the radial operation constraint in an computationally inexpensive way. Rstudio offers a package 'igraph' in which a function 'vertex.connectivity' is offered that can check the connectivity of a graph.

Other design criteria concern the voltages and currents in a network. To calculate the voltages and currents in a network, load flow equations have to be solved. The Newton Raphson AC method is traditionally used. However, this method is computationally expensive to use. Luckily, we found a much faster method that is proposed by Van Westering et al. (2019).

The n-1 principle is challenging to check in an optimization algorithm. An exact n-1 check relies on many load flow calculations. Approximation methods seem most obvious to apply. Various simplifications were discussed in this chapter. We revisit this subject in Chapter 7. Last, we considered a thesis about applying expert rules to prevent impractical solutions and to reduce the solution space.

In Chapter 4, we present our mixed integer linear programming approach. After this, we changed our approach to the simulated annealing approach. In Chapter 5 and 6 we develop simulated annealing algorithms that incorporates the knowledge gathered in this chapter.

4 Mixed integer linear programming approach

The first approach that we explored is to model the problem as a Mixed Integer Linear Programming (MILP) model. Inspired by the classical minimum cost flow problem, a MILP was formulated. A different approach was taken after a first attempt of using MILP, mainly because of the limitations that we experienced. Although different choices are made, it could be interesting to see that the option was explored at least.

Section 4.1 describes a toy problem that we modelled using MILP. The limitations are discussed and a conclusion is given.

4.1 Mathematical formulation

A toy problem approach is used to start with an easy problem. This formulation is based on the minimum cost flow problem.

Consider a graph with $V = \{A, B, C, D, E, F\}$, where *A* represents a substation and *B-F* represent MV station. A should deliver power to *B-F*. Some fictional numbers are used as parameters.

Parameters

c = {0, 1, 2, 3} cable types, where 0 means no cable is laid.
w_c *= {0, 50, 100, 150} maximum power through cable c in MVA.*
p_c *= {0, 100, 150, 200} Price per kilometer of cable c.*
a_j*= {0, 50, 50, 100, 55, 70} Demand at node j in MVA.*
d_{ij}*= distance matrix from* i *to* j *in kilometers.*
$M = Big\ number.$
$s_A = \sum_{j=B}^{F} a_j$ *= supply of the substation, which is equal to the sum of the demand at all MV stations.*

Decision variables

$$X_{i,j,c} = \begin{cases} 1, & If\ cable\ type\ c\ is\ chosen\ between\ node\ i\ and\ node\ j \\ 0, & otherwise \end{cases}$$

$$F_{i,j} = Power\ flow\ between\ node\ i\ and\ node\ j\ in\ MVA$$

$$Y_{i,j} = \begin{cases} 1, & if\ there\ is\ flow\ between\ node\ i\ and\ node\ j \\ 0, & otherwise \end{cases}$$

Objective function

$$\min \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{c \in C} X_{i,j,c} * p_c * d_{ij}$$

The objective function minimizes the total cost of all cables that are laid. The costs are based on the chosen cable between installation i and j, multiplied by the price per kilometer of the cable and the distance between i and j.

Constraints

$$F_{i,j} \leq \sum_{c \in C} X_{i,j,c} * w_c \qquad \forall i, \forall j \qquad (4.1)$$

$$F_{i,j} \leq Y_{i,j} * M \qquad \forall i, \forall j \qquad (4.2)$$

$$Y_{i,j} + Y_{j,i} \leq 1 \qquad \forall i, \forall j \qquad (4.3)$$

$$\sum_{i=1}^{I} Y_{i,j} = 1 \qquad \forall j \qquad (4.4)$$

$$\sum_{i=1}^{I} F_{i,j} + s_j = \sum_{i=1}^{I} F_{j,i} + a_j \qquad \forall j \qquad (4.5)$$

$\sum_{c \in C} X_{i,j,c} = 1$ $\forall i, \forall j$ (4.6)

$F_{i,j} \geq 0$ $\forall i, \forall j$ (4.7)

(4.1) Flow cannot exceed the capacity of the chosen cable.
(4.2) Make sure that variable $Y_{i,j}$ becomes 1 when flow is bigger than 0.
(4.3) Power flows only in 1 direction.
(4.4) Only one branch delivers to an MV/LV transformer.
(4.5) Power flow balance equations. Power that flows in is equal to the power that flow through an node plus its demand.
(4.6) Only one choice for a cable may be made.
(4.7) The flow between each node is non-negative.

In reality, more constraints are present that are not linear, such as the load flow equations. A design criteria is that the solution should take into account the n-1 principle (see Section 2.4.4), which is difficult to model in MILP models. Metaheuristic are suitable for more complex problems. We discussed this in Section 3.2. Next chapter will consider our SA approach.

4.2 Conclusion

This chapter presented our try to use MILP to model the distribution network expansion problem. We experienced the limitations of this approach and decided to try a metaheuristic approach. For the sake of completeness, we decided to include the MILP approach in this thesis.

In the next chapter, a simulated annealing procedure is proposed to move NOPs. Electricity can be directed through different paths by moving NOPs, such that the capacity violations are mitigated.

5 Swapping switches to solve capacity problems

One way to solve voltage and current capacity problems is to redirect the power flow by using a different configuration. This can be achieved by using switches that can turn a cable 'on' and 'off'. A simulated annealing algorithm is proposed to solve capacity problems for small theoretical network using these switches. This algorithm is programmed in R on a shared server of Alliander.

Before we can optimize using simulated annealing, we need to model an MV network and find a way to generate neighbor solutions by moving NOPs. Section 5.1 discusses the assumptions of the model. Section 5.2 shows how a small theoretical network is modelled. The test network that is optimized in this chapter is presented in Section 5.3. The constraints and the objective function are discussed in Section 5.4 and 5.5 respectively. After this, the way to define neighbor solutions by relocating NOPs is discussed in 5.6. A simulated annealing algorithm requires a proper cooling scheme that is discussed in Section 5.7. Last, the results are presented in 5.8 and a conclusion is given in 5.9.

5.1 Assumptions

Before explaining the model and algorithm, we specify the assumptions and choices made.

- We use a static model to evaluate the performance of the network at one point in time. The alternative would be a dynamic approach that adds an additional time dimension.

- Fictional peak loads that happen simultaneously on MV stations are used. We assume that a simultaneity factor has been applied. Note that predicting future demand is not the scope of this project.

- The test network does not contain distributed generation, such as wind parks. This means that we assume that the loads are calculated based on 100% load and 0% generation.

- Every cable has a switch that can turn a cable on and off.

- We restrict ourselves to reconfiguring the network (by moving NOPs) as a planning option.

- We apply the linear load flow method that is developed by Van Westering et al. (2019). Our version does not take into account reactive power. This means that the estimation of the voltages and currents are off by a small percentage. We could solve this later by programming the version with the reactive power included. At this point, this is not necessary to prove the point of this chapter.

- In this model, the n-1 principle is ignored. A configuration in the normal state does not have an impact on the feasibility of the n-1 principle. Only the number of switching actions is influenced. In fact, the algorithm proposed in this chapter can possibly be used to determine an adequate reconfiguration state.

- For simplicity, every cable has the same characteristics.

- The algorithm developed in this chapter assumes that the input network has a configuration that is radial.

- Every MV station contains one rail key. We assume that every MV station has one peak load.

- There is no limit on the amount of resources, such as labor.

5.2 Modelling a network in R

We define variables to describe the network and the configuration. The following tables are defined: *Network, Configuration, Trans_edges, OSlist* and *MSRlist*. This is based on the way that Fritschy (2018) modelled an MV network. This structure is chosen in such a way that we are able to do a linear load flow calculation and generate neighbor solutions by moving NOPs. A description for each table is now discussed.

Network

The *Network* table describes all edges (cables) of the network, including the ones that are a NOP. The following characteristics of the edges are described:

Edge: A unique ID number for the edge. Numbered {1,2,…, m edges}.
Node1: Starting point of the cable.
Node2: Ending point of the cable.
Impedance: A constant impedance of the cable in ohm (Ω).
Current Capacity: The capacity of the cable in ampere (A).

When plotting the *Network* table, the result is a meshed network. Figure 5.1 is an example of this.

Configuration

Configuration is a vector containing all edge IDs that are in use and therefore excluding the edges that are NOPs.

Trans_edges

The *Trans_edges* table is a subset of the *network* table. It describes the same characteristics of the edges as the *Network* table. The difference is that it only contains the edges in use, while the *Network* table also considers the cables that are NOP. When plotting this table, the result is a radial network. Figure 5.2 shows an example. After a linear load flow calculation is executed, the currents on the edges are added in a column named *I_cable*.

OSlist

The OSlist table contains data about the substation (onderstation in Dutch). This contains the following columns:

OS ID: A unique number to describe the substation. Numbered 1.
Nominal voltage level: The nominal voltage level of MV network that the substation feeds into the network in volt (V).

MSRlist

The MSRlist contains the necessary characteristics of the MV stations (middenspanningsruimte in Dutch). The following columns are present:

MSR railkey: A unique number that represents a MSR. Numbered {2,…, n nodes}.
Power consumption: The power consumption in watt (W)
Minimum voltage level: The minimum voltage level that is allowed in volt (V).
Maximum voltage level: The maximum voltage level that is allowed in volt (V).
U_MSR: The voltages on the MV stations after a linear load flow calculation is executed in volt (V).

5.3 Test network

A small test network is modelled in R to test our algorithm. We define a network as a graph $G(\{v_1, v_2, \ldots, v_{31}\},\ \{e_1, e_2, \ldots, e_{32}\})$. The network is similar to the test network used by Grond (2016). The difference is that we replaced large customers for MV stations. The network has 1 substation, 30 MV stations and 32 cables. We assume that every cable has the same characteristics: a constant impedance of 0.1 Ω and a capacity of 100 A. The MV stations all have a peak load of 98000 W and the received voltage should remain between 9,500 – 10,500 V. The substation feeds the network with a voltage of 10,500 V.

By using the 'igraph' package in R, we can visualize this graph. Figure 5.1 presents the (meshed) network as a result of plotting the *Network* table. Figure 5.2 presents the configuration (spanning tree) as a results of plotting the *Trans_edges* table. The purple node (node 1) represents a substation, while the blue nodes represent MV stations.

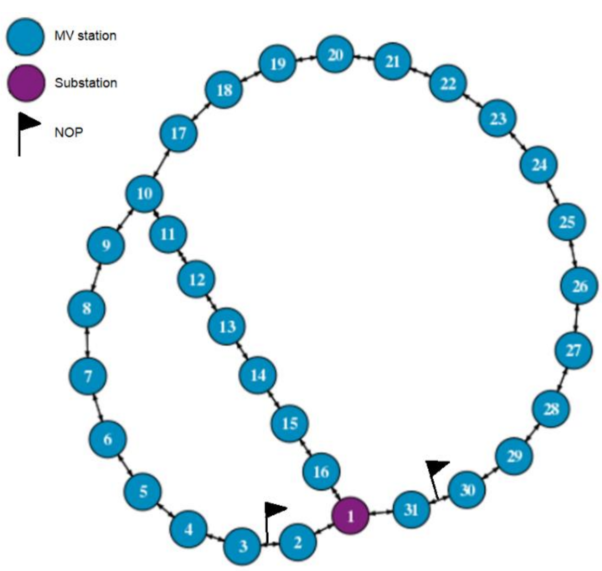

Figure 5.1 - Test network.

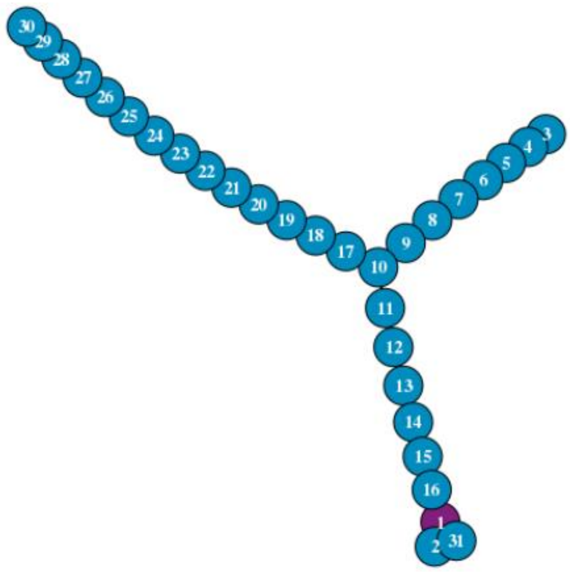

Figure 5.2 - Configuration of the test network.

To demonstrate the effectiveness of the algorithm, two NOPs are placed at possibly the worst places of the network, the cable connecting nodes (2 – 3) and cable (30 – 31). The reason that these are bad choices is that cables from node 1 (substation) to 2 and 31 are relatively under loaded compared to cable (1 – 16). The cable (1 – 16) should have a capacity that is able to deliver power to all underlying nodes.

An initial load flow calculation is performed to show that the network is overloaded in the current situation. This results in a *MSR_list* table and a *Trans_edges* table containing the voltages on the MV station and the currents on the cables. Figure 5.3 and 5.4 show the *MSR_list* and *Trans_edges* tables, respectively. The tables show that there some cables that exceed the current capacities, but there are no voltage problems. As expected, cable (1 – 16) has the biggest load.

The loadflow calculation was validated by comparing the results to the load flow calculations used by Fritschy (2018), where the same method was used. The results were identical.

	MSR_railkey	Power Consumption	Minimum Voltage Capacity	Maximum Voltage Capacity	U_MSR
1	2	98000	9500	10500	10499.11
2	3	98000	9500	10500	10322.43
3	4	98000	9500	10500	10323.30
4	5	98000	9500	10500	10325.05
5	6	98000	9500	10500	10327.68
6	7	98000	9500	10500	10331.18
7	8	98000	9500	10500	10335.56
8	9	98000	9500	10500	10340.82
9	10	98000	9500	10500	10346.95
10	11	98000	9500	10500	10366.17
11	12	98000	9500	10500	10386.26
12	13	98000	9500	10500	10407.24
13	14	98000	9500	10500	10429.10
14	15	98000	9500	10500	10451.85
15	16	98000	9500	10500	10475.48
16	17	98000	9500	10500	10334.74
17	18	98000	9500	10500	10323.41
18	19	98000	9500	10500	10312.95
19	20	98000	9500	10500	10303.37
20	21	98000	9500	10500	10294.66
21	22	98000	9500	10500	10286.82
22	23	98000	9500	10500	10279.86
23	24	98000	9500	10500	10273.76
24	25	98000	9500	10500	10268.54
25	26	98000	9500	10500	10264.19
26	27	98000	9500	10500	10260.71
27	28	98000	9500	10500	10258.10
28	29	98000	9500	10500	10256.37
29	30	98000	9500	10500	10255.50
30	31	98000	9500	10500	10499.11

Figure 5.3 - Initial voltages on the MV stations.

	Edge	Node1	Node2	Impedance	Current Capacity	I_cable
1	1	1	2	0.1	100	8.903518
2	2	1	16	0.1	100	245.199966
3	3	1	31	0.1	100	8.903518
4	5	3	4	0.1	100	8.753687
5	6	4	5	0.1	100	17.508116
6	7	5	6	0.1	100	26.264030
7	8	6	7	0.1	100	35.022172
8	9	7	8	0.1	100	43.783283
9	10	8	9	0.1	100	52.548107
10	11	9	10	0.1	100	61.317388
11	12	10	11	0.1	100	192.184687
12	13	10	17	0.1	100	122.092819
13	14	11	12	0.1	100	200.975465
14	15	12	13	0.1	100	209.783287
15	16	13	14	0.1	100	218.608898
16	17	14	15	0.1	100	227.453048
17	18	15	16	0.1	100	236.316487
18	19	17	18	0.1	100	113.328692
19	20	18	19	0.1	100	104.574176
20	21	19	20	0.1	100	95.828529
21	22	20	21	0.1	100	87.091007
22	23	21	22	0.1	100	78.360871
23	24	22	23	0.1	100	69.637381
24	25	23	24	0.1	100	60.919796
25	26	24	25	0.1	100	52.207377
26	27	25	26	0.1	100	43.499385
27	28	26	27	0.1	100	34.795082
28	29	27	28	0.1	100	26.093730
29	30	28	29	0.1	100	17.394591
30	31	29	30	0.1	100	8.696927

Figure 5.4 - Initial currents on the cables.

5.4 Constraints

In Section 2.4 we discussed that the network should meet some design criteria. We use them as input for our constraints. We add a constraint, namely that all buses should be connected. We have the following constraints:

1. All buses should be connected.
2. NOPs are placed such that the network is operated radially.
3. The voltages are within the allowed bandwidth for each MV station.
4. The currents are below the maximum capacity levels.
5. The n-1 principle holds.
6. ΔU constraint.

Constraint (1) can be checked in different ways. One way is to use the function '*vertex.connectivity*' from the 'igraph' package available in R. This is a relatively inexpensive way to check for connectivity of the graph. To check whether constraint (2) holds, we use the fact that a radial network has the property that the number of NOPs is given by the equation:

$$number\ of\ NOPs = number\ of\ edges - number\ of\ nodes + number\ of\ substations \quad (5.1)$$

Conversely, if this equation holds and the graph is connected, we know that the network is radial (Andrei & Chicco, 2008). This has been explained in Section 3.4.2. We already checked whether the graph is connected for constraint (1).

Constraints (3) and (4) are checked using linear load flow calculations by Van Westering et al. (2019) as described in Section 3.5.2. This approximation is only a few percentage off compared to the true values. Reactive power is ignored for now as discussed in Section 5.1, but can be added later. The advantage of this linear load flow approximation is that it is relatively computationally inexpensive to use. We model constraints (3) and (4) as soft constraints, meaning that a neighbor solution may violate these constraints. Solutions violating these constraints are penalized in the objective function, which is discussed in the next section.

Constraint (5) is ignored, which was discussed in the Section 5.1. Constraint (6) is also ignored, as we only use loads under the 100% load and 0% generation scenario.

5.5 Objective function

Each neighbor solution is measured by an objective function. Many evaluation criteria can be used to measure the performance of a solution. We propose a cost for turning a switch on and off. In addition, we penalize neighbor solutions for violating the capacity constraints. We attribute a cost of 100 to cables that are turned on or off. Solutions exceeding the current capacity constraint are penalized by 100 per ampere. Solutions that violate the voltage constraint are penalized 10 for each voltage outside of the specified width. This results in the following objective function:

The parameters are:
Weight current = 100
Weight voltage = 10
Cost per switch = 100

The objective function that should be minimized is:

$$objective = (cost\ per\ switch * number\ of\ switches) + penalization\ for\ overloading \tag{5.2}$$

Where the penalization for overloading is described as:

$$\begin{aligned} &penalization\ for\ overloading \\ &= (weight\ current * total\ amount\ of\ currents\ exceeded) \\ &+ (weight\ voltage \\ &* total\ amount\ of\ voltages\ outside\ specified\ bandwidths \end{aligned} \tag{5.3}$$

Note that the penalization is not parameter dependent. This will be applied in the next chapter when we add cables as a planning option. The reason is that bottlenecks are often not solvable using the switches only. When parameter penalization is applied, only feasible solution are accepted.

5.6 Swapping switches to create neighbor solutions

Every solution should be reachable by creating neighbor solutions in a simulated annealing algorithm. We propose to use a swap operator to create neighbor solutions. This means that one cable is switched 'on' and one cable 'off'.

Applying a move operator is not possible. Section 5.4 showed that for a network to be radial, Equation 5.1 should hold, combined with that the network should be connected. Turning a cable off without turning another cable on will violate the equation, thus generating an infeasible solution.

A function called 'Swap_two_switches' is created that randomly chooses one NOP and one cable in the configuration. The NOP will be added to the configuration and the random cable from the configuration is removed from the configuration. We define this as a swap. Each cable or NOP has an equal chance of being chosen and has therefore a uniform distribution. After a swap, a connectivity check is done by a function called '*vertex.connectivity'* from the 'igraph' package. This determines the degree of connectivity of the graph. A degree bigger than 0 means that the graph is connected. This function is computationally inexpensive. If a swap results in a configuration that is not radial, the swap is reversed. The function keeps swapping switching until it finds a configuration that results in a radial network. It then returns this configuration. An overview of this function is given below in Figure 5.5.

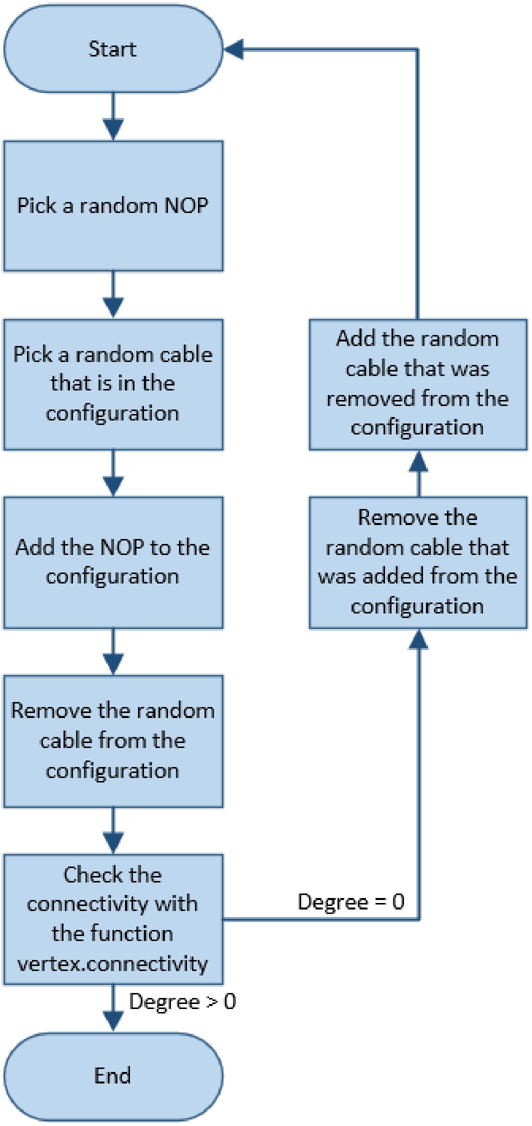

Figure 5.5 - Flow chart of the 'Swap_two_switches' function.

5.7 Cooling scheme

Recall from Section 3.3 that the simulated annealing algorithm needs a proper cooling scheme. The initial temperature, stop temperature, the number of Markov chains and the decreasing factor have to be determined. We use the acceptance ratio to determine the initial and de stop temperature.

With an initial temperature of 100,000 and a stopping temperature of 100, the acceptance ratio after each iteration is shown in Figure 5.6. The y-axis represents the acceptance ratio and the x-axis represents the corresponding Markov chain. Initially, almost all neighbors are accepted, while at the end almost no neighbor is accepted anymore. The decreasing factor is set to 0.97 and the Markov chain length to 10. A decreasing factor closer to 1 means that algorithm is cooling more slowly. This increases the algorithm running time. In this case, it is unnecessary to increase the decreasing factor, as the algorithm finds the best solution already after a few seconds.

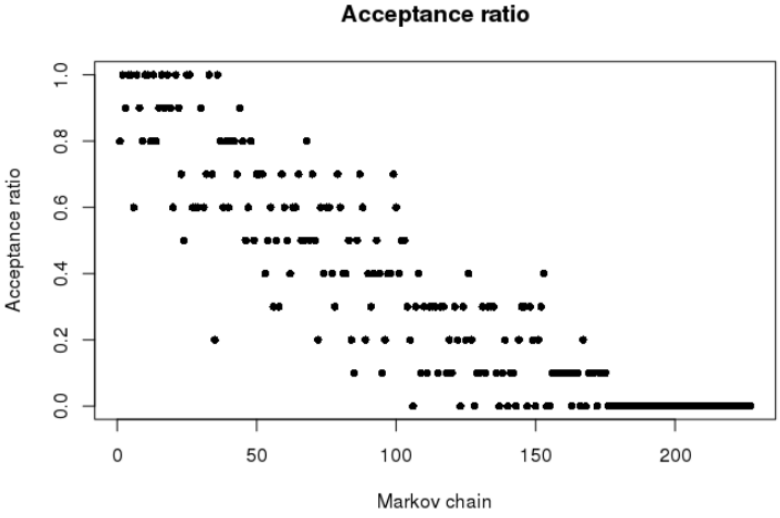

Figure 5.6 - Acceptance ratio when running the SA algorithm.

5.8 Results

The simulated annealing algorithm returns the tables *Current network*, *Trans edges*, *MSRlist* and *OSlist* as described in Section 5.2 of the network with the best objective value found. In addition, it attaches the currents on the cables to the *Trans_edges* table and the voltage values on the MV stations to the *MSRlist* table.

The network is plotted again after the simulated annealing algorithm optimizes the network. Figures 5.7 and 5.8 show the optimized network. The network on the left has not changed in comparison with the original network. This is expected, as the topology of the network is not modified, but the configuration has. The *Trans_edges* on the right shows that the MV stations are almost equally distributed over each path. This has changed compared to the original configuration shown in Figure 5.2. This result is what we expected, as each cable has the same capacity and each MV station has the same peak load.

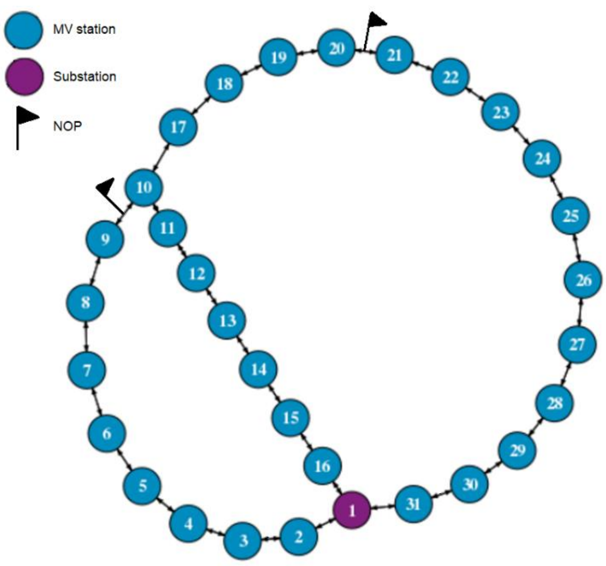

Figure 5.7 - Network after SA optimization.

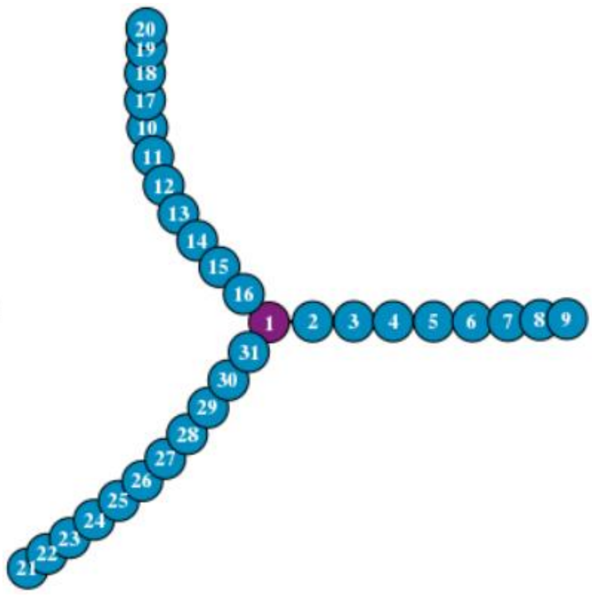

Figure 5.8 - Trans_edges after SA optimization.

The algorithm running time is 34.54 seconds with the cooling scheme applied from Section 5.7. A shared server of Alliander was used. The server has 32 cores, which is limited to a single core for each session. The algorithm running time is based on the performance of this single core.

The NOPs were cables (2 - 3) and (30 - 31) and are replaced by two NOPs that are cables (9 - 10) and (20 - 21). Resulting in a cost of 400. The objective value is also 400, as there are no voltage or current capacity problems in the solution found. The algorithm returns an *MSRlist* and a *Trans_edges* table as shown in Figures 5.9 and 5.10. Two new columns are added. The 'U_MSR' column show the voltage on the MV stations. The 'I_cable' represents the current on the cable in Ampère.

	MSR_railkey	Power Consumption	Minimum Voltage Capacity	Maximum Voltage Capacity	U_MSR
1	2	98000	9500	10500	10492.89
2	3	98000	9500	10500	10486.67
3	4	98000	9500	10500	10481.34
4	5	98000	9500	10500	10476.90
5	6	98000	9500	10500	10473.35
6	7	98000	9500	10500	10470.69
7	8	98000	9500	10500	10468.91
8	9	98000	9500	10500	10468.03
9	10	98000	9500	10500	10395.46
10	11	98000	9500	10500	10407.74
11	12	98000	9500	10500	10420.90
12	13	98000	9500	10500	10434.95
13	14	98000	9500	10500	10449.88
14	15	98000	9500	10500	10465.70
15	16	98000	9500	10500	10482.41
16	17	98000	9500	10500	10384.06
17	18	98000	9500	10500	10373.54
18	19	98000	9500	10500	10363.90
19	20	98000	9500	10500	10355.14
20	21	98000	9500	10500	10347.26
21	22	98000	9500	10500	10340.25
22	23	98000	9500	10500	10334.12
23	24	98000	9500	10500	10328.87
24	25	98000	9500	10500	10324.50
25	26	98000	9500	10500	10321.00
26	27	98000	9500	10500	10318.37
27	28	98000	9500	10500	10316.62
28	29	98000	9500	10500	10315.75
29	30	98000	9500	10500	10497.33
30	31	98000	9500	10500	10498.22

Figure 5.9 - Results: voltages for each MV station.

	Edge	Node1	Node2	Impedance	Current Capacity	I_cable
1	1	1	2	0.1	100	71.080517
2	2	1	16	0.1	100	97.566625
3	3	1	31	0.1	100	97.566625
4	4	2	3	0.1	100	62.182272
5	5	3	4	0.1	100	53.289301
6	6	4	5	0.1	100	44.400848
7	7	5	6	0.1	100	35.516161
8	8	6	7	0.1	100	26.634486
9	9	7	8	0.1	100	17.755069
10	10	8	9	0.1	100	8.877158
11	12	10	11	0.1	100	44.288358
12	13	10	17	0.1	100	35.426180
13	14	11	12	0.1	100	53.154291
14	15	12	13	0.1	100	62.024732
15	16	13	14	0.1	100	70.900433
16	17	14	15	0.1	100	79.782147
17	18	15	16	0.1	100	88.670626
18	19	17	18	0.1	100	26.567007
19	20	18	19	0.1	100	17.710086
20	21	19	20	0.1	100	8.854668
21	23	21	22	0.1	100	8.854668
22	24	22	23	0.1	100	17.710086
23	25	23	24	0.1	100	26.567007
24	26	24	25	0.1	100	35.426180
25	27	25	26	0.1	100	44.288358
26	28	26	27	0.1	100	53.154291
27	29	27	28	0.1	100	62.024732
28	30	28	29	0.1	100	70.900433
29	31	29	30	0.1	100	79.782147
30	32	30	31	0.1	100	88.670626

Figure 5.10 - Results: currents on the cables.

Note that in both, voltage and current constraints are not violated anymore.

5.9 Conclusion

This chapter shows our first step in creating a model for MV network expansion problems. We proposed a model that optimizes the repositioning of NOPs to mitigate capacity problems.

We used knowledge gathered in our literature review (see Chapter 3) to model a theoretical network. The radial operation constraint is checked in an computationally inexpensive way. We exploited the fact that Equation 5.1 holds for radially operated networks. Performing a connectivity check, while keeping the number of cables in de configuration constant, results in radially operated networks. The connectivity of a graph is easily checked using the 'vertex.connectivity' function from the 'igraph' package in R.

Using the fast load flow calculation proposed by Van Westering et al. (2019), we were able to check the voltages and currents in the network in an relatively computationally inexpensive way.

The simulated annealing algorithm seems promising for optimizing the configuration of the network. By starting with a bad placement of the NOPs, the simulated annealing algorithm optimized the network and reacts as expected. Our approach resulted in a very fast algorithm running time of only 35 seconds.

Interesting to note is that this algorithm may be useful for optimizing the network to reduce power losses in an MV network, as we are able to manipulate the network in a model by repositioning NOPs. However, power losses are not the scope of this research project. The algorithm can be used for short term planning. Sometimes in practical cases, it is known that a new substation will soon be completed. A temporarily low cost solution is desirable, which this algorithm fulfills.

6 Adding cables as a planning option

In this chapter, we add more complexity to the model by introducing the possibility of adding cables as a planning option. The topology of the network changes when cables are added between two nodes that did not have a connection before. The new operators used in this chapter require some considerations to apply it in the algorithm. There are also some changes made to the objective function.

In addition, adding cables as expansion options requires an estimation for the properties of the cable, such as length and impedance. The cable length determines the cost of the cable as well as the assumed constant impedance that is used for a load flow calculation.

This chapter is structured in a similar way as Chapter 5. We first discuss the assumptions of the model in Section 6.1. We have made some small changes to the test network, which is discussed in Section 6.2. The constraints and a decision rule to reduce the solution space by using expert knowledge is discussed in Section 6.3. In Section 6.4 we discuss the objective function. The way we translated the planning option into two operators is discussed in Section 6.5. After this, we specify the cooling scheme in Section 6.6. Last, we discuss the results and the conclusion is given in Section 6.7 and 6.8, respectively.

6.1 Assumptions

We make the same assumptions as in Chapter 5 and add some additional assumptions.

- First assumption is that candidate cables are always between a substation and an MV station. We apply expert knowledge to prevent impractical solution, as discussed in Section 2.6 and Section 3.7. We discuss the applied decision rules further in Section 6.3.

- In this model, the n-1 principle is ignored. Checking the n-1 principle tends to be a computationally expensive task to perform. We revisit this subject in Chapter 7.

- In this chapter two functions are proposed that add and remove cables to the network. The latter cannot remove existing cables from the input network.

6.2 Test network

The same topology of the theoretical network is used as in Chapter 5. However, an additional vector is introduced, representing the distances from the substation to every node. Random distances between 40 and 50 are generated. Table 6.1 shows the distances from the substation to every MV station.

to:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
distance:	0	46	45	47	49	46	49	48	48	50	42	46	42	42	45	48

to:	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
distance:	42	49	46	46	47	49	40	50	45	48	44	48	45	44	44

Table 6.1 - Distances from the substation to the MV stations.

Figure 6.1 shows the network topology and Figure 6.2 shows the configuration of the network. Both are the same compared to the network used in Chapter 5.

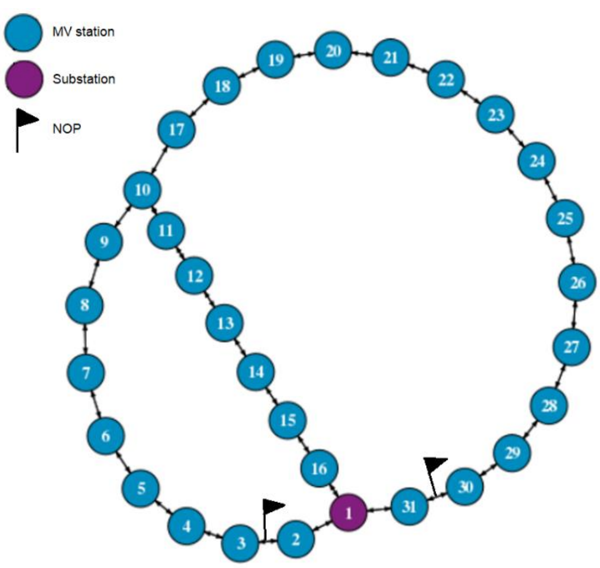

Figure 6.1 - Configuration of the test network.

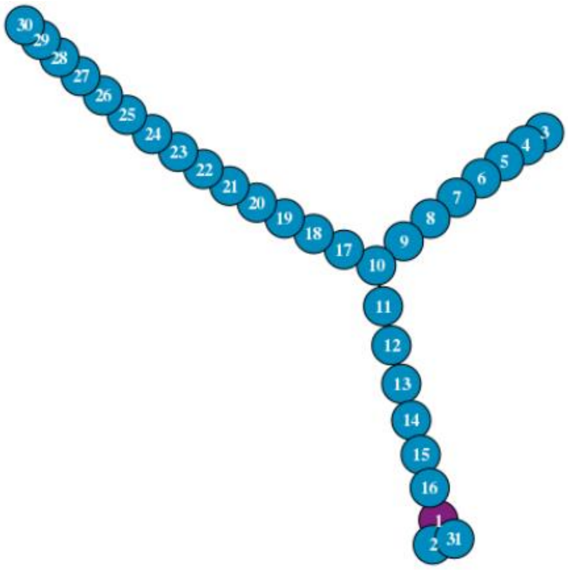

Figure 6.2 - Configuration of the test network.

Another difference compared to the network of Chapter 5 is that the loads are increased to 105,000W. The extra loads make sure that the network cannot become feasible without adding extra cables. An initial linear load flow calculation is executed to get the currents on the cables and the voltages on the MV stations.

	MSR_railkey	Power Consumption	Minimum Voltage	Maximum Voltage	U_MSR
1	2	105000	9500	10500	10499.05
2	3	105000	9500	10500	10309.98
3	4	105000	9500	10500	10310.92
4	5	105000	9500	10500	10312.79
5	6	105000	9500	10500	10315.60
6	7	105000	9500	10500	10319.35
7	8	105000	9500	10500	10324.04
8	9	105000	9500	10500	10329.66
9	10	105000	9500	10500	10336.22
10	11	105000	9500	10500	10356.79
11	12	105000	9500	10500	10378.29
12	13	105000	9500	10500	10400.74
13	14	105000	9500	10500	10424.13
14	15	105000	9500	10500	10448.47
15	16	105000	9500	10500	10473.76
16	17	105000	9500	10500	10323.16
17	18	105000	9500	10500	10311.04
18	19	105000	9500	10500	10299.85
19	20	105000	9500	10500	10289.60
20	21	105000	9500	10500	10280.28
21	22	105000	9500	10500	10271.90
22	23	105000	9500	10500	10264.45
23	24	105000	9500	10500	10257.93
24	25	105000	9500	10500	10252.35
25	26	105000	9500	10500	10247.70
26	27	105000	9500	10500	10243.97
27	28	105000	9500	10500	10241.18
28	29	105000	9500	10500	10239.32
29	30	105000	9500	10500	10238.39
30	31	105000	9500	10500	10499.05

Figure 6.3 - Initial voltages on the MV stations.

	Edge	Node1	Node2	Impedance	Current Capacity	I_cable
1	1	1	2	0.1	100	9.539425
2	2	1	16	0.1	100	262.405174
3	3	1	31	0.1	100	9.539425
4	5	3	4	0.1	100	9.367643
5	6	4	5	0.1	100	18.736137
6	7	5	6	0.1	100	28.106334
7	8	6	7	0.1	100	37.479084
8	9	7	8	0.1	100	46.855240
9	10	8	9	0.1	100	56.235653
10	11	9	10	0.1	100	65.621175
11	12	10	11	0.1	100	205.633914
12	13	10	17	0.1	100	130.621254
13	14	11	12	0.1	100	215.044083
14	15	12	13	0.1	100	224.473791
15	16	13	14	0.1	100	233.923894
16	17	14	15	0.1	100	243.395252
17	18	15	16	0.1	100	252.888724
18	19	17	18	0.1	100	121.241637
19	20	18	19	0.1	100	111.873037
20	21	19	20	0.1	100	102.514601
21	22	20	21	0.1	100	93.165480
22	23	21	22	0.1	100	83.824823
23	24	22	23	0.1	100	74.491783
24	25	23	24	0.1	100	65.165511
25	26	24	25	0.1	100	55.845161
26	27	25	26	0.1	100	46.529884
27	28	26	27	0.1	100	37.218835
28	29	27	28	0.1	100	27.911168
29	30	28	29	0.1	100	18.606036
30	31	29	30	0.1	100	9.302596

Figure 6.4 - Initial currents on the cables.

Figure 6.3 shows that the voltage remain within the specified boundaries, while Figure 6.4 shows that currents on the cable exceeds the capacity constraint for many cables.

6.3 Constraints and decision rules

We use the same set of constraints as in Chapter 5, and evaluate them the same way. We add one constraint which is about the number of outgoing cables at a substation. In this case we limit them to 6. In practice, there is a limit to how many cables that are physically able to be attached to a rail in a substation. The outgoing cables are easily checked by counting how often node 1 is listed in the *network* table.

Decision rules

When adding the possibility of cables between nodes, the solution space may grow very fast. A way to reduce the solution space is to exclude new cable options that are less likely of making the solution better. (Grond, 2015) applied expert knowledge to discard many cable expansion options, which is described in Section 3.7. A test network was used that only contained one substation. Decision Rule 1 is that there should be no subrings, due to protection reasons. In addition, cables are not replaced due to the long lifetime of the cables. As a result, only new connections that start at a substation and end at an MV-station are candidate options, which is option 1 in Figure 2.9. We apply this expert knowledge in this chapter.

6.4 Objective function

The objective function from Chapter 5 is the starting point for the objective used here. We add the costs of new cables that is defined as a constant costs per unit of length. We also apply a different version of the penalization of alternatives that violate the capacity constraint. We apply the parameter dependent penalization as described in Section 3.3. We divide the total overload by the current temperature. This means that at the start of the algorithm, neighbors that violate the capacity constraint are not penalized that heavily. After each Markov chain the temperature decreases and capacity exceedances are penalized more heavily. This forces the algorithm into finding solutions that are feasible. In addition, we only accept solutions as best solutions if also the overload is zero. Summarizing, the objective function is as following:

The parameters are:

Weight current = 1,000,000
Weight voltage = 100,000
Cost per switch = 100
Cost cable per unit of length = 200

The weights are increased a lot compared to the weights in Chapter 5, as we now divide the overload by the temperature.

The objective function that should be minimized is:

$$\begin{aligned} objective = {} & (cost\ per\ switch * number\ of\ switches) \\ & + (cost\ per\ unit\ of\ length * total\ length\ of\ new\ cables) \\ & + \frac{penalization\ for\ overloading}{temperature} \end{aligned} \tag{6.1}$$

The investments costs contain a fixed cost for turning a switch on or off and the total length of new cables multiplied by a cost per unit of length. The penalization for overloading is described as:

$$\begin{aligned} & penalization\ for\ overloading = (weight\ current * \\ & total\ amount\ of\ currents\ exceeded) + (weight\ voltage * \\ & total\ amount\ of\ voltages\ outside\ specified\ bandwidths) \end{aligned} \tag{6.2}$$

The objective is penalized by total amount of currents and voltages outside the specified limits. Weights have been used to compensate for the relative importance between exceeding one voltage and one current. The total penalization is divided by the current temperature as explained.

6.5 Additional operators: remove and add cables

As stated in Section 6.3, we restrict ourselves to new solutions that add cables from a substation to an MV station. We discuss the considerations that were dealt with while translating the option to add cables into actual operators.

When deriving a neighbor solution, we try to make a change that is as small as possible. In addition, every solution should be reachable. When adding a cable to the network, we know that Equation 5.1 does not hold anymore as we add a cable to the network without adding a NOP. This means that we have to add a NOP as well.

We created a function that adds a cable as a NOP to the network, to create a change as small as possible. Adding a cable as a NOP only makes the solution worse, initially. This is because a cable is added, with investment costs, while not actually creating more capacity. This does not mean that cables are never added to the network, as simulated annealing is capable of overcoming this by being able to accept worse neighbor solutions. However, the algorithm is restrained to add cables.

Complementary, a function is created that is able to remove cables. We decided that this function is restricted to removing the cables that were added by the algorithm before. Removing a cable from the configuration requires a current NOP to be closed to ensure a radial configuration. To resemble a change as small as possible, we created a function that randomly removes cables that are not in the configuration. Only cables that are NOP are candidates.

Before each Markov chain, a function is called that randomly chooses an operator from the three that we have: swap two switches, add cable and remove cable. It first identifies which operators are possible. A remove function is not possible when there are no more added cables to remove. An add function is not possible when we have reached the maximum amount of outgoing cables from the substation. From the set of possible operators, the function chooses one with an equal probability. The chosen operator is then repeated by the length of the Markov chain. In case of a remove or add function, the Markov chain may be stopped before the Markov chain length is reached. This may be the case when we have reached the limit of outgoing cables with an add function. It is also possibly that there no more candidate cables that can be removed, in case of the remove cable function.

When using the functions described above, we created an algorithm that is restrained and has weak means to add and remove cables. The main reason is that a cable has a relatively small probability of being added, because it does not make the solution better when added as a NOP. The added cable could only make the solution better when it is switched into the configuration by the swap operator later. The second disadvantage is that it is relatively hard to remove cables, as only cables that are NOP are candidates for the remove function.

To cope with these disadvantages we made some changes to the functions. A cable that is added, is now immediately followed by a swap that adds the new cable into the configuration. The advantage is that an added cable has the possibility to immediately add capacity to the network and therefore a better decision can be made to accept or decline the solution with the new cable.

The other change is that the remove function now also removes new cables that are in the configuration. If this happens, another cable that is an NOP is added into the configuration to make the configuration radial again. The advantage is that cables do not necessarily have to be a NOP to be removed and therefore the algorithm has more flexibility to remove cables.

We will now explain the add cable and remove cable functions by means of two flow charts. In Figure 6.5 and 6.6 the add cable function and remove cable functions are presented, respectively.

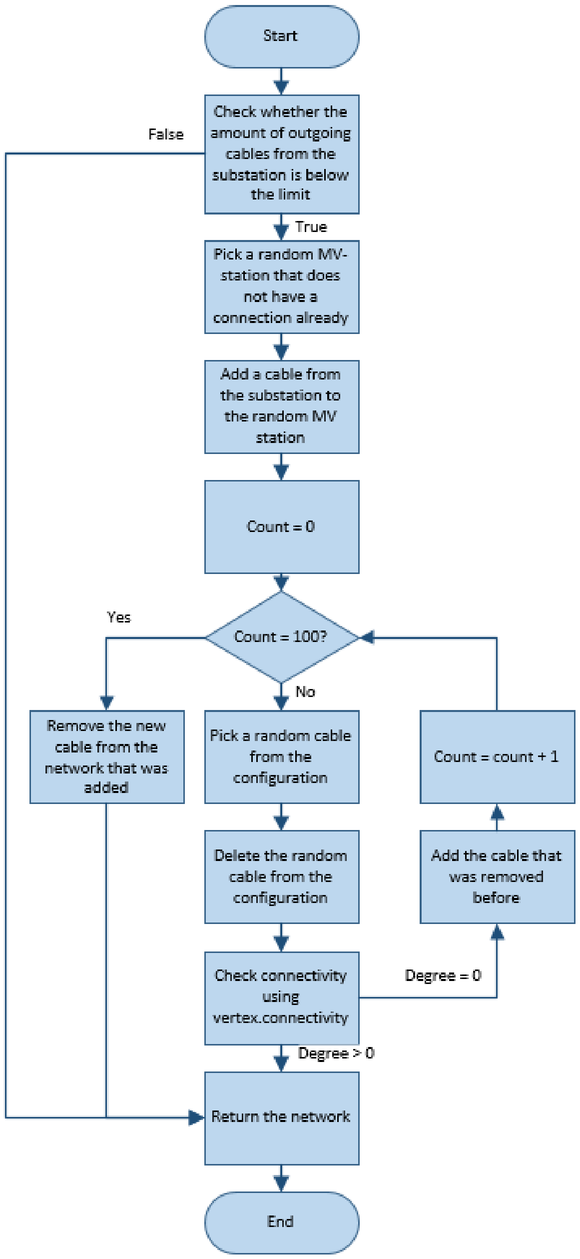

Figure 6.5 - Flowchart of the 'Add cable' function.

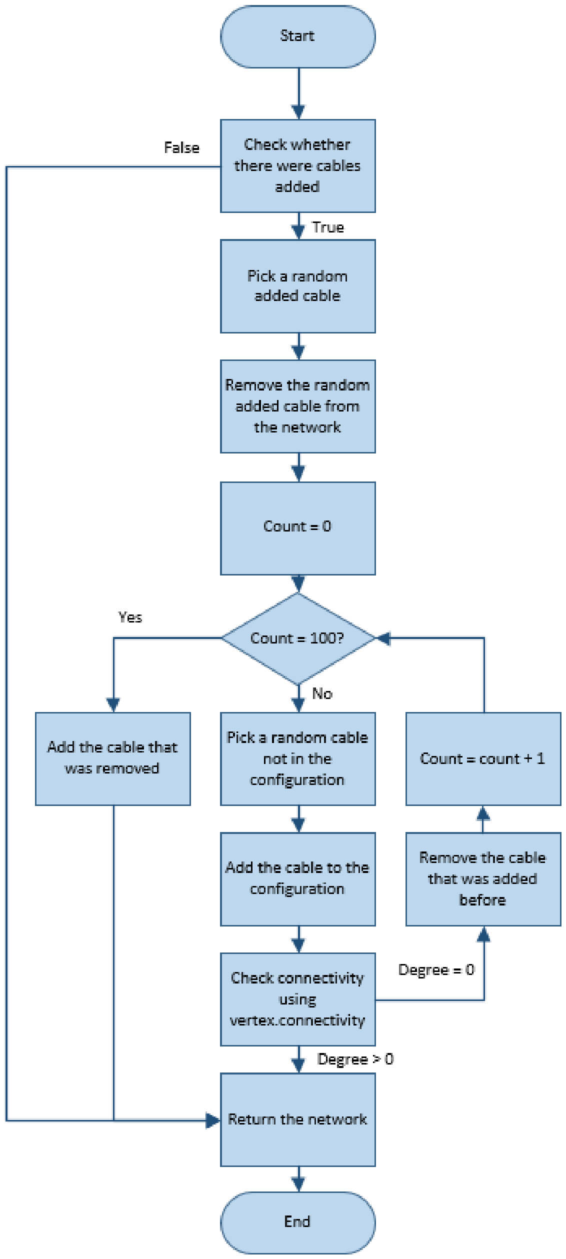

Figure 6.6 - Flowchart of the 'Remove cable' function.

'Add cable' function

The function 'add cable' starts by checking the number of outgoing cables. If the number exceeds the maximum of outgoing cables that we are able to connect, the function returns the same network that was input for the function. If we can still add a cable, a random MV station that has no connection yet to the substation is picked and gets a cable connection to the substation. The cable is then put into the configuration. To maintain a radial configuration, we have to remove a cable from the configuration as well. A random cable from the configuration is chosen and removed from the configuration. Note that the cable is not removed from the network, but from the configuration only. A connectivity check is performed to check whether the network is connected. If the graph is not connected, the cable is added to the configuration again to undo the previous action. We count this action and repeat the process of removing cables from the configuration until a connected (and radial) configuration is found. We set a maximum number of tries to remove a cable from the configuration to 100. If we do not find a feasible solution after 100 tries we remove the new cable from the network completely and return the network that was input for the function. Only when the new configuration passes the connectivity check, the new network is returned.

'Remove cable' function
The function 'remove cable' works in a similar way as the add cable function, but the other way around. The other difference is that instead of checking the number of outgoing cables, we check whether the network contains cables that were added before by the algorithm. If the network has no new cables, we cannot remove one, so the function returns the input network.

6.6 Cooling scheme

The cooling scheme is determined the same way as in Chapter 5. We have an algorithm with three different operators and therefore we choose a cooling scheme that is more extensive than the one used in Chapter 5. The decreasing factor is increased to 0.99, so it cools more slowly. The Markov chain length is increased to 50. Summed up, the following parameters have been applied:

Starting temperature c_0 = 50,000
Stopping temperature c_{stop} = 100
Decreasing factor α = 0.99
Markov chain length k = 50

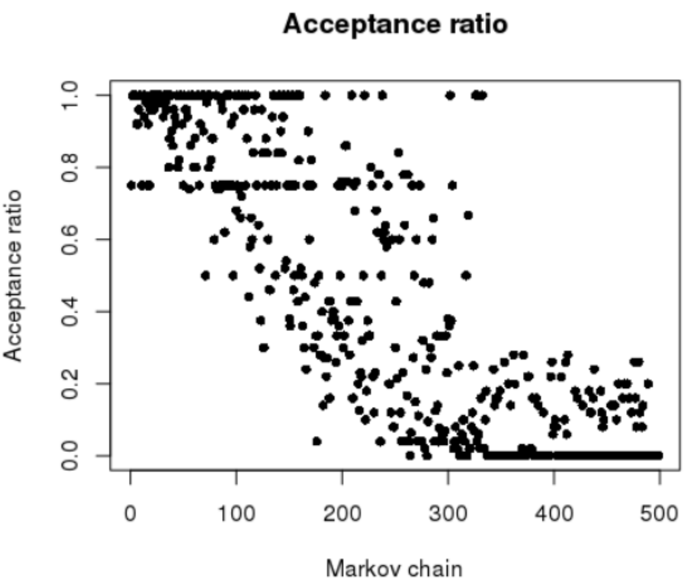

Figure 6.7 - Acceptance ratio when running the SA algorithm.

The acceptance ratio per Markov chain is plotted in Figure 6.7. The Markov chains are logically numbered and plotted on the x-axis. The y-axis shows the acceptance ratio in each Markov chain. It shows that initially almost all neighbors are accepted, while in the end almost no neighbors are accepted.

6.7 Results

After running the simulated annealing algorithm a network and configuration is returned. These are plotted in Figure 6.8 and 6.9 respectively. An extra cable is added between the substation and node 23. The extra cable means that we also need an additional NOP. The NOPs are cables (8 – 9), (18 – 19) and (24 - 25). The result is that we have an additional path from the substation. The objective function value is 8,600. 8,000 is spent on a new cable of length 40. 3 switches are opened and 3 switches are closed, which costs 600 in total.

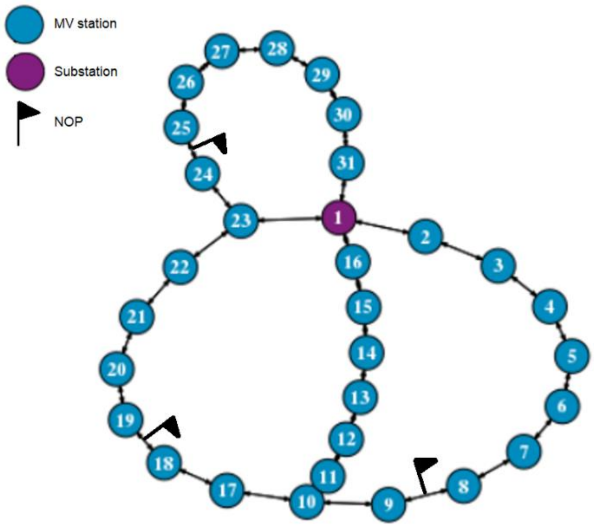

Figure 6.8 - Network topology after SA optimization.

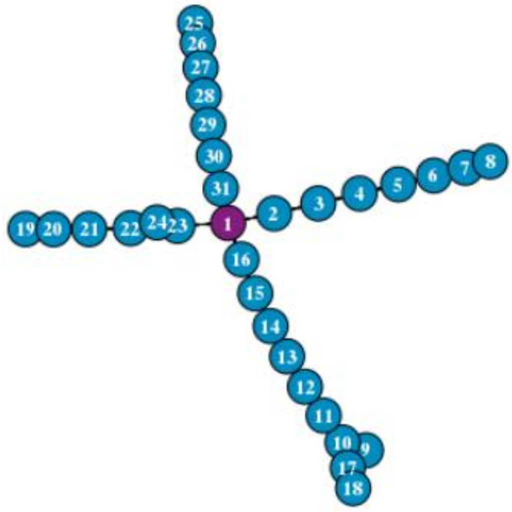

Figure 6.9 - Configuration after SA optimization.

Figure 6.10 and 6.11 show that the voltage and current capacities constraints are satisfied. The algorithm running time is 2 minutes and 55 seconds.

	MSR_railkey	Power Consumption	Minimum Voltage	Maximum Voltage	U_MSR
1	2	105000	9500	10500	10493.33
2	3	105000	9500	10500	10487.62
3	4	105000	9500	10500	10482.86
4	5	105000	9500	10500	10479.05
5	6	105000	9500	10500	10476.20
6	7	105000	9500	10500	10474.30
7	8	105000	9500	10500	10473.34
8	9	105000	9500	10500	10452.49
9	10	105000	9500	10500	10453.44
10	11	105000	9500	10500	10457.24
11	12	105000	9500	10500	10461.99
12	13	105000	9500	10500	10467.69
13	14	105000	9500	10500	10474.34
14	15	105000	9500	10500	10481.94
15	16	105000	9500	10500	10490.49
16	17	105000	9500	10500	10451.54
17	18	105000	9500	10500	10450.59
18	19	105000	9500	10500	10484.75
19	20	105000	9500	10500	10485.71
20	21	105000	9500	10500	10487.61
21	22	105000	9500	10500	10490.47
22	23	105000	9500	10500	10494.28
23	24	105000	9500	10500	10493.33
24	25	105000	9500	10500	10473.34
25	26	105000	9500	10500	10474.30
26	27	105000	9500	10500	10476.20
27	28	105000	9500	10500	10479.05
28	29	105000	9500	10500	10482.86
29	30	105000	9500	10500	10487.62
30	31	105000	9500	10500	10493.33

	Edge	Node1	Node2	Impedance	Current Capacity	I_cable
1	1	1	2	0.1	100	66.660937
2	2	1	16	0.1	100	95.077395
3	3	1	31	0.1	100	66.660937
4	4	2	3	0.1	100	57.126702
5	5	3	4	0.1	100	47.597657
6	6	4	5	0.1	100	38.072937
7	7	5	6	0.1	100	28.551676
8	8	6	7	0.1	100	19.033010
9	9	7	8	0.1	100	9.516073
10	11	9	10	0.1	100	9.497123
11	12	10	11	0.1	100	37.986767
12	13	10	17	0.1	100	18.991658
13	14	11	12	0.1	100	47.488204
14	15	12	13	0.1	100	56.993957
15	16	13	14	0.1	100	66.504887
16	17	14	15	0.1	100	76.021861
17	18	15	16	0.1	100	85.545741
18	19	17	18	0.1	100	9.495398
19	21	19	20	0.1	100	9.526439
20	22	20	21	0.1	100	19.053744
21	23	21	22	0.1	100	28.582781
22	24	22	23	0.1	100	38.114414
23	25	23	24	0.1	100	9.534230
24	27	25	26	0.1	100	9.516073
25	28	26	27	0.1	100	19.033010
26	29	27	28	0.1	100	28.551676
27	30	28	29	0.1	100	38.072937
28	31	29	30	0.1	100	47.597657
29	32	30	31	0.1	100	57.126702
30	33	1	23	0.1	100	57.183740

Figure 6.10 - MSRlist after SA optimization. *Figure 6.11 - Cables in use after SA optimization.*

The Figures 6.10 and 6.11 show that the current and voltage constraint are not violated anymore.

6.8 Conclusion

In this chapter, we expanded the model proposed in Chapter 5 by adding new cable connections as a planning option.

To test the algorithm, we used the same test network as in Chapter 5, but increased the power consumption of MV station to make sure that the addition of new cable connection is inevitable. By adding one additional cable the algorithm could anticipate the additional loads. Surprisingly, the algorithm still finished with a fast running time of only 2 minutes and 55 seconds.

Expert knowledge proposed by Grond (2016) is applied to prevent impractical solutions. Additionally, it helps to reduce the solution space and speed up the algorithm running time.

The parameter penalization method is introduced in the model. This way we are able to model the voltage and current constraints as soft constraints. The overloads on the cables and the voltages outside the limits are increasingly penalized as the temperature of the SA algorithm decreases. The test that we performed in this chapter suggests that the parameter penalization method is effective as the algorithm eventually converged to feasible solutions.

In this chapter we ignored checking the n-1 principle as an exact method is a computationally expensive task. In Chapter 7 we revisit this subject and check the appropriateness of an approximation method that we found in literature.

7 Checking the n-1 principle in heuristic approaches

Checking the n-1 principle in an optimization algorithm is a challenge, as current algorithms are computationally expensive to use. Recall that we discussed approximation approaches for checking the n-1 constraint in Section 3.6. Two simplifications for the n-1 principle were proposed. One simplification by Grond (2016) is to close all NOPs and simulate a failure for each cable. In this chapter, we aim to get a better idea about the accuracy of this approximation.

7.1 Checking the appropriateness of the approximation that closes all NOPs

The method by Grond (2016) closes all NOPs as an approximation for the (optimal) reconfiguration in an n-1 situation. This way, long computation times are prevented. However, the radial operation criterion is violated. If we would apply this method, we should at least have some idea of how good the approximation method is. To test this, we do an experiment. What the approximation method by Grond (2016) suggests, is that the loads of the optimal reconfiguration can be estimated by closing all NOPs in the network. The following question arises: 'How accurate is the method by proposed by Grond (2016) for estimating the optimal (re)configuration of an MV network?'

We again consider the network used in Chapter 6. The capacities of the cables are set to 120 such that a feasible configuration exist. We optimized this configuration of the network using our 'swap two switches' algorithm. In addition, we did a load flow calculation for the network in which all NOPs are closed. Last, we performed a load flow calculation using the initial bad configuration that was used in Chapter 6.

In Figure 7.1 the x-axis represent the 32 cables of the network and the y-axis represent the cable load in ampere (A). The three situations which we just described are plotted in Figure 7.1.

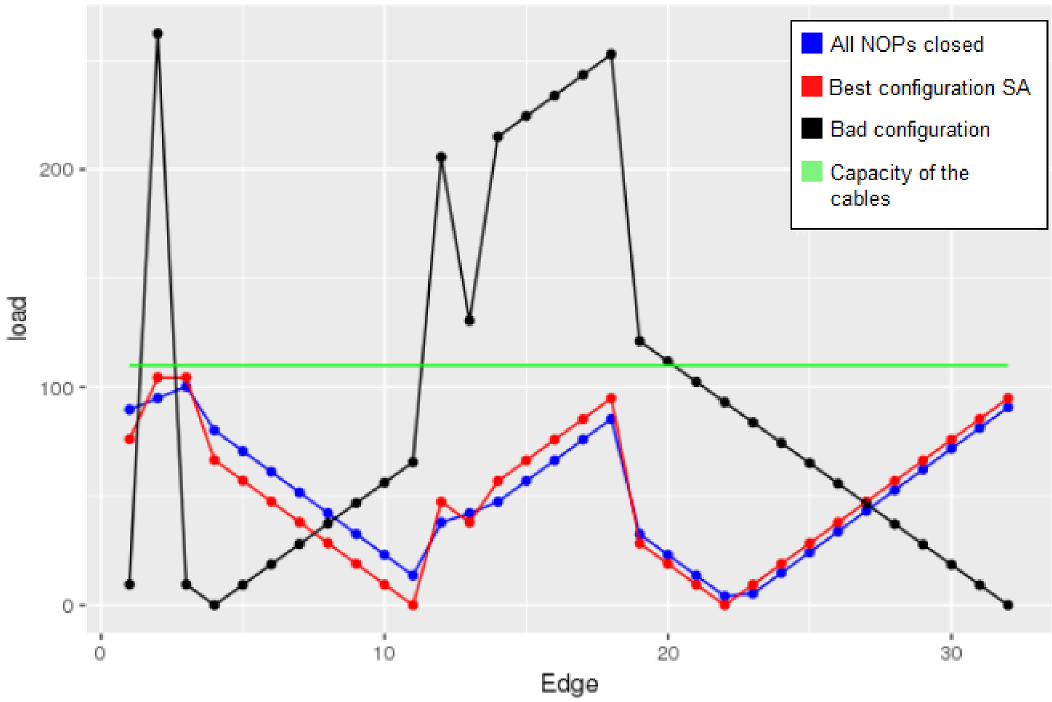

Figure 7.1 - Loads per edge for the approximation method (blue) good configuration (red) and bad configuration (black)

The results that are presented in Figure 7.1, are also presented in table form in Figure 7.2.

	edge	node1	node2	All_switched_closed	Good_configuration	Bad_configuration
1	1	1	2	89.774389	76.145968	9.539425
2	2	1	16	95.034179	104.506698	262.405174
3	3	1	31	100.375429	104.506698	9.539425
4	4	2	3	80.242253	66.612594	0.000000
5	5	3	4	70.717409	57.085273	9.367643
6	6	4	5	61.198990	47.563139	18.736137
7	7	5	6	51.686132	38.045326	28.106334
8	8	6	7	42.177969	28.530970	37.479084
9	9	7	8	32.673639	19.019207	46.855240
10	10	8	9	23.172278	9.509171	56.235653
11	11	9	10	13.673022	0.000000	65.621175
12	12	10	11	37.943469	47.434068	205.633914
13	13	10	17	42.118478	37.942084	130.621254
14	14	11	12	47.444930	56.930362	215.044083
15	15	12	13	56.950702	66.431829	224.473791
16	16	13	14	66.461648	75.939332	233.923894
17	17	14	15	75.978633	85.453735	243.395252
18	18	15	16	85.502522	94.975902	252.888724
19	19	17	18	32.624291	28.453547	121.241637
20	20	18	19	23.133069	18.967595	111.873037
21	21	19	20	13.643948	9.483367	102.514601
22	22	20	21	4.156068	0.000000	93.165480
23	23	21	22	5.331436	9.483367	83.824823
24	24	22	23	14.819423	18.967595	74.491783
25	25	23	24	24.308757	28.453547	65.165511
26	26	24	25	33.800300	37.942084	55.845161
27	27	25	26	43.294914	47.434068	46.529884
28	28	26	27	52.793462	56.930362	37.218835
29	29	27	28	62.296806	66.431829	27.911168
30	30	28	29	71.805811	75.939332	18.606036
31	31	29	30	81.321340	85.453735	9.302596
32	32	30	31	90.844258	94.975902	0.000000

Figure 7.2 - Analysis of the approximation method for reconfiguration.

Both figures show that the loads of the cables in the meshed operation (all NOPs closed) and the best solution by SA are very similar. The bad solution is definitely different from the other two solutions.

An explanation for this behavior could be as following: The meshed form of the network seems to be most effective in distributing the loads proportionally over the network. In most cases, this will be a very good configuration, because all loads are then distributed over all cables as evenly as possible. However, we have to meet the radial operation constraint. The NOPs placed by the SA algorithm are placed in such a way that the loads are similar to the meshed operation. Note that the NOPs placed by SA algorithm are also the minima in Figure 7.1. When making a cable a NOP, our expectation is that we generally want to choose a cable that has a low load when the network is calculated in its meshed form. The additional load that other cables have to take over is then minimal.

We also note that the difference in percentage is especially low for the highest loads in the network, which are of most interest as these cables approach the maximum capacity of the cable.

This experiment suggests that the method gives a reasonable estimation of the loads on the cables of the optimal configuration. This suggests that we could use estimate the optimal reconfiguration, in case of a cable outage, as well.

Using the approximation method we can reduce the number of load flow calculations from many per cable, to just one load flow calculation per cable. This can also be reduced to one load flow calculation for the whole network when LODF are applied (Grond, 2016). This again introduces an error to the apparent power flow of maximally +/- 6% for high loaded branches (Grond, 2016).

7.2 Conclusion

The n-1 principle is a challenge to be incorporated in expansion planning models that rely on the evaluation of many alternatives. The constraint itself is a combinatorial optimization problem with a solution space of 2^k, where k is the number of switches (Mendes et al., 2010). One approximation that is used in a recent paper (Grond, 2016), is analyzed in this chapter. We tested how closing all NOPs in the network compares to a good configuration found by the SA annealing algorithm and a really bad configuration. The analysis showed that the loads of the approximation method are very similar to the best configuration found by SA, for our test network. The analysis suggests that the method gives a reasonable estimation of the loads on the cables of the optimal configuration.

In the next chapter, we will apply the algorithms developed in Chapter 5 and 6 on a real MV network in a case study. In addition, we incorporate an n-1 check in the algorithm of Chapter 6 in Section 8.7.

8 Case study

The algorithms proposed in this thesis were all tested on a theoretical network. This chapter considers the algorithms in regard to a real network. We need to gather data about the required characteristics of the network. These data consist of the topology of the network itself, an estimation of candidate cable lengths and a prediction of future peak loads. In this case study we will use the demand forecast of the year 2040.

In Section 8.1 we describe the MV network that we choose for our case study. Section 8.2 addresses the data preparation to be able to model the network. In Section 8.3 we describe a tool that is created to easily apply the algorithms proposed in this thesis. Section 8.4 and 8.5 present the results of both algorithms. We have presented the results to experts and received feedback. We describe this in Section 8.6. In Section 8.7, we apply an n-1 check within the second algorithm. In Section 8.8 a conclusion is given for this chapter.

8.1 MV network: (confidential)

The case that we choose to test our algorithms on is the MV network that covers most of *(confidential)*. The reason that we choose this test network is that this network is already used as a case by another team within Liander. The team already modelled the network as a graph and therefor the data is easily available.

The MV network is relatively large with one substation (located in *(confidential)*), 358 MV stations and 394 cable sections. Consequently, 36 NOPs are placed to keep the configuration radial. Liander has around 350 substations and 42,000 MV stations averaging 120 MV stations per substation. A schematic overview of the network is presented in Figure 8.1.

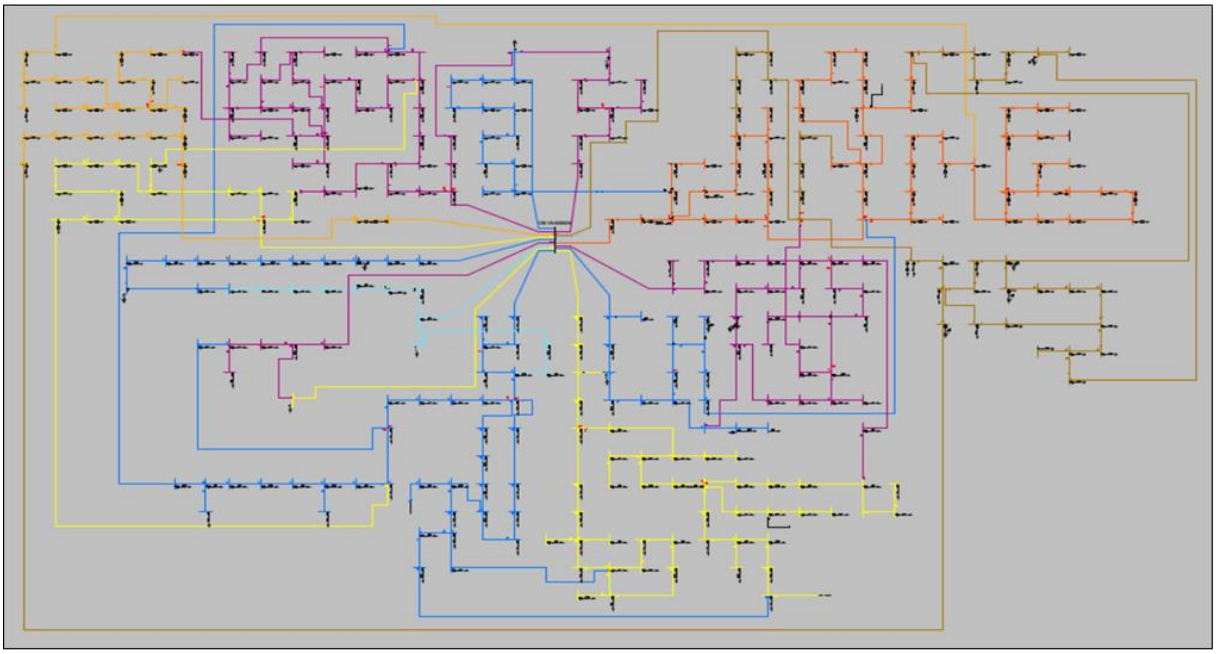

Figure 8.1 - Schematic overview of the MV network: (confidential).

This figure shows the meshed structure of the network that is presented in Vision, the software tool that network planners use. The rail that is placed in the middle is the substation. The bars that are perpendicular on each path, represent MV rails. Most of the MV rails have transformers connected to feed LV networks. Each path that starts at the substation is colored differently. A NOP is placed at the places where two paths connect to ensure a radial configuration. If you look closely, you can see how a lot of paths are connected to each other, showing the complexity of the problem.

8.2 Data preparation

In this section, we discuss the data that we have to collect to test the models of Chapter 5 and 6. An overview of the data and the source are presented in Table 8.1.

Data	**Source:**
Topology	Test network of the team 'Optimale mix'
Load forecasts for 2040 & simultaneity factors	ANDES data for AC1-AC4 forecasts. Baseloads for AC5 customers.
MS_HLD_IDs	Based on the SCH_HLD_ID and link asset ID cables were linked to the data from 'state estimation'. Some missing IDs were found manually in Vision.
Impedances	'State estimation' network. Some missing IDs were found manually in Vision.
New cable characteristics	'Klant Inpassingstool' is used to draw new cables realistically.
Simultaneity factor	Vision file.

Table 8.1 - Data and the sources that were used.

The topology of the network was obtained from another team within Liander called the 'Optimale mix'. This choice seems logical, as the data is already available as a graph. However, the disadvantage is that the data originate from the end of 2017. This might have caused some problems in matching the other data, as we are matching data from different times.

The MS_HLD_IDs are IDs for the current cables. This data is important for the visualization of the cables, which will be discussed in Section 8.3. The MS_HLD_IDs are linked to the coordinates of the cables. Internal sources were used to link the edges to MS_HLD_IDs, such as the 'State estimation' network and a network file from the 'Vision' software package. The MS_HLD_IDs were not found for around 20 of the 358 cables. This could be due to the fact that our topology originates from 2017. This is not a huge problem for proving the effectiveness of the algorithms, as this only affects the visualization of cables on a real map and not the solution.

The peak loads for AC1-AC4 customers were acquired from the 'ANDES' tool, using the 'Decentraal duurzaam' scenario. There is no long term prediction for AC5 customers. However, there is data about the peak loads of last year. These loads are extrapolated by using a conservative growth rate of 1.5% per year. In some cases the data was missing. This happened for the peak loads on the MV stations. For 28/358 nodes, no peak load was found. In these cases, we added a small but realistic peak load of 50,000 W.

The network was linked to its 'State estimation' variant to acquire the impedances of the cables. The impedances of the cables were not found in some specific cases. The average of the remaining cables is then used as an approximation.

The estimation of the characteristics of new cable connections are discussed in Section 8.5.1.

8.3 Tool to visualize the results on a map

The goal of this thesis is to find good investment strategies that can be easily applied by network planners. To this end, we designed an application within the 'Waardegedreven Assetmanagement' team. The application is called the 'Netuitbreidingstool'. It incorporates the algorithms proposed in this thesis. At the moment, the application is a Proof of Concept (PoC) and only the data for *(confidential)* is included. In Figure 8.2 this application is presented. The nodes and edges are visualized on a real map. In this version of the master thesis, the locations of the assets are anonymized. Liander does not publish the locations of their assets. We use a grey plane instead of a real map.

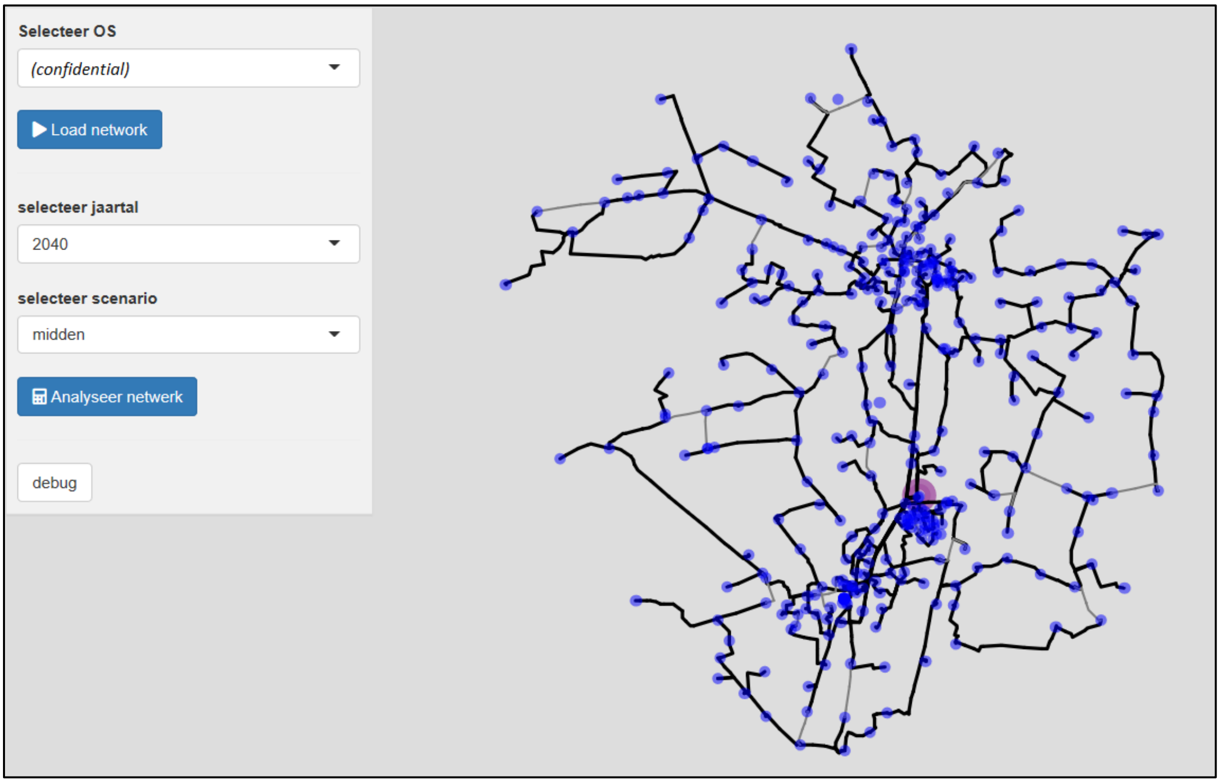

Figure 8.2 - Visualizing an MV network in the tool (anonymized).

The purple dot represents the substation and the blue dots represent the MV stations. The black lines are the cables that are in use, while the NOPs are presented as grey lines.

Using the panel on the left, one should be able to load the future demand forecast (peak loads) of a certain year in the future and a scenario of choice. Using the button 'Analyseer netwerk', one can perform a load flow calculation using the loads that were selected. The results is the visualization voltages and currents of the network in comparison to the allowed boundaries. This is shown in Figure 8.3.

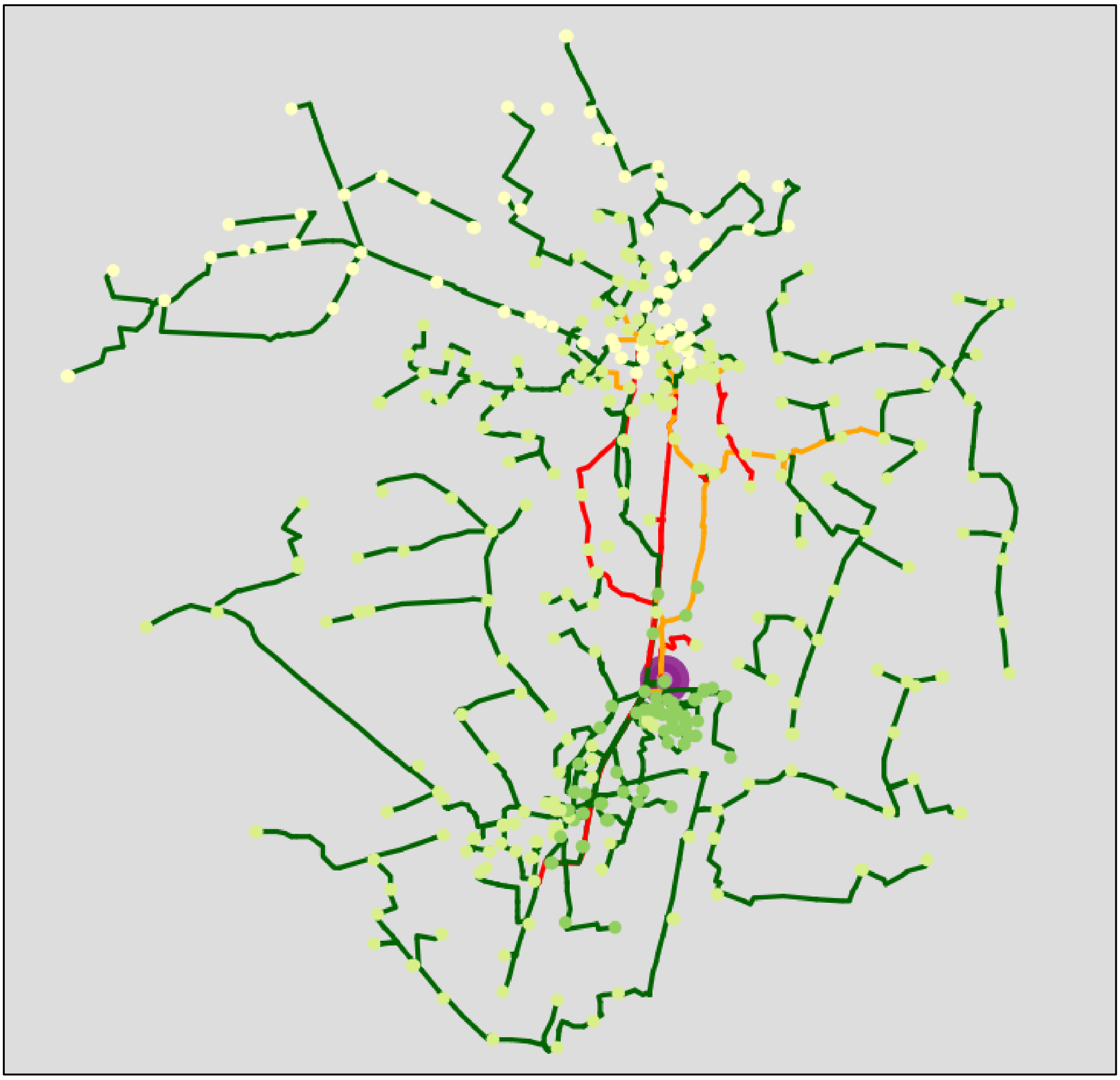

Figure 8.3 - Initial load flow calculations visualized on a map (anonymized).

The colors of the cables are colored red, orange or green. The colors on the cables have the following meaning:
Green: The capacity of the cable is utilized for 70% or less.
Orange: The capacity of the cable is utilized for more than 70% and less than 100%.
Red: The capacity of the cable is utilized for more than 100%.

For MV stations the same colors are used, but they relate to the voltages on the MV station. The more green the nodes, the higher the voltage. The more red the lower the voltage. When moving the cursor on an MV station or cable, the characteristics of the asset are shown. This is presented Figure 8.4.

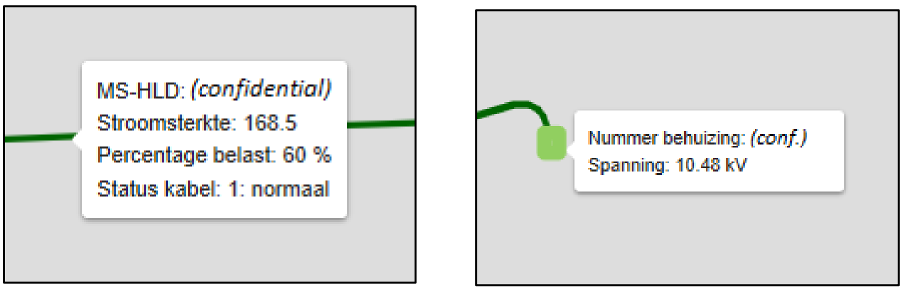

Figure 8.4 - Examples when moving the cursor over a cable (left) and an MV station (right) (anonymized).

Last, an overview of some KPIs are presented, which is shown in Figure 8.5.

	Waarde	Waarde huidig net
1	Onderstation	*(confidential)*
2	Aantal overbelaste kabel segmenten	15
3	Aantal spanningsknelpunten	0
4	Totaal aantal knelpunten	15
5	Aantal schakelingen	n.v.t.
6	Overbelasting totale net	1245.05 A
7	Lengte nieuwe kabels	0
8	Kosten nieuwe kabels	0

Figure 8.5 - Overview of KPIs in the 'Netuitbreidingstool'.

Key Performance Indicators (KPIs) are given such as the amount of cables that are overloaded and the number of MV station where the voltage is outside the allowed bandwidth. 'Overbelasting totale net' is the sum the sum of all overloads of each cable that is overloaded. This is calculated the same way we do in our objective function. In our case this is 1245.05 A divided over 15 overloaded cables.

The algorithms proposed in Chapter 5 and 6 can be run in the tool. A panel is presented in which the cooling scheme can be set. This is presented in Figure 8.6.

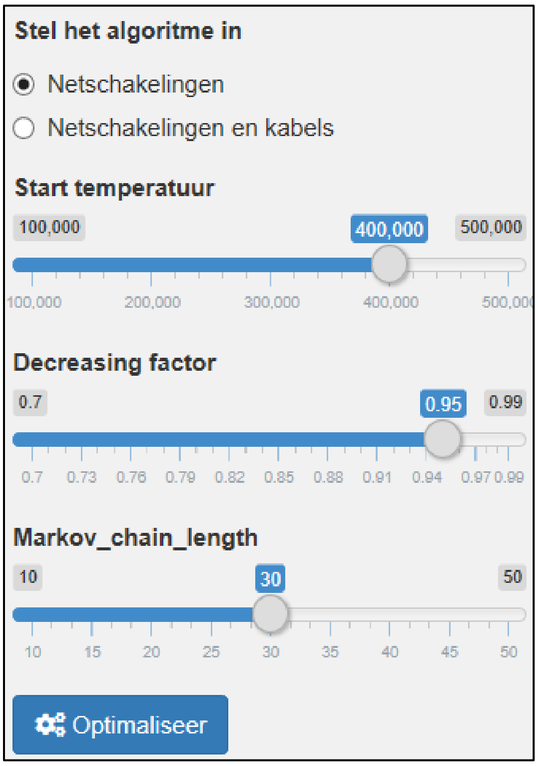

Figure 8.6 - Panel to set the cooling scheme.

After optimization, the network that results is visualized again. In the next Section 8.4 and Section 8.5, we describe the results of both algorithms, using the network of *(confidential)*.

8.4 Simulated annealing using 'swap two switches' only

With the data collected, we are able to test the first algorithm that was proposed in Chapter 5. We try to minimize the violation of current and voltage constraints by only moving NOPs.

The costs of opening or closing a switch is estimated by internal sources to be *(confidential)* euro.

8.4.1 Cooling scheme

We again determine the cooling scheme by means of the acceptance ratio. After a few iterations of tuning the parameters, the acceptance ratio after each Markov chain is plotted in Figure 8.7.

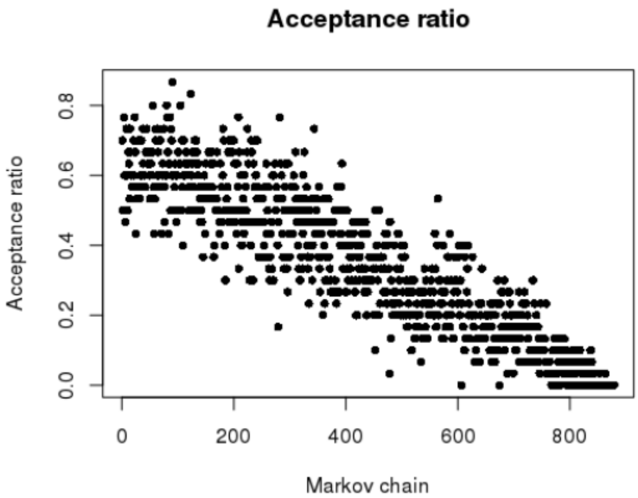

Figure 8.7 - Acceptance ratio 'Swap two switches' algorithm

Using the acceptance ratio we determined the following cooling scheme:
Starting temperature c_0 = 400,000
Stopping temperature c_{stop} = 100
Decreasing factor α = 0.99,
Markov chain length k = 30.

The weights can be chosen such that they represent the relative importance between costs, overload and voltage problems. We chose the following weights:
Weight current = 150
Weight voltage = 100

The algorithm stops when the stopping temperature is reached or when every proposed transition is declined for 15 consecutive iterations of Markov chains.

8.4.2 Results

The best solution that we found using the algorithm has an objective value function of *(confidential)*. In total 22 switches were opened or closed and the sum of overload on the cables is reduced from 1245.05A to 297.06A, which is a difference of 947.99A. The algorithm running time is 11 minutes and 35 seconds. A single core processor of a shared R server was used. An overview of the results is given in Table 8.2.

Objective function value:	*(confidential)*
Number of switches switched:	22
Sum of all overloads on the cables (A):	297.06
Voltage outside the bandwidth (V):	0
Algorithm running time (HH:MM:SS):	00:11:35

Table 8.2 - Results after 'swap two switching' algorithm

In Figure 8.8, the plot on the left presents the progress of the current solution value over time. It shows the behavior of the algorithm. The process of random search in the beginning to local search in the end is visible. In the beginning it accepts lots of solutions that are worse, while in the end it almost only accepts better solutions. We have also plotted the behavior of the best objective per Markov chain on the right side of Figure 8.8.

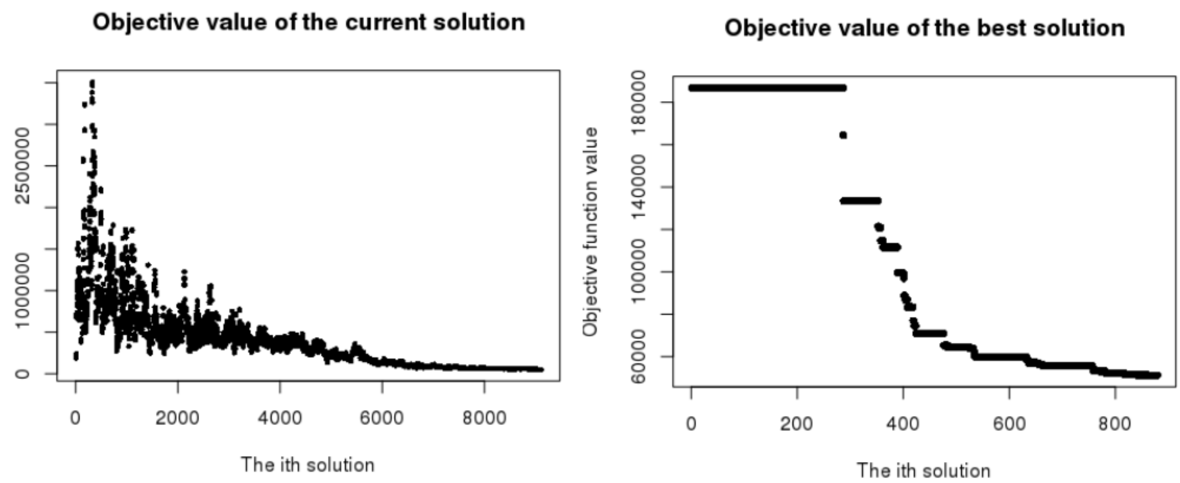

Figure 8.8 - Progress of the current solution value (left) and the best objective value (right).

The results of all cables and MV stations like we did in Chapter 5 may be a rather long table to be presented in this thesis. However, we can plot the results using the application that is build. Figure 8.9 presents the results after optimizing the network by means of the ‘swap two switches’ algorithm.

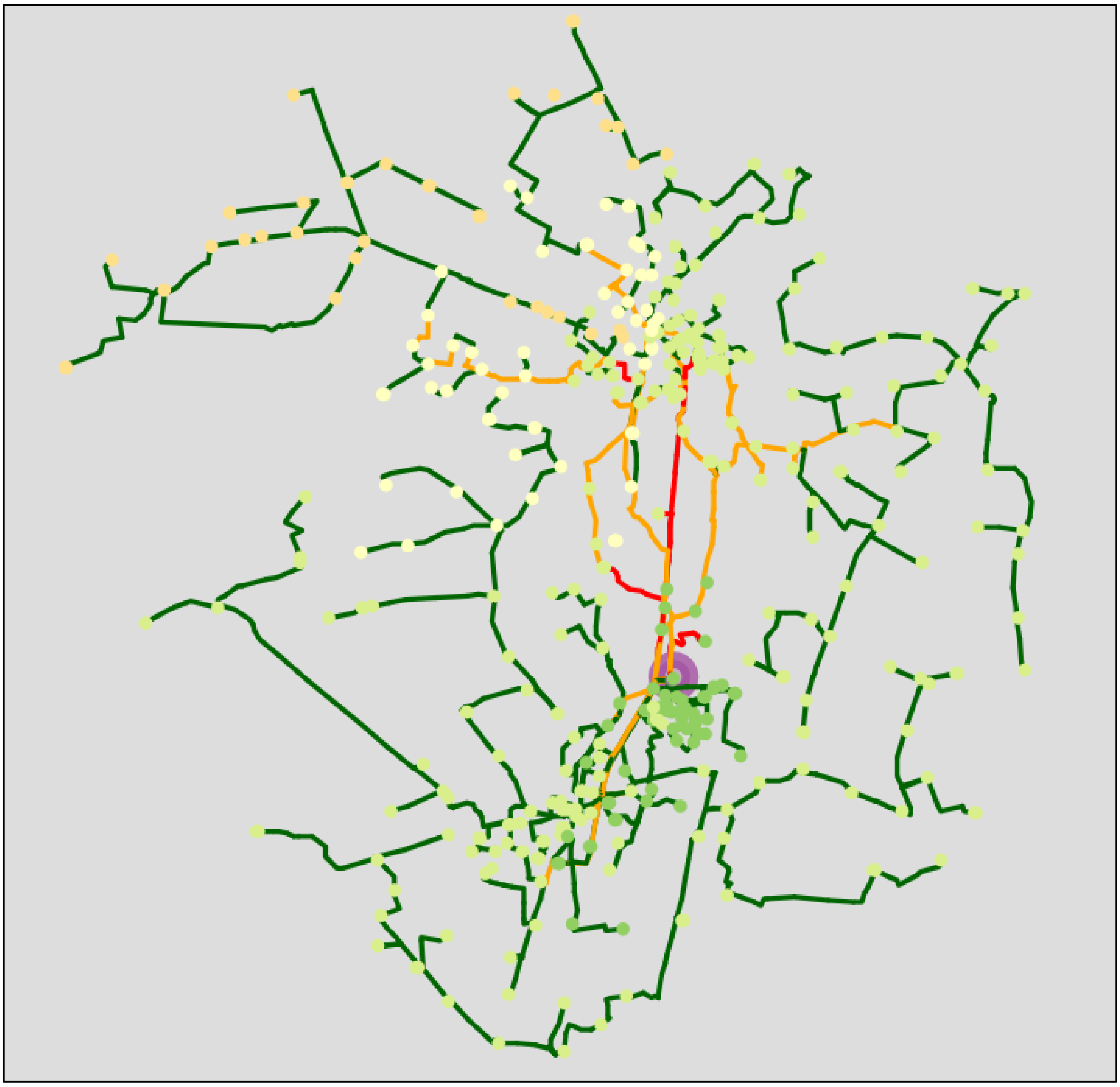

Figure 8.9 - Visualization of the results of the 'swap two switches' algorithm (anonymized).

At first sight the situation looks worse than the initial solution. Some cables that were colored green are now orange. This is because the load from overloaded cables is transferred through other paths compared to the initial network. The redirection of flow balances the load over the cables. This means that the situation becomes worse for some cables and making it better for overloaded cables. The overall solution is more balanced and therefore the overload is less. The voltages on the MV station at the top are also slightly worse, but still remain within the bandwidth.

8.4.3 Experiments

The algorithm is run multiple times to see how the results differ each time the algorithm runs. The results of the best solution found are presented in Table 8.3.

Experiment number	Objective function value	Number of switches switched	Overload cables (A)	Voltage outside the bandwidth (V)	Algorithm running time (HH:MM:SS)
1	*(confidential)*	20	315.39	0	00:07:56
2		18	305.18	0	00:10:58
3		18	305.18	0	00:13:35
4		20	315.39	0	00:11:38
5		20	305.18	0	00:12:43
6		22	299.14	0	00:12:08
7		24	299.64	0	00:12:15
8		24	299.30	0	00:12:33
9		18	305.18	0	00:12:10
10		24	299.30	0	00:11:27
11		26	299.30	0	00:17:15
12		24	299.30	0	00:12:57
13		22	297.06	0	00:11:35
14		24	297.91	0	00:12:11
15		26	517.57	0	00:12:06
16		28	538.76	0	00:11:15
17		22	297.06	0	00:12:43
18		20	319.00	0	00:11:23
19		18	305.18	0	00:12:29
20		18	305.18	0	00:12:17

Table 8.3 - Results of 20 runs of the 'swap two switches' algorithm.

For the ‘swap two switches’ algorithm two outliers are noticed (experiment 15 and 16) that have an objective value much higher compared to the other experiments.

8.5 Simulated annealing using switches and cables as planning options

In this section we consider the results of the implementation of the algorithm of Chapter 6 on the case network *(confidential)*. We first have to determine the way we estimate the characteristics of new cables. Next we discuss a new operator that we have added. After that, we discuss the cooling scheme and the results.

8.5.1 Estimation of new cable characteristics

Before we can test the simulated annealing algorithm that also considers new cables, we have to determine a realistic way to estimate the characteristics of a new cable connection. We used a method that is also used by another team for the ‘Klant inpassingstool’. The method draws cables in a realistic way by following paths such as the sides of the roads. The only cables that we consider are cables between a substation and an MV station. This means that the possible options are the number of MV stations, subtracted by the number of MV stations that already have a connection to the substation. This provides a manageable set of potential cables of which the routes can be determined beforehand. This way we can save some computation time. When a cable is drawn, we can calculate the length of that cable using a package in R. The polygons are input for this function.

We consider two standardized types of cables that are currently used in practice. These are the types as shown in Table 8.4.

Cable type	Capacity (A)	Costs per meter (€)	R (Ω/km)
20 kV 3 x 240 mm^2 Al rm + as 50 mm^2 Cu	360	*(confidential)*	0.162
20 kV 3 x 1 x 630 mm^2 Al rm + as 50 mm^2 Cu	575		0.063

Table 8.4 - Standardized cables that are planning options in the algorithm.

The costs and resistance can be estimated using the constants in Table 8.4 multiplied by the length of cable. Note that we only include the resistance R and not the reactance (X). The load flow calculations can be extended to include also the reactance as described in Section 3.5.2.

8.5.2 Additional operator: 'Swap new cables'

After running the algorithm, we noticed that the algorithm was rather inflexible in removing or adding cables at lower temperatures, especially when few cables are needed. This is due to the fact that the cables heavily impact the objective function. To cope with this, we add a function that swaps a new cable for another new cable. This way a cable does not first have to be added such that another can be removed. After a few runs we concluded that this operator helps finding better solutions more reliably.

8.5.3 Cooling scheme

Recall again from Section 3.3 that the SA algorithm needs a proper cooling scheme. We have analyzed different plots to determine the behavior of the algorithm. These plots are shown in Figure 8.10. The plot in de upper left corner shows the acceptance ratio for each Markov chain. In the upper right corner the average overload is shown for each Markov chain. The acceptance ratios are also disaggregated such that we can see what operator was used. At the bottom this is shown for the 'add cable' and 'remove cable' operators. Note that a zero was noted when the operator was not the 'add cable' or 'remove cable'.

This insights are helpful in determining the weights of the penalty and the start and stop temperature of the algorithm. Recall that we use a parameter dependent penalization approach and only solutions that are feasible (no overload/voltage exceedance) are considered as possible solutions. We want to know in which Markov chain we can expect the overload to become zero. This is the moment when feasible solutions start to occur. At this point in time, the algorithm should still be able to add and remove cables, to decide which cables are good.

We can describe the behavior of the algorithm as following. From the first Markov chain to the 500th, the algorithm is randomly searching for solution. In this phase no feasible solutions are found. From the 500th to the 1500th Markov chain, the first feasible solutions are found. The temperature is still high enough to add and remove cables. From the 1500th and onwards, mainly switches are swapped to find better solutions. The 'swap new cables' function, as proposed in Section 8.5.2, also accepts some solutions in this phase. Swapping a new cable has less impact on the objective value than adding a cable or removing a cable, meaning that this option is still accepted sometimes at lower temperatures.

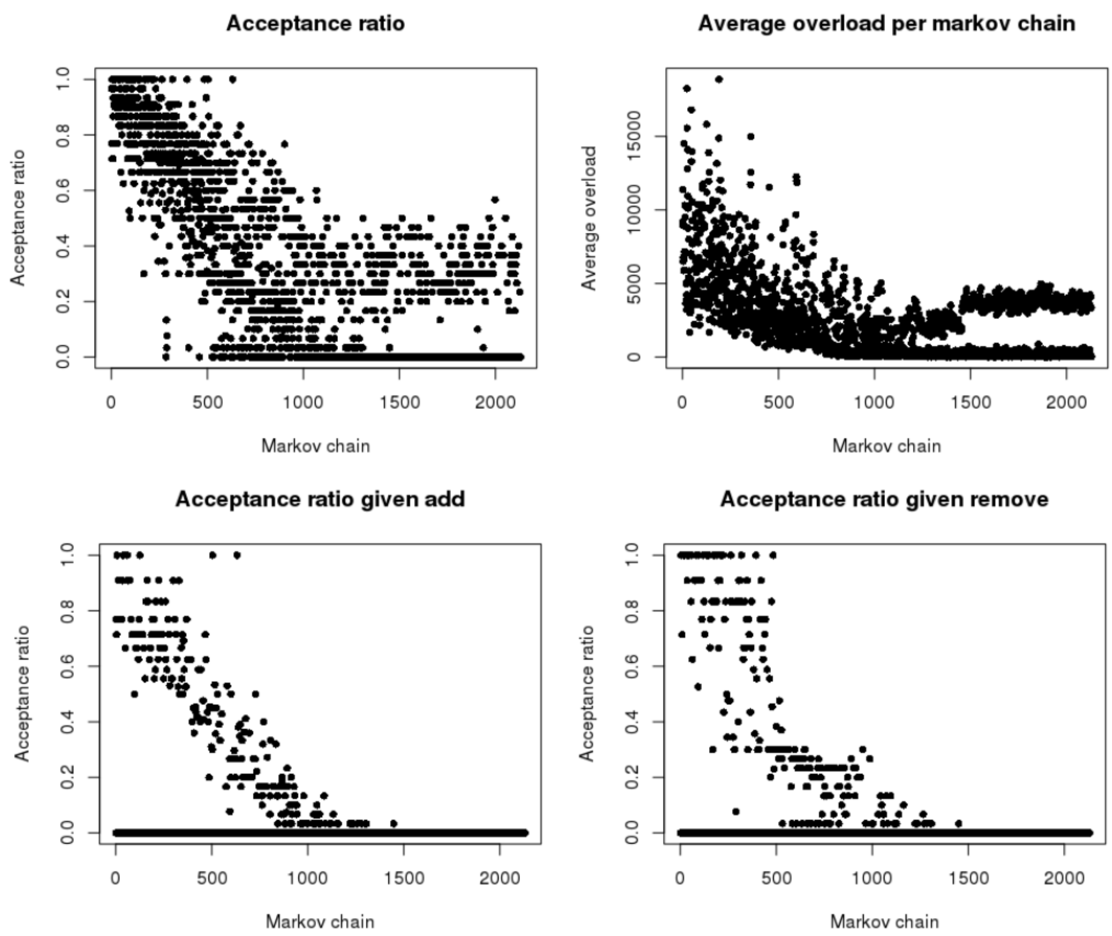

Figure 8.10 - Various plots of the algorithm.

We found that the following cooling scheme and parameters work well:

Cooling scheme
Starting temperature c_0 = 3,000,000
Stopping temperature c_{stop} = 5,000
Decreasing factor α = 0.997
Markov chain length k = 30

Parameters
Weight current = 1,333,000,000
Weight voltage = 333,000,000
Costs per meter 3x240 = *(confidential)*
Costs per meter 3x630 = *(confidential)*
Costs for switching a switch = *(confidential)*

In addition, the algorithm stops if no solution is accepted for 20 Markov chain iterations.

8.5.4 Results

The best solution that we found using the algorithm has an objective value function of *(confidential)*. The total overload of 1,245.05A is reduced to 0. One cable of type '20 kV 3 x 630 mm^2 Al rm + as 50 mm^2 Cu' was added that has a length of 5260.99 meters. In total 42 switches were opened or closed. The algorithm running time was 1 hour, 1 minute and 43 seconds. An overview of the results is given in Table 8.5.

Objective value function:	*(confidential)*
Amount of new cable(s):	1
Length new cable(s) in meters:	5,260.99
Number of switches:	42
Algorithm running time (HH:MM:SS):	01:01:43

Table 8.5 - Results after optimization.

We visualize the results using the application, as presented in Figure 8.11. The blue cable is the new cable that is proposed by the algorithm.

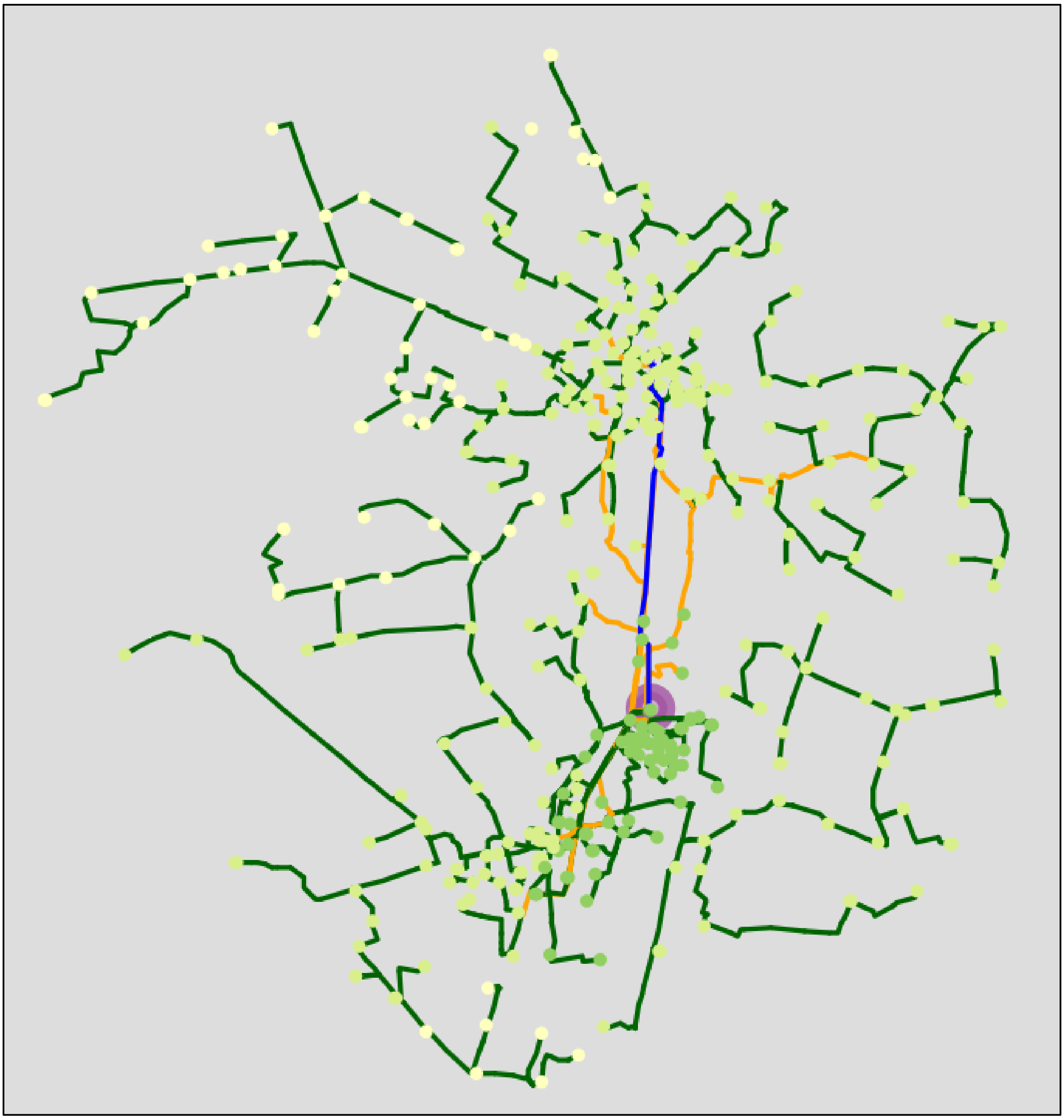

Figure 8.11 - Optimized network visualized in the 'Netuitbreidingstool' (anonymized).

The new cable goes to MV station *(confidential)*. Figure 8.12 shows how the new cable is drawn into the *(confidential)*. The cable follows routes that already have cables, so this cable seems a feasible option. The loading of the cable is 505 A of the available 575 A.

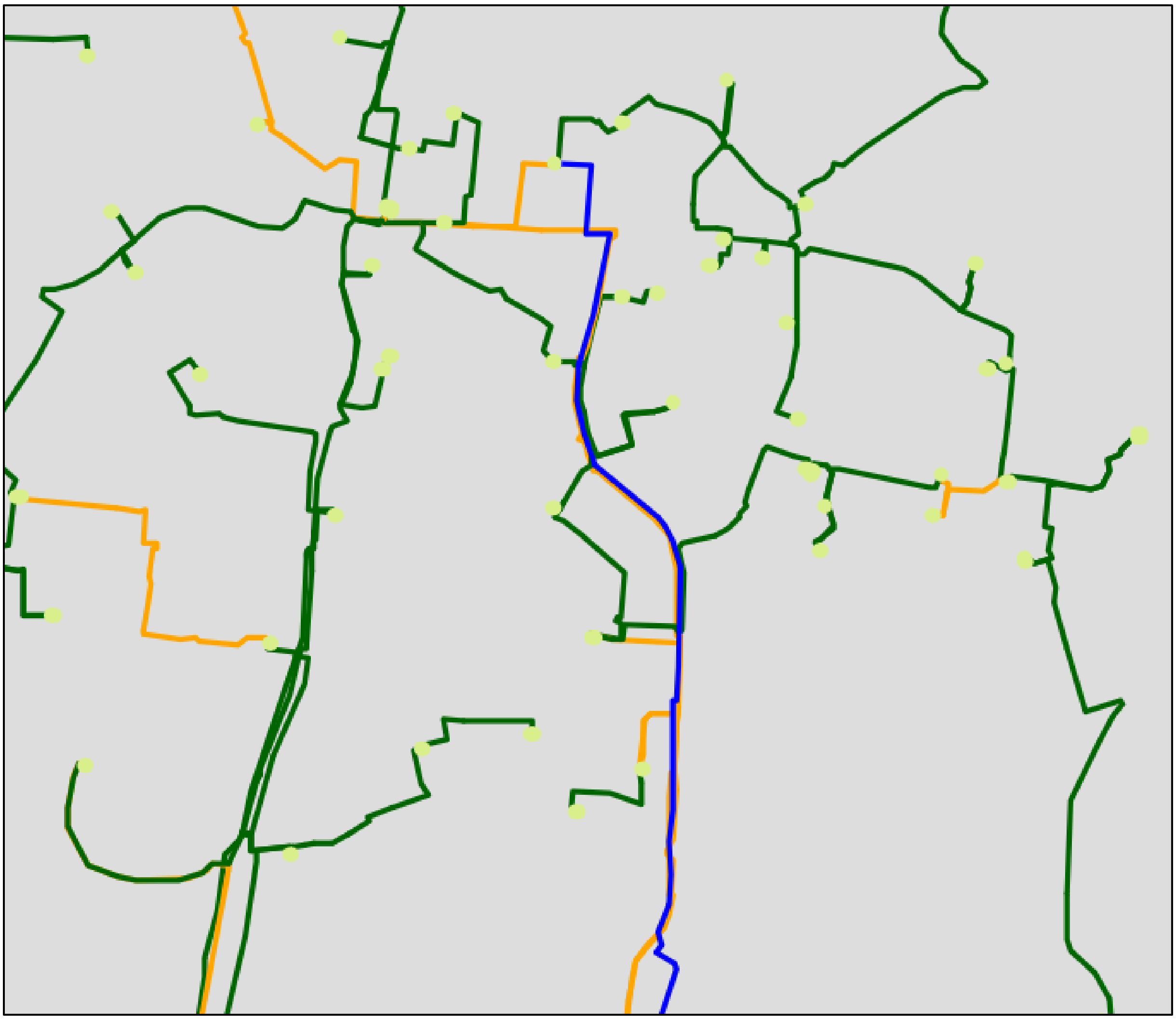

Figure 8.12 - Zoomed in visualization of the added cable (colored blue) (anonymized).

8.5.5 Experiments

We again run the algorithm multiple times to see how reliable the results are, like we did in Section 8.4.3. The results of the best solution found in each experiment are shown in Table 8.6.

Experiment number	Objective value function	Amount of new cables	Length new cable(s) in meters	Number of switches	Algorithm running time (HH:MM:SS)
1	*(confidential)*	1	5,597.49	42	00:57:12
2		1	5,260.99	42	01:01:43
3		2	10,428.39	52	01:04:26
4		1	5,597.49	44	01:06:14
5		1	5,597.49	48	01:00:02
6		1	5,597.49	42	00:58:36
7		1	5,597.49	44	01:00:42
8		1	5,597.49	42	01:00:45
9		1	5,597.49	42	01:03:29
10		1	5,597.49	44	01:01:48

Table 8.6 - Results of 10 runs of the switches and cables algorithm.

We observe one outlier that is much higher than the other experiments. 8 out 10 times the same cable was added in the best solution found.

8.6 Feedback from experts

The results of both algorithms tested on a real case (Section 8.5 and Section 8.6) were presented to a group of experts of Liander. We got feedback that we summarized in the following points:

- Reinforce the current cables of the network as a planning option.
- Instead of planning on the peak loads, we should investigate the option to plan on load profiles instead of peak loads. When the composition of MV stations in each path changes, the simultaneity factor changes as well. This effect can be taken into when using load profiles.
- Integration with other models such as a cable replacement model that aim to minimize outages. Another option is to include power losses in the objective function.
- A different view in the application that shows the new cables and NOPs only.
- Provide insight in how many the load has risen compared to the current situation.
- Check the amount of cables that can be physically attached to each MV station.

8.7 Enforcing the n-1 principle

Recall from Section 3.6 that we discussed two simplifications of the n-1 principle. The first one is that we only simulate a failure for the first cable connecting to a substation as these cables are often seen as worst-case scenario. The second one is to approximate the optimal reconfiguration by closing all NOPs. In Chapter 7, we discussed the appropriateness of this method. In this section we apply these simplifications to the n-1 principle, such that we can use it in our algorithm. We do this for our second algorithm, proposed in Chapter 6. As we close all NOPs to approximate a reconfiguration in an n-1 situation, the current configuration does not influence the feasibility of the n-1 principle. Consequently, it does not make sense to apply the approximation method for the algorithm ‘Swap two switches’ proposed in Chapter 5.

8.7.1 The n-1 check

The n-1 check that we propose is a combination of the two simplifications discussed in Section 3.6. It consists of a simulation of a cable failure for each outgoing cable from the substation. After each cable failure we close all NOPs to approximate the optimal reconfiguration. We perform a load flow calculation to check the voltages and currents in the reconfigured state. We sum all of the voltages outside the bandwidth and overloads on the cables, for each cable failure. The average overloads are then penalized in the objective function the same way as the overload in a normal situation. We also incorporate the parameter d5ndent penalization method by dividing the average overload in n-1 situations by the current temperature. Additionally the overloads from this n-1 check are multiplied by a weight.

8.7.2 Cooling scheme

The weights and cooling scheme are determined by using similar plots as before. These are plotted in Figure 8.13. The acceptance ratio is used as we did before. In the beginning of the algorithm, the overload per Markov chain should be allowed as the algorithm starts with a random search. In the end, overloads should be around zero such that we find feasible solutions.

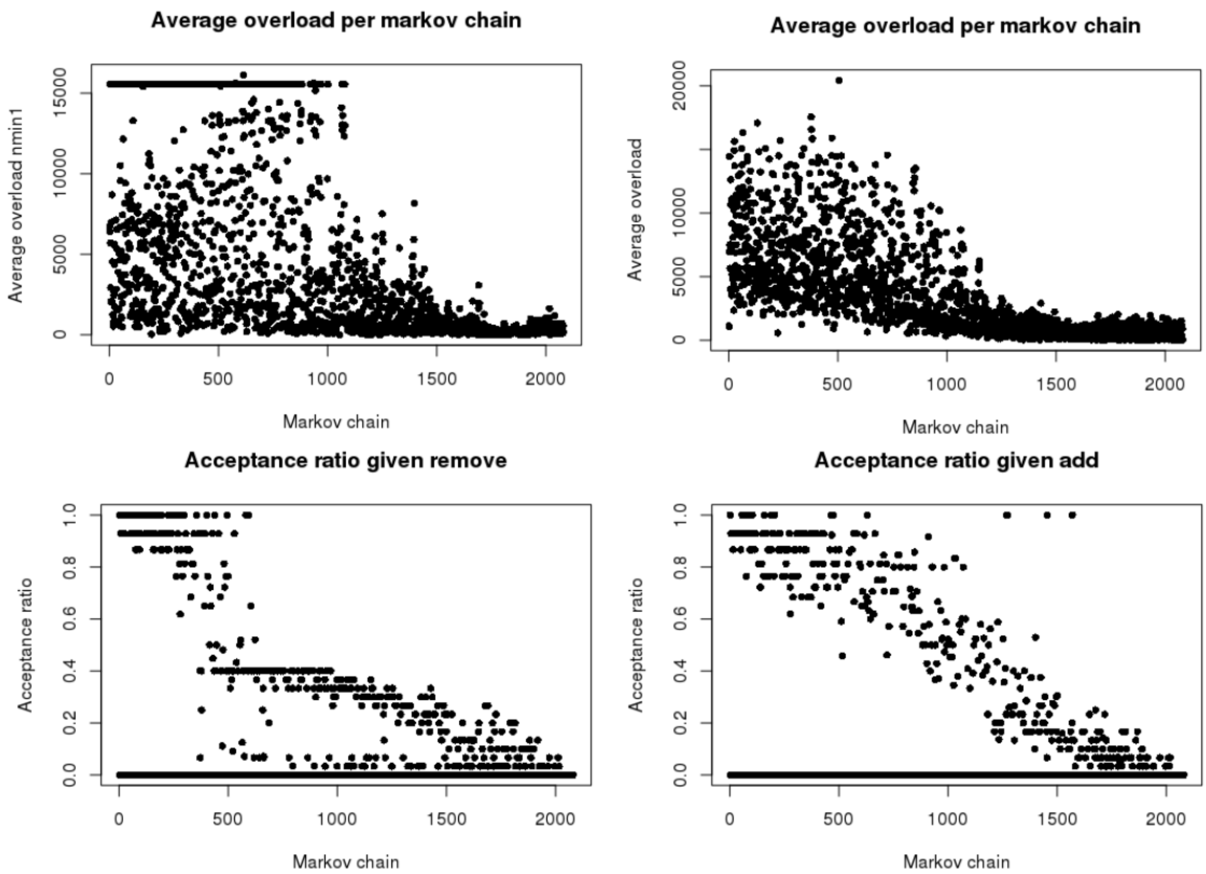

Figure 8.13 - Relevant plots to determine the cooling scheme and penalization weights.

This resulted in the following cooling scheme:

Cooling scheme
Starting temperature c_0 = 5,000,000
Stopping temperature c_{stop} = 20,000
Decreasing factor α = 0.998
Markov chain length k = 30

Parameters
Weight current = 1,333,000,000
Weight voltage = 333,000,000
Weight voltage n-1: 3,330,000,000
Weight current n-1: 13,330,000,000
Costs per meter 3x240 = *(confidential)*
Costs per meter 3x630 = *(confidential)*
Cost per switching a switch = *(confidential)*

The complexity of the algorithm increases when incorporating the n-1 principle. Therefore, we slightly increase the decreasing factor compared to Section 8.5 that did not incorporate the n-1 check. This way, the algorithm cools down slightly slower than before.

The n-1 penalty is an extra component to the objective value function. We therefore expect higher objective values during the algorithm. To allow the same number of transitions, we increase the starting- and stopping temperature.

8.7.3 Results

The results after optimization are shown in Table 8.7.

Estimated total costs:	*(confidential)*
Estimated cost new cables:	*(confidential)*
Amount of new cable(s):	7
Length new cable(s) in meters:	27,946.64
Number of switches:	76
Algorithm running time (HH:MM:SS):	03:57:57

Table 8.7 - Results after optimization, using the proposed n-1 check.

The amount of cables that we need heavily increased compared to the solution that did not take into account the n-1 principle. In addition, the algorithm running time quadrupled to almost 4 hours. This is still manageable. Note that we are considering a large scale MV network.

The best solution is visualized in Figure 8.14.

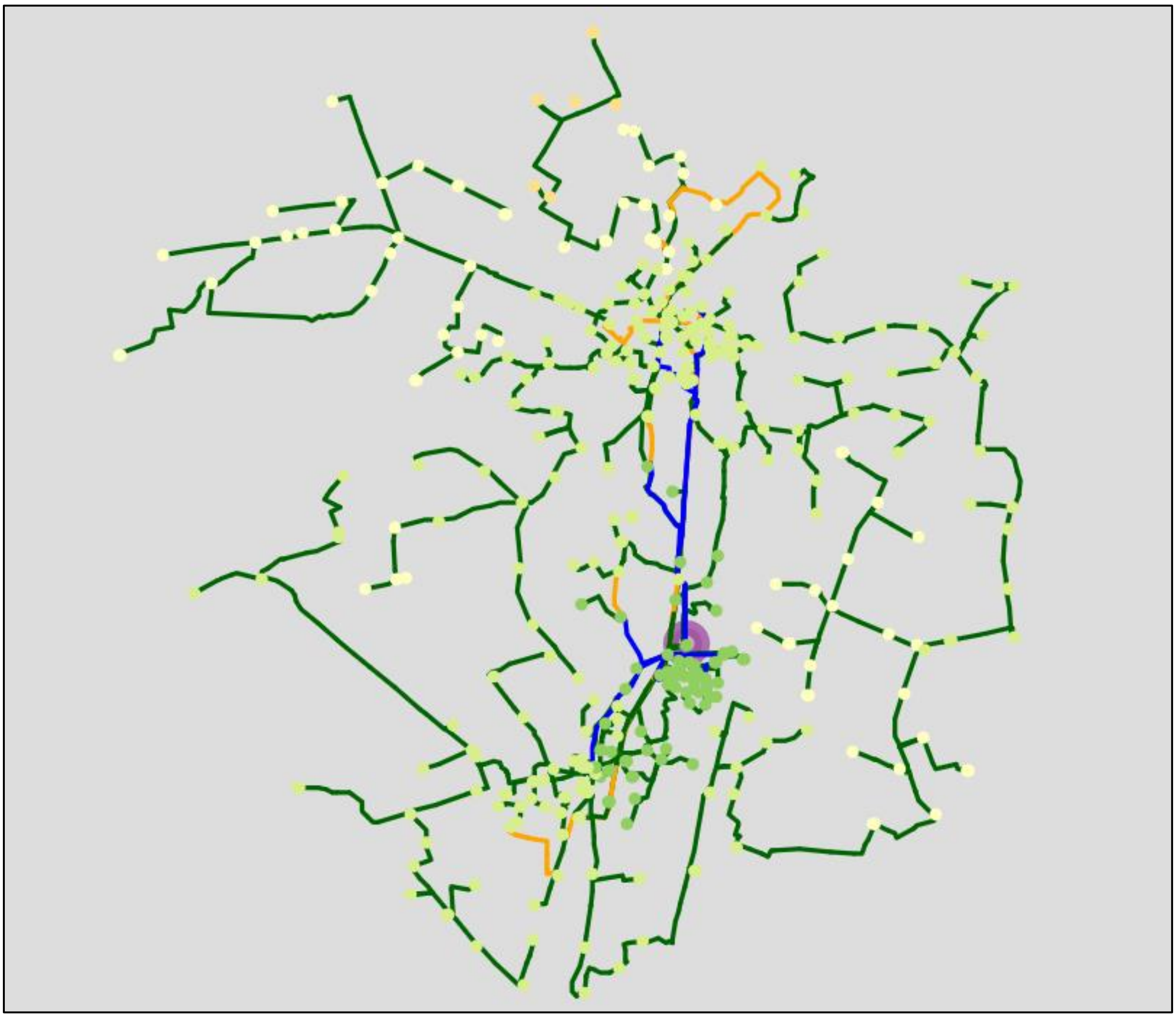

Figure 8.14 - Best solution after the optimization, using the proposed n-1 check (anonymized).

8.8 Conclusion

In this chapter, we tested the algorithms that were developed in Chapter 5 and 6 on a real network of Liander. The network is a large-scale, highly meshed MV network with 358 nodes and 394 cable sections. We gathered relevant data, but for some data assumptions were made. This chapter presents how our algorithms can be incorporated in a tool called 'Netuitbreidingstool'

The first algorithm (switches only) showed that the sum of all overloads on the cable could be reduced from 1,245.05 A to 297.06 A, a reduction of 76.14%. In total 22 switches were switched to achieve this. The algorithm running time is 11 minutes and 35 seconds.

The second algorithm solved all capacity problems by adding one cable to the network and switching 42 switches. The new cable is estimated to be 5260.99 meters long and is expected to cost *(confidential)*.The algorithm running time is 1 hour, 1 minute and 43 seconds.

We did experiments by running both algorithm multiple times. For the algorithm that only uses switches, 18 out of the 20 experiments came to similar solutions, while the other two deviated by a large portion. The second algorithm that also considers cables was run 10 times. 9 out 10 experiments came to similar results while 1 outlier was observed. Our

The results were presented to a group of experts and feedback was received. Most of the feedback is about adding more complexity to both algorithms, while some feedback concerns the representation of the network in the application.

We proposed an n-1 check which is a combination of two simplification that were used in literature. The first simplification is to check only the outgoing cables from the substation (Luong et al, 2013). The second simplification is the estimation of loads in a reconfigured state by closing all NOPs (Grond, 2016). The n-1 check has been incorporated in the second algorithm that includes cables as a planning option. The number of cables that is needed heavily increased compared to the solution without n-1 check. Instead of 1 additional cable connection, we need 7. The cables have an expected length of 27,946.64 meters. The total expected investment costs are *(confidential)*. The algorithm running time is 3 hours, 57 minutes and 57 seconds.

9 Conclusions and recommendations

This chapter is about the conclusions and recommendations. We will also discuss the limitations and the recommendations for future research.

9.1 Conclusions

The following research question was aimed to be answered in this study:

'What is a model for generating adequate investment strategies to prevent capacity problems in medium voltage networks?'

Two models are proposed to solve the distribution network expansion problem. Both algorithms are based on the simulated annealing (SA) algorithm.

The first algorithm only uses the switches of the network as a planning option to minimize the overload of the network. This can be used for temporary low cost solutions. The second algorithm also uses new cable connections as a planning option. This goal of this algorithm is to solve all capacity problems. This algorithm uses the parameter dependent penalization method, which to the best of our knowledge, has never been used before on distribution network expansion problem. Both algorithms were tested on a real MV network of Liander.

Both algorithms were tested on a real MV network in: *(confidential)*. Forecasts for the year 2040 were used as input for the models. Table 9.1 shows the results of the best solutions found by the algorithms. The algorithm that incorporates cables as a planning option is run with and without an n-1 check.

Surprisingly, the first algorithm showed that the sum of all overloads on the cable could be reduced from 1245.05 A to 297.06 A, a reduction of 76.14%. There were no voltage problems before and after the optimization. In totoal, 22 switches were switched to achieve this. The algorithm running time is 11 minutes and 35 seconds. The second algorithm solved all capacity problems by adding one cable to the network and switching 42 switches with an expected total cost of *(confidential)*. The algorithm running time is 1 hour, 1 minute and 43 seconds.

	Optimization using the switches	Optimization using switches and cables	Optimization using switches and cables (including n-1 check)
Amount of added cable(s):	0	1	7
Sum of the overloads on the cables (A):	297.06	0	0
Voltage exceedances (V):	0	0	0
Length new cable(s) in meters:	0	5,260.99	27,946.64
Number of switches turned on/off:	22	42	76
Total expected investment costs:	*(confidential)*		
Algorithm running time (HH:MM:SS):	00:11:35	01:01:43	03:57:57

Table 9.1 - Overview of the best solutions in the case study

The n-1 principle is a challenge to incorporate in expansion planning models. Approximation methods for an n-1 check within the second algorithm are required. A way to simplify the problem is to approximate the optimal reconfiguration by closing all normally open points, as suggested by Grond (2016). We did an analysis to determine the accuracy of this method. The analysis suggest that the method is relatively accurate, although more validation work should be done here. Another simplification is to only check the n-1 principle for outgoing cables from the substation. The breakdown of the first cables are seen as worst-case scenarios. It seems therefore justifiable to only check the outgoing cables from a substation. We proposed a combination of both methods to maintain a reasonable algorithm running time. We incorporated the n-1 check in our second algorithm and tested it on the MV network of *(confidential)*. The required number of cables increased to 7. The total expected cost are *(confidential)*. The algorithm running time is 3 hours, 57 minutes and 57 seconds.

We did experiments by running both algorithms multiple times. For the algorithm that only uses switches, 18 out of the 20 experiments came to similar solutions, while the other two deviated by a large portion. The second algorithm that also considers cables was run 10 times. 9 out 10 experiments came to similar results while 1 outlier was observed. Our experiments suggest that both SA algorithms find adequate solutions for a representative MV network in a reliable manner.

The algorithms are incorporated in a tool called the 'Netuitbreidingstool', which currently is a proof of concept. The goal of the tool is to make sure that the algorithms can be easily applied for every MV network by network planners.

9.2 Contributions to practice and literature

In this research we laid the foundation for an automated distribution network planning tool. Liander can use this to accelerate the process of finding alternative solutions for capacity problems. We have demonstrated how this could be integrated in a tool called 'netuitbreidingstool' to make sure that the algorithms suggested in this thesis can be easily applied by end users.

Our contribution to literature is threefold. Firstly, we introduced a comprehensive and detailed solution approach to the distribution network expansion planning problem.

Secondly, we employed the parameter penalization method in combination with SA for the first time to the distribution network expansion planning problem. In this thesis we showed how it can be applied by a temperature dependent penalization of the voltage exceedances and cable overloads. The method was tested on a real MV network. Our experiments suggest that both SA algorithms find adequate solutions for a representative MV network in a reliable manner.

Thirdly, we incorporated in our algorithm the fast load flow method recently developed by Van Westering et al. (2019). As for the latter, note that the Newton-Raphson AC method is traditionally used to solve the load flow equations. This method is computationally expensive to apply within heuristic optimization methods. We applied the method by Van Westering et al. (2019) to accelerate the constraint evaluation process.

9.3 Recommendations for future research

The models proposed in this thesis can be expanded in different ways. One should note that when adding more complexity to the model, the algorithm running time will most likely increase. We recommend doing more research on the following topics:

n-1 principle

We deem it worthwhile to conduct research to the approximation method by Grond (2016) for checking the n-1 principle to validate the results of Chapter 7. If the results are positive, the approximation can be applied in the second algorithm that uses cables as a planning option.

Consider larger parts of the network, with multiple feeder groups

The current algorithms are designed and tested on an MV network with only one substation. The models can be extended to consider multiple MV networks at the time. One additional planning option can be added, which is the possibility to take some MV stations over to a neighboring MV network that still has capacity left. To include this option, the solution space will increase greatly. This is due to the fact that every MV station of a feeder group can now also have a possible connection to every other MV station of a neighboring feeder group. To cope with this we suggest to select beforehand which connections between neighboring networks are logical options.

Adding more planning options
In this research we noted that besides cables and switches, other options are available such as the addition of new MV stations and storage systems. It is also noted that the MV station expansion planning can be seen as an isolated problem (Grond, 2016). However, we think the cable expansion planning algorithm is more powerful when first the additional (optimal) MV stations and their locations are identified. In addition, another option is to add storage systems to the model.

Static versus dynamic models
The difference between static and dynamic models is that dynamic models take into account a time dimension. Dynamic models are often used for long term planning. The advantage of dynamic models is that they are able to find an adequate investment strategy for each year. The trade-off is that this will most likely increase computation time significantly. One should decide whether the longer algorithm running time is worth the information about when an investment should be made.

Incorporate power losses and breakdown minutes in the model
In this research we focused on the capacity of the network. However there are more objectives for which expansion planning could be used. The first is the addition of power losses as this can be influenced by the configuration and the addition of new cables. Power losses are also a large portion of the operational costs. Research can be done to check whether we can extend our models by incorporating breakdown minutes. Cables are usually replaced when they reach the end of their lifetime. When this happens, the decision can also be to replace the cable with one that has more capacity.

9.4 Discussion on the limitations

This section discusses the limitations of the research.

Accurately checking the n-1 principle many times in an iterative optimization method is quite challenging. We have done literature review and analyzed the methods and simplifications that we found. However, due to time restrictions of this research, we could not fully validate the accuracy of the applied simplifications.

The ΔU criterion is a Liander specific criterion for MV networks. It is currently not incorporated in our algorithms. The criterion was discovered at a later stage in the research and can be implemented by running one additional load flow calculation for the low load variant per alternative solution.

During the presentation of both algorithms, discussion started about the applied simultaneity factors. The simultaneity factor is calculated per feeder group. This is done by comparing the sum of the peak loads of each separate MV station to the actual peak load of the whole feeder group. However, when relocating NOPs, the composition of each feeder group changes. To be accurate, the simultaneity factor has to be recalculated each time the composition of the feeder group changes. To do this, we would need a forecast of the whole load profile. Currently this is not applied in both algorithms.

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Appendix I – Reflection

Due to personal interest in the energy transition, I decided to look for a master assignment in which I could contribute to the energy transition. One organization that encounters the challenges of the energy transition is Liander. I came in first contact with some representatives of Alliander N.V. at the 'Bedrijvendagen' at the University of Twente. This sparked my interest and so I submitted an open application to Alliander. After some introductory conversations, an assignment topic was found at the 'Waardegedreven Assetmanagement' team within Liander.

I look back at an educational period at Liander. At the start of this period, I experienced quite some difficulties. The assignment was quite broad and therefore demarcation of the assignment was needed. We first started modelling a network using a mixed integer linear programming approach based on the classical minimum cost flow problem, see Chapter 4. We recognized the limitations of this approach. I remember a meeting that lasted two and a half hours with my first UT supervisor P.C. Schuur. We brainstormed for a long time and with success. The meeting was clarifying and a new approach was chosen.

This was not the first challenge that I experienced. I had little knowledge about electrical systems and therefore load flow calculations was a though topic. Luckily, there were many colleagues at Liander willing to explain the electrical engineering aspects that were needed to complete this assignment. I am very grateful for the motivation that the colleagues of Liander gave me and their willingness to help me.

Finding a way to apply an n-1 check was is also challenging. We eventually contacted researchers from relevant studies at the Erasmus University Rotterdam. They endorsed that finding an n-1 check that is computationally inexpensive is a though problem. They eventually sent some relevant papers on this topic to work with. I am glad that in the end we have been able to apply an n-1 check, although further research should be done on the validation of the method.