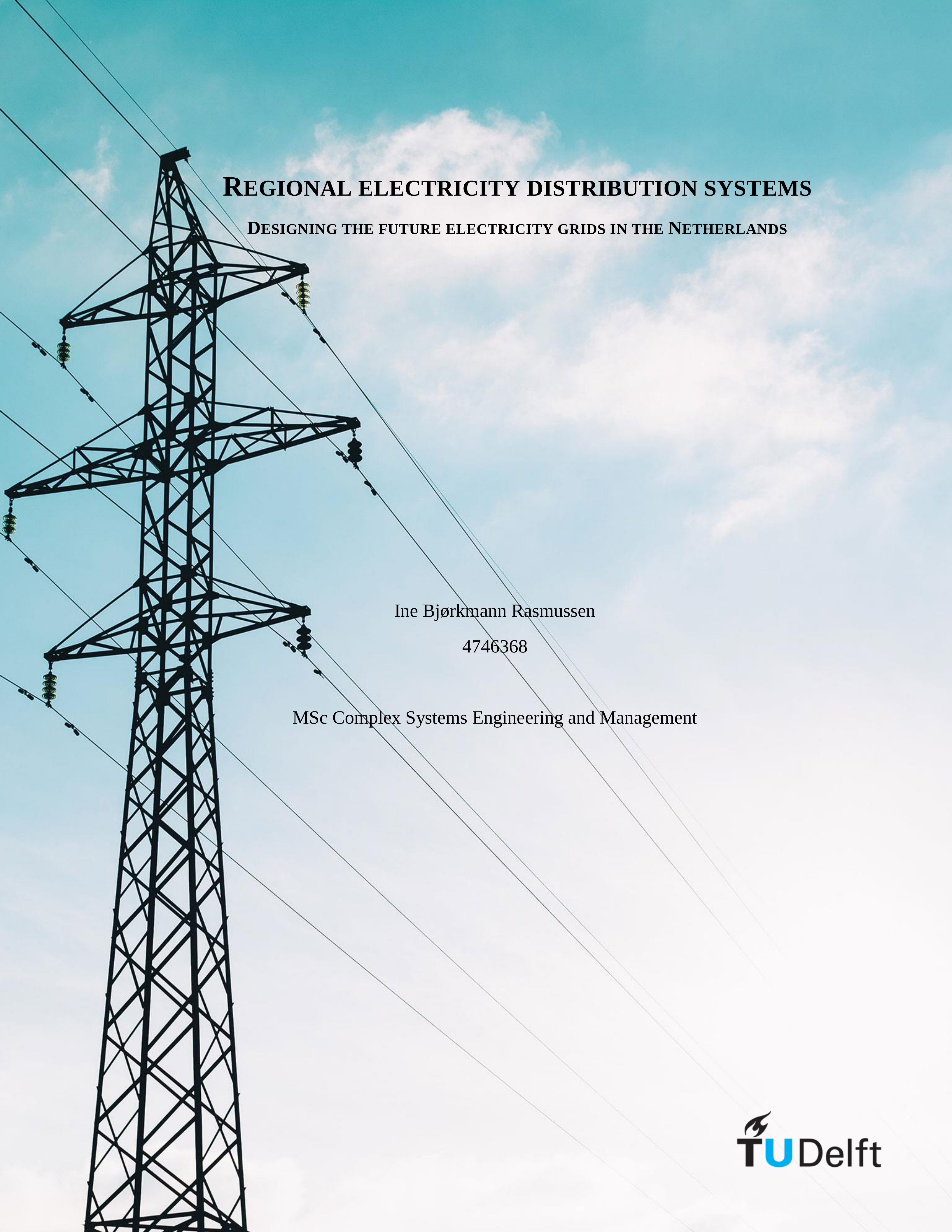

Regional electricity distribution systems

Designing the future electricity grids in the Netherlands

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MSc Complex Systems Engineering and Management

TU Delft

Regional electricity distribution systems

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by

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Preface

Dear reader,

This thesis paper marks the completion of the master programme Complex Systems Engineering and Management at Delft University of Technology and the end of my five-year journey as a student.

Firstly, I would like to thank my committee. Petra Heijnen and Ni Wang, thank you for taking the time to have weekly contact and for many interesting discussions. Petra, I appreciate your practical approach to the challenges I was faced with in this project. This is something that I will make sure to take with me into my working life. Ni, thank you for sharing information and giving insights on your PhD project. Your inputs have proven very useful and it would make me very happy if some of my findings can in the future also be useful for your work. I have truly learnt a lot from working with both of you. I would also like to thank Tina Comes and Ivo Bouwmans for your feedback on my work and a heads up when my scope is a little optimistic. Your comments have lead me to focusing my thesis in addition to improving several parts of the argumentation and validation of my project.

During both the fun and challenging times of my thesis project, the importance of the people around me has become apparent. I want to thank my parents for always being there for me, although from a distance, during my five years as a student in Perth, Montréal and finally in Delft. I truly appreciate that no matter where I live, I know you are just a call away. Also, thank you for taking the time and making the effort to dive into my thesis topic sufficiently to be able to ask critical questions and for me to be able to think out loud. I am lucky! Thank you also to my big little brother, Erik, for your fun and positive attitude while still being there if I need someone to talk to. I wish you all the best with your studies in Trondheim and I am looking forward to coming for a visit soon! I would like to thank my friends in Delft for sharing experiences and helping each other out during the thesis period. And, maybe even more importantly, the coffee breaks while studying as well as dinners and activities in the evenings that have enabled me to switch off in an otherwise busy period. Finally, I would like to thank good friends in Norway and abroad for pep-talks and support along the way. The past six months would not have been the same without you.

Ine Bjørkmann Rasmussen

Delft, September 2019

Executive summary

During the next few decades, a significant increase in the use of intermittent renewable energy sources is expected in the Netherlands as well as a general increase in electricity consumption. Due to the increased demand as well as a more uncertain, volatile supply, substantial upgrades and redesign of the current Dutch electricity grids are needed. These upgrades will inevitably require large investments as the design and installation of electricity grids is costly. Additionally, the investments are lumpy and irreversible. It is therefore important that the investments will be made in such a way that the future grids will operate successfully, supplying consumers with the demanded electricity at sufficient quality with a low rate of interruptions. Recently, the Netherlands has been divided into 30 energy regions, which allows the Netherlands to work on its climate agreements both from a regional and from a national level. These regions will work on generation and consumption of electricity and heating as well as on the energy infrastructures needed to supply this energy.

This aim of this research paper has been to create a method that can be used to design suitable electricity distribution networks for the energy regions in the Netherlands. One approach to designing electricity grid topologies is with the use of graph theory heuristics, which has shown to be a useful way of approaching the electricity design problem by discretising plots of land into a graph. It is also a versatile approach that can be changed in order to capture the set of relevant characteristics that are to be captured in the model. The research paper has shown that by taking into account spatial constraints specific for the Dutch regions, more valid networks can be created. This further leads to increased implementability of the final networks in addition to a reduction in the possibility for unforeseen costs related to building on certain plots of land.

The proposed method aims to minimise investment costs of the future regional electricity distribution networks in the Netherlands, taking both cable lengths and capacities into account. A radiality constraint is applied, ensuring that the network is connected but does not contain any cycles, as it is the topology that in general contributes to the lowest investment costs. Additionally, a flexible way of ensuring that the final networks do not overlap with unavailable land is applied and demonstrated. A heuristic method aiming to minimise network length is applied before assigning the required capacities to the network. An improvement procedure is thereafter performed in order to further reduce investment costs. The cost function is formulated as a non-linear function, incorporating the characteristic that savings can be made by combining lines in order to create a shorter, high-capacity network instead of a longer, low-capacity network. The proposed method has thereafter been verified with respect to the problem formulated and demonstrated using a case study on the energy region Goeree-Overflakkee. Experimental results have also been generated in order to assess the effectiveness of the method. In comparison to an alternative simultaneous topology and production optimisation, it has been found that the proposed method leads to a shorter final network that additionally leads to lower total investments costs.

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List of Acronyms and Abbreviations

AC	alternating current
CLC	CORINE (Coordination of information on the environment) Land Cover
DC	direct current
DN	distribution network
DSO	distribution system operator
EA	evolutionary algorithm
HV	high voltage
KCL	Kirchoff's current law
KVL	Kirchoff's voltage law
LV	low voltage
MCF	minimum cost flow
MILP	mixed-integer linear programming
MINLP	mixed-integer non-linear programming
MST	minimum spanning tree
MSTG	minimum Steiner tree in a graph
MV	medium voltage
OHL	overhead line
PCC	point of common coupling
PDH	path distance heuristics
PV	photovoltaic
RES	renewable energy sources
SPH	shortest path heuristic
TN	transmission network
UGC	underground cabling
VoLL	value of lost load

Chapter 1: Introduction

1.1 Future regional electricity grids in the Netherlands

The *IPCC Special Report on Global Warming of 1.5°C* released in 2018 included a statement by the United Nations Secretary-General stating that limiting global warming to 1.5°C is far more urgent than previously assumed and that changes will be needed in all aspects of society (United Nations Secretary-General, 2018). One of the most crucial transitions will be the replacement of fossil fuels with renewable energy sources (RES), and intermittent electricity sources such as solar and wind will likely be part of the solution (Vujanic, Mariethoz, Goulart, & Morari, 2012). Congestion and a more volatile loading of the current grid is therefore inevitable, and upgrades to the current grid will be needed both in the Netherlands and in Europe in general (Ergun, 2015).

On a European level, investments reaching several hundred billion euros are expected to the transmission network (TN) during the next few decades (Ergun, 2015). In the Netherlands, significant upgrades are needed for the Distribution Networks (DNs) due to a more volatile and uncertain electricity supply as well as an overall increased electricity demand in the future. The grid capacities will therefore have to be increased in order to ensure grid survivability and security of supply during future maximum supply and demand conditions. The requirements are also changing for Dutch DNs due to the increased use of distributed generation, where their previous role as a passive electricity distributor is expected to change to an electricity balancer due to the direct connection of active electricity generators to the grid (Bauknecht & Brunekreeft, 2008).

The urgency of Dutch DN upgrades has recently become apparent, as the municipality of Haarlemmermeer for the first time experienced having to use the emergency grid for electricity distribution in order to prevent grid failure (Reijn, 2019). The reason for the emergency was in this case the increased demand due to the connection of a data centre for internet traffic in addition to postponement of already identified required grid updates. However, the incident paints a picture of how static, essential infrastructure systems such as electricity networks need to be studied and upgraded during times of changing market conditions.

Figure 1 Division of energy regions in the Netherlands. Reprinted from (Regionale Energie Strategie, 2019)

Alongside national energy governance, the Netherlands has recently been divided into 30 energy regions that will be used to facilitate the energy transition (Figure 1). This Regional Energy Strategy is a cooperation between municipalities, energy stakeholders and provinces in order to solve some of the Netherlands' energy challenges on a more local level. One possible way of upgrading the Dutch grid is replacing the currently connected grids with regional grids for electricity distribution. As the electricity is being generated in fairly close proximity to electricity consumption, this can lead to decreased electricity losses and therefore to a more efficient use of the electricity generated (He et al., 2008). From a socio-technical perspective, regional grids also have the advantage of helping increase local identity and promoting an increased feeling of responsibility for consumption and climate change (He et al., 2008). This will be likely to further stimulate the willingness of people to participate in demand side flexibility, which is another crucial aspect of the energy transition (Albadi & El-Saadany, 2008). Although regional grids have several advantages, there are also several difficulties. Electricity networks are socio-technical systems, meaning that they exhibit complexities in both a physical and a social or political sense. Additionally, due to the large investment risks of re-building such complex systems, the characteristics and requirements to be included in the design of future regional DNs will need to be analysed thoroughly.

1.2 Characteristics of electricity network design

In general, electricity network design requires long-term planning, as can be seen in Figure 2. For low-voltage systems, such as DNs, the process often exceeds 10 years, whereas for high-voltage systems, such as TNs, the process can take up to 20 years (Schlabbach & Rofalski, 2008). This implies that choices in electricity network design are required to be based on expected future conditions at the earliest 10-20 years ahead and until the expected lifetime of the networks. Historically, electricity networks have been designed in incremental steps, as the infrastructures have often existed for several decades and have incrementally needed expansions or improvements due to changing requirements. Designing the system in fragments makes it difficult to achieve even close to an optimal solution (Carrano, Soares, Takahashi, Saldanha, & Neto, 2006). The networks may therefore be more expensive, they may suffer from higher power losses or are less reliable than desired.

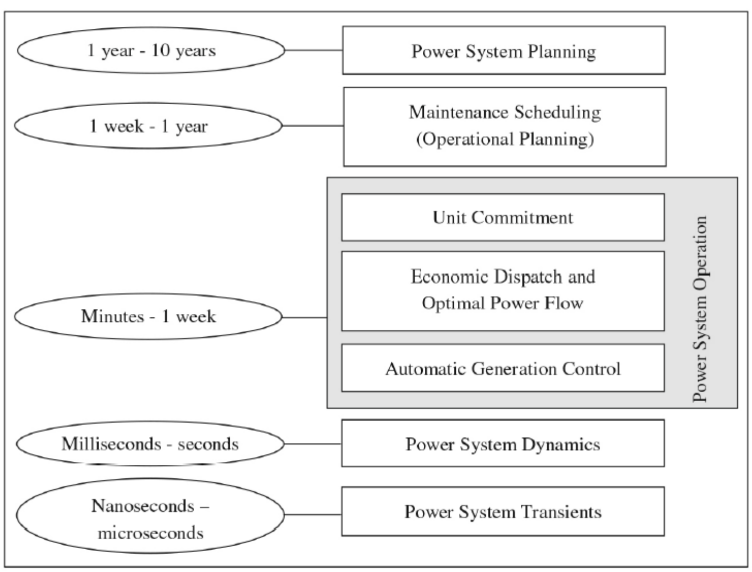


Figure 2 Time-horizon perspective of power systems studies. Network design falls under the category of Power Systems Planning, which has the longest time horizon and can take more than a decade (Seifi & Sepasian, 2011)

1.3 Electricity network design using graph theory

Mathematical models on electricity network design are characterised by high computational complexity due to both non- linear expressions, discrete variables and a high degree of uncertainty (Dahmani et al., 2015). In most cases, and especially for large networks, it is necessary to make assumptions and simplifications in order to achieve feasible computation times. These assumptions and simplifications should be made as reasonable as possible in order to achieve simplified mathematical formulations while still returning valid designs. By discretising land areas into graphs, the land areas can be simplified. This also makes it much easier to analyse and optimise connections between different locations in the space. Graphs are therefore one of the most commonly used tools in network design (André et al., 2013).

A graph is a pair G=(V,E) of sets such that E ⊆ [V]2; thus, the elements of E are 2-element subsets of V (Diestel, 2017).

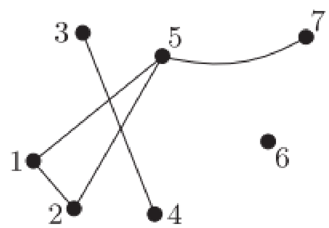


Figure 3 "The graph on V = {1,..., 7} with edge set E = {{1, 2}, {1, 5}, {2, 5}, {3, 4}, {5, 7}}". Reprinted by Diestel (2017)

Graphs consist of a set of vertices, *V*, also called nodes, and a set of edges, *E*, also called links. The vertices are drawn as dots and in the case where vertices share a connection, a line is drawn between them, representing the edge. When graph theory is used for electricity network design, vertices are set to represent the points to be connected, such as production sites, consumers and, in some cases, technical components such as substations. The edges represent the connections between the vertices, the overhead or underground cables. Graph theory heuristics developed several decades ago are still in use. However, they are often improved and adapted to the specific design cases, depending on their characteristics and requirements. How appropriate such assumptions are depends on the nature of the problem and should therefore be made case-specific.

1.4 Knowledge gap

In order to define knowledge gaps in literature, a review has been performed on papers aiming to design electricity grids. In addition to creating an overview of what has been done in literature so far, the research goal of the literature review was to evaluate whether existing methods can be applied to the design of electricity DNs for regions in the Netherlands.

From the literature review it has been found that there are clear differences between TNs and DNs. Firstly, TNs normally have meshed topologies whereas DNs are normally designed as trees or rings. Models aiming to design transmission systems are therefore not directly applicable to DN design. These differences will be further discussed in Chapter 2. In terms of DNs, four network models have been found and analysed. One of the models is specifically created for developing cities and does not take any spatial constraints into account (Tang, 1996). Additionally, it is solved using a Maximum Flow Algorithm which only considers linear cost functions. Another DN design model is made on a generic basis and aims to both minimise costs and minimise system failure index (Carrano, Soares, Takahashi, Saldanha, & Neto, 2006). Although spatial constraints are considered, they are based on a set of edges that have manually been set as available. The final DN design paper assumes a fixed network layout and only optimises the use of switches in order to achieve a radial topology (Enacheanu et al., 2008). In the problem at hand, new networks are to be built and not just optimised based on the opening and closing of switches. The final DN design model, (Duan & Yu, 2003), assumes all land to be available. It is therefore found that none of the specific DN models analysed can be directly transferred to the Dutch, regional networks as they assume that all land is available to build electricity networks on. For a spatially limited country like the Netherlands, spatial constraints are important in the design of electricity networks.

Other papers analysed in the literature review aim to design multi-commodity networks, including infrastructure for both gas and electricity simultaneously (Chaudry, Jenkins, Qadrdan, & Wu, 2014; Unsihuay, Lima, & de Souza, 2007). (Chaudry et al., 2014) argues that if both gas and electricity networks are used, it is important to consider both when optimizing flows. However, with the Dutch Cabinet deciding to phase out gas production in Groningen by 2030 and prohibiting new houses and buildings to be connected to the gas grid (Van ’t Hof, 2018), the future DNs in the Netherlands should not be co-optimised with the Dutch gas grid. One option could be to simplify the already created problem formulations to only include expressions related to electricity. However, the papers are focused on how the operation of electricity and gas networks is interrelated and it is therefore not a good approach for the future DNs in the Netherlands.

A finding from the literature review is the fact that graph theoretical approaches has been used successfully in the past in the design of electricity networks, but choices have not been made specifically for regions in the Netherlands. Several papers use graph theory to design electricity grids for offshore wind farms. Similarly to DNs, these networks are often built as tree structures. However, they normally only include one sink, the connection point to the transmission network that the offshore wind system is to deliver electricity to. Additionally, these grids are designed for offshore use, where there are often less obstacles for cables to be laid. Choices have therefore not been made on which land types to avoid and how to avoid these areas in the best way. Whereas (Ergun, 2015) takes spatial weights into account, the method designs meshed systems which are not likely to be appropriate for the future DNs in the Netherlands. It is therefore found that none of the models found are directly transferrable to the problem at hand.

1.5 Research questions

The literature aiming to identify knowledge gaps has found that none of methods created in reviewed papers can be directly applied to the case of designing the future DNs of regions in the Netherlands. This is particularly due to the lack of spatial considerations, which is important for a spatially constrained country like the Netherlands. It is also important that the networks have low costs, while still allowing supply to meet demand. The networks should in this way be cost-effective with respect to costs and delivering the demanded electricity.

The main research question of this thesis project is therefore;

RQ. How to choose and adapt graph theoretical approaches in order to design cost-effective electricity distribution grids for regions in the Netherlands while taking spatial constraints into account?

In order to answer the main research question, seven sub questions must be answered. The sub questions are formulated as follows:

SQ1. What are the requirements of future regional electricity distribution networks in the Netherlands? (Problem identification and motivation)

SQ2. Which network characteristics have an influence on the identified requirements? (Definition of objectives)

SQ3. Which aspects of costs should be considered for the electricity distribution networks? (Definition of objectives)

SQ4. How should the objective function, decision variables and constraints be formulated for the electricity distribution grid design? (Design and development)

SQ5. Which graph theory heuristics should be used for optimizing the electricity distribution grid topologies? (Design and development)

SQ6. How can graph theoretical approaches be adapted to further improve the solution? (Design and development)

SQ7. How effective is the model in doing what it is intended to do? (Demonstration using case studies and communication)

SQ8. Does the model create valid electricity grid designs? (Evaluation and communication)

1.6 Research contribution

1.6.1 Scientific research contribution

The main scientific contribution of this thesis paper is the fact that the method does not only consider technical challenges of electricity networks, but also takes social factors into account in the design of electricity networks. A method is created that takes spatial constraints into account and ensures that the future electricity networks avoid these areas. Because the choices are made explicit and with the method being flexible, similar networks, such as DNs for other spatially limited countries, can adapt and use the method also for other cases.

Additionally, with the release of the Regionale Energiestrategie, regions in the Netherlands are working on optimising their generation. PhD student at Delft University of Technology, Ni Wang, is currently working on a project that aims to find cost-optimal locations for generation that will also lead to good placement for transmitting the electricity. The generation locations are optimised specifically for the Dutch energy regions. In the topology part of the optimisation, the cost function is linearised and spatial constraints are disregarded. By creating a method specifically for electricity DN design, this method may be of scientific contribution to the co-optimisation project of Ni Wang in order to improve the overall optimisation for regions in the Netherlands.

1.6.2 Social research contribution

The research paper also makes social research contributions. By taking spatial constraints into account and ensuring that the future networks will avoid these, more realistic networks can be created which makes them more implementable. Additionally, it may reduce the total costs of building new electricity networks by avoiding areas that are likely to lead to additional costs or that may even be illegal to build on. The method created in this paper can also be used as a decision-making tool in order to explore the additional costs of rerouting with respect to unavailable land compared to the expected costs of building on the land.

Additionally, the design of the future DNs in the Netherlands affect consumers and society as a whole both directly and indirectly. In terms of direct effects, choices on reliability have an effect on the number and duration of blackouts experienced by consumers. Indirectly, the society is affected though monetary losses during blackouts. Additionally, the costs of new DNs in the Netherlands directly affect the relevant DSO's, whereas the costs will indirectly be passed on to end consumers. In this research paper, trade-offs between reliability and costs are taken into account when making design choices for the final networks, which, if the networks were to be implemented, would lead to consumers experiencing good security of supply under normal operating conditions, while still paying an acceptable price for electricity.

1.7 Report outline

The structure of the thesis report is as follows;

Chapter 2 presents a literature review on problem formulations in electricity grid design and identifies the requirements of regional electricity distribution grids in the Netherlands and the characteristics that have an impact on the defined requirements.

Chapter 3 presents the proposed method, including the problem formulation, discussions and final choices of graph theoretical approaches and the definition of a cost improvement procedure. Finally, choices of how to take time into account are made.

Chapter 4 defines the required input data to design the electricity grids, taking the chosen method into account. Discussions on the data credibility are made.

Chapter 5 discusses the effectiveness of the proposed method by creating experimental results, consisting of the method being applied to 50 randomly created networks.

Chapter 6 presents a case study on the energy region Goeree-Overflakkee using the method presented in Chapter 3 including a comparison of the method to an alternative approach.

Chapter 7 provides a discussion and final conclusions of the research paper. The chapter also includes implications for practice and recommended future points of research.

Chapter 2: Literature review

2.1 Collection method for literature review on electricity grid design

From the research questions formulated in Chapter 1, sub-questions 1 to 6 are to be answered using desk research in the form of a literature review. The chosen papers for the review are papers that aim to design electricity grids, with all electricity network types included so that the differences between electricity network types become apparent. The results are used in order to identify what has been done in electricity grid design in literature so far, which aspects have been included in the problem formulations and what the effect of these included and disregarded aspects have been on the final designs. Choices are thereafter made on what should be included in the problem formulation of the design of the future electricity DNs in the Netherlands and how the problems should be solved.

The search for relevant research papers has resulted in 17 papers from the time period 1996-2017. In the literature review, objective functions aiming to increase system reliability and minimise costs and power losses are discussed. The decision variables reviewed are cable lengths and capacities, voltage levels, the use of technical components, the choice of alternating versus direct current and underground versus overhead cables. The constraint types analysed are voltage levels and voltage drops, spatial constraints and three different topology types. Finally, the methods used to solve similar problems are analysed, including graph theory and mathematical programming, the use of reduction rules and improvement procedures. A review on how to take time into account for the final, static networks has been performed. Finally, conclusions are made on which aspects to include in the problem formulation of the design problem at hand. The table containing the full results from the literature review can be found in Appendix B.

2.2 Objectives of electricity grid design

2.2.1 Low cost

One of the characteristics of essential infrastructures such as electricity networks is the fact that they require large investments and that these investments are irreversible (Ergun, 2015). When an electricity system has been planned, designed and finally built, it is very difficult to move the cables and components to a more suitable location. This means that in cases where a part of an energy system does not perform as intended, it may be left stranded instead of moving it to a more desirable location (Ergun, 2015). Electricity networks are also characterized by a long lifetime. The design choices made today should therefore hold during changing production and consumption patterns in the future. With estimates stating that the electricity demand in the Netherlands will double within the next 30 years, the need for the right investment for both today and the future becomes crucial in the design of electricity networks (Ongkiehong, 2006). For a point of reference regarding investment costs, Ongkiehong (2006) has estimated that if the current Dutch electricity grid (including TN and DNs) were to be re-built today, it would cost a total of €20 billion. With the increasing electricity demands in the future, even larger total investment costs are to be expected.

There are several aspects of costs that together make the total cost of electricity networks, such as material costs, installation costs, operation and maintenance. If a cost expression is to be included in the design of electricity networks, choices need to be made in order to find the balance between including all the aspects that play a role in the total costs and achieving acceptable computational complexity. An overview of the costs included in the design papers reviewed is presented in Table 1. In the large majority of papers reviewed, the objective function included minimising investment costs. This may be due to investment costs in electricity grid design usually having considerably more importance than operational costs (Ergun, 2015). As can be seen in Table 1, this holds true for TNs, DNs, networks for offshore wind farms and for multi-commodity networks.

Operational costs are in some papers also included, although it is not as frequently used as investment costs. Operational costs are included by (Unsihuay et al., 2007), which creates a design for a multi-commodity network including both gas and electricity. In this case, the operational costs are related to the generators and not building the grid topology itself. Maintenance costs are included in the design of DNs for undeveloped cities (Tang, 1996) and income is included in conjunction with investment costs in a general electricity network design problem by (Heijnen, Ligtvoet, Stikkelman, & Herder, 2014).

From the literature review on cost aspects, it is found that the investment costs make the biggest impact on the total costs of electricity networks. Investment costs of the networks should be included in the cost expression. Because generation is disregarded, profit does not need to be included in the cost function.

Table 1 Literature review on cost aspects

Author (year)	Network type	Cost types considered
(Ergun, 2015)	Transmission - European supergrid	Investment
Aghaei, J., Amjady, N., Baharvandi, A., Akbari, M. (2014)	Transmission - generic	Investment (edges and units), operational cost of units, VoLL
Chaudry, M., Jenkins, N., Qadrdan, M., Wu, J. (2014)	Multiple Energy Carrier System (electricity and gas) – Great Britain	Investment of edges and units, operational cost of units, VoLL
Carrano, E., Soares, L., Takahashi, R., Saldanha, R., Neto, O. (2006)	Distribution - generic	Investment, power losses, faults (occurrence of faults, fault time)
Geidl, M., Andersson, G. (2006)	Multiple energy carrier system - generic	Total energy cost (port powers, coupling matrices, line flows)
Banzo, M., Ramos, A. (2011)	Power system for offshore wind farms	Investment, power losses, VoLL
Hou, P.,	Power system for offshore	Investment

Hu, W., Chen, Z. (2015)	wind farms	
Unsihuay C., de Souza, L (2007)	Multiple energy carrier system (electricity and gas) - tested on Belgium gas network	OPEX
Hu, Y., Bie, Z., Ding, T., Lin, Y., (2016)	Multiple energy carrier system (electricity and gas)	Investment, OPEX and CO2 emission cost
Tang, Y. (1996)	Distribution – developing city	Investment, OPEX, power losses, outages, maintenance, cost of switching devices
Chen, Y., Dong, Z., Meng, K., Luo, F. & Yao W. (2013)	Power system for offshore wind farms	Investment and power losses
Dahmani, O., Bourguet, S., Machmoum, M., Guérin, P., Rhein, P., & Jossé, L (2015)	Power system for offshore wind farms	Investment, profit
Sensarma, P., Rahmani, M., Carvalho, A. (2002)	Transmission – generic	Investment, power losses
(Heijnen et al., 2014)	Generic	Investment, Present Worth Ratio
(Duan & Yu, 2003)	Distribution	Investment

2.2.2 Ensuring consumers' security of supply under current and future operating conditions

One of the objectives often included in papers aiming to design electricity networks is reliability or security of supply. On a physical level, one of the core concepts is the fact that generation needs to meet demand. If generation does not meet demand or generation transmitted on the grid exceeds demand, the imbalance may lead to blackouts or damages to the grid (Vujanic, Mariethoz, Goulart, & Morari, 2012). Blackouts can lead to high societal costs, both direct loss of revenue for the electricity supply company and indirect costs of the loss of utility for the consumer. Maintaining security of supply is in most countries valued highly and the Netherlands is considered to be a country with reliable electricity networks.

An interruption of the Dutch networks is classified as an interruption of at least 5 seconds (Council of European Energy Regulators, 2016) and the "average" Dutch customer experiences a total of 15 to 38 minutes of blackouts during a year (Ongkiehong, 2006). This is considered low compared to other countries, due to both a well-developed grid and due to relatively stable climate conditions (Ongkiehong, 2006). Despite security of supply being valued highly in the Netherlands, in DNs it is often not prioritized as highly as with transmission networks and fewer redundant lines are therefore often in place. (Bauknecht & Brunekreeft, 2008). This is due to the assessed importance of the potentially lost load. Whereas blackouts in DNs often are local, blackouts in TNs can be widespread and therefore lead to much larger costs for both the electricity company and the consumers. In general, this means that most of the interruptions in energy supply therefore also occur in the DNs (Carrano, Soares, Takahashi, Saldanha, & Neto, 2006).

Whereas making choices with respect to reliability of electricity systems may be difficult for any network, it becomes increasingly difficult under the highly uncertain operating conditions of the future. Firstly, electricity demand is expected to grow during the coming decades due to the increased share of electric vehicles (EVs), the use of electricity for heating purposes instead of gas and the increasing use of data centres for internet traffic. In addition to this, a change in required capabilities of the future DNs is expected. Whereas TNs traditionally have included both small and large power generating facilities as well as control systems, DNs have traditionally neither included active sources of supply nor control systems and have merely worked as passive distributors of power. (Bauknecht & Brunekreeft, 2008). The lack of control systems in current DNs makes it difficult for distribution system operators (DSOs) to influence generation and stability. Flows in DNs have in the past also been unidirectional from higher to lower voltage levels. However, with the increase of distributed generation (such as electricity generation from PV modules on household roofs), DNs will need to be connected to active sources of supply and therefore allow for bidirectional flows (Bauknecht & Brunekreeft, 2008). This will particularly be a topic for the Netherlands, as the Netherlands already has a high share of decentralised electricity generation compared to the rest of Europe and this is likely rising (van der Weijden, 2015). The requirements of future DNs are in other words changing and will in the future be likely to share some of the characteristics of transmission grids.

It should be noted that achieving complete security of supply and reliability is close to impossible and it is also not needed in the design of electricity systems. A compromise must be made between reliability and costs that takes the final customers' interest into account. According to Schlabbach and Rofalski (2008), this trade-off should be guided by the following principle: "Reliability as high as necessary, design and operation as economical as possible". This can be seen under varying formulations in papers on electricity grid design. (Che, Zhang, Shahidehpour, Alabdulwahab, & Abusorrah, 2017) maximises reliability for the interconnection network of microgrids. Several other papers include reliability as a cost expression, such as the DN design paper by (Carrano et al., 2006). The function includes investment costs, power losses, occurrence of faults as well as fault time, but aggregates these four aspects into two cost functions in order to simplify the optimisation (investment with power losses and occurrence of faults with duration of faults), with the rationale being that minimizing the total failure costs will lead to a more reliable network (Carrano et al., 2006). Some papers include reliability in terms of Value of Lost Load (VoLL), which can be set as part of the cost function (Aghaei, Amjady, Baharvandi, & Akbari, 2014; Hu, Bie, Ding, & Lin, 2016). It should be noted, however, that these are papers that take generation into account.

Reliability has shown to be especially important to include in the objective function when the network topology is co-optimised with generation. Because generation is disregarded in this case, VoLL as an expression of reliability. However, it should be noted that under normal operating conditions, supply is able to meet demand.

2.2.3 Minimising power losses

In addition to DNs having the largest share of electricity interruptions in power systems, they also have the largest share of power losses (Carrano et al., 2006). This is partly due to the use of lower voltages in distribution which means a higher current. This is due to power losses being proportional to current squared, so higher currents lead to higher power losses (Schlabbach & Rofalski, 2008). The downside to this is partly that DNs have limited capacity and that power losses represent a waste of the commodity being sold, in other words a loss in revenue. Additionally, with the increased awareness of the environmental impact on electricity generation and the increasing pressures on using the world's electricity sources more efficiently, distribution system operators have become more focused on minimizing losses of electricity during its transportation (Enacheanu et al., 2008). The topic of how to design electricity distribution topologies with minimal power losses has therefore received increasing focus. Power losses can be divided into two categories: real and reactive power losses (Kashem, Le, Negnevitsky, & Ledwich, 2006). Real power losses originate from line resistance and therefore depends on total line lengths, whereas reactive power losses originate from reactive elements such as transformers, capacitors and insulators (Kashem et al., 2006).

An interesting finding is the fact that although DNs have the largest share of power losses, power losses are less included in DN designs than TNs and offshore wind farms. Related to TNs and offshore wind farms, (Sensarma, Rahmani, & Carvalho, 2002) and (Banzo & Ramos, 2011) consider power losses of transmission lines and connected components. Power losses are also included for DNs by (Enacheanu et al., 2008), but the paper considers opening and closing of switches rather than designing new electricity grids. The reason for this difference could be the differences in transmission lengths for TNs compared to DNs and the fact that DNs have historically used less technical components than TNs.

Because power losses as part of the objective function of electricity network design have only been included for DNs when finding the optimal topology using switches and not through design of new electricity grids, power losses can be considered less important in DN design. The aspect therefore does not have to be included in the problem formulation.

2.2.4 Length and capacities of electrical cables

Building costs of networked infrastructures depend to a large degree on cable lengths (Heijnen et al., 2014). This is due to both the costs of buying the cables and the digging costs depending on the length of the cables. Out of the papers that consider investment costs, all of the papers include length as a decision variable (full overview in Appendix A). In the calculation of cable lengths, all papers but one consider two-dimensional space. (Sensarma et al., 2002) considers building in three-dimensional space. In addition to latitude and longitude, altitude is considered.

Investment costs also depend on cable capacities due to the use of more material (Heijnen et al., 2014). The importance of cable capacities in electricity network design can be seen by a large majority of papers including capacities as a decision variable in their methodologies (Appendix A). Cable capacities can be formulated as a continuous variable, as in (Banzo & Ramos, 2011; Ergun, 2015) or a discrete variable, as in (Dahmani et al., 2015). By making the capacity variable discrete, the fact that cables are only available on the market in certain capacities is incorporated. However, in general, treating capacity as a discrete variable increases computational time (Ergun, 2015). An interesting finding is that although capacities have shown to be important for electricity networks, it is not always included in problem formulations (Che et al., 2017; Hu et al., 2016). It should be noted that in the design of topologies, this may create sub-optimal designs.

The relationship between lengths and capacities in the investment cost function is non-linear. It is for example cheaper to invest in one cable of capacity 2 than two cables of capacity 1 (Heijnen et al., 2014). This is due to only one installation campaign required. For underground cables, the differences in costs could for example be due to only one trench needed to be dug and prepared as well as covered when the laying of the cable has been completed. One of the main findings in this case is that most papers consider the non-linear costs (Banzo & Ramos, 2011; Chaudry et al., 2014; Tang, 1996). (Aghaei et al., 2014; Ergun, 2015) linearise the cost function in order to decrease complexity.

In order to conclude, due to the importance of length in electricity network design and due to investment costs being considered, length should be included as a decision variable. In the choice of two-dimensional versus three-dimensional space, it should be noted that when space is considered as an x y plane, distance calculations where there is a large slope are underestimated. However, considering three-dimensional space significantly increases the complexity of the problem. Additionally, as the Netherlands is a relatively flat country, including altitude gives little benefit compared to the additional computational complexity. It is therefore sufficient to calculate length in two-dimensional space. Capacity should also be included in order to achieve topologies that are based on more realistic variables. For simplicity, the capacities can be set as continuous variables. It should be noted that the cable capacities can easily be transformed into the closest capacity cable on the market at some additional cost. Finally, in order to incorporate the economies of scale of lengths and capacities, the investment cost function should be formulated as a non-linear function.

2.2.5 Voltage levels as a decision variable

Electricity grids are often characterized by their voltage levels. DNs are generally either in the category LV or MV, with LV distribution being used for transmitting electricity to small enterprises and retail customers and with MV distribution being used to supply electricity to larger users, such as hospitals and industry (Ongkiehong, 2006).

The TN design by (Sensarma et al., 2002) includes nominal voltage as a decision variable by repeating the topology optimisation for a range of voltage levels before choosing the level that leads to the cheapest design. Higher voltages lead to increased investment costs due to higher required insulation levels of equipment, whereas the indirect cost of power losses decreases when voltage levels are increased (Sensarma et al., 2002). For wind farm design, (Hou, Hu, & Chen, 2016) evaluates which voltage level is most in line with the voltage ratings of the chosen technical components. For DN design, voltage levels have not been included as a decision variable, but voltage drop constraints included in DN design will be discussed in Chapter 2.3.2.

Although a suitable voltage level will be ultimately decided upon for the DN in Dutch regions, it does not need to be included as a decision variable. The literature review has shown that voltage levels are more important in the design of TNs and offshore wind farm networks due to longer transmission distances. In addition to DNs having shorter transmission distances, voltage levels are stanardised and the effect of the optimisation would therefore be limited.

2.2.6 Installation of technical components

The most commonly included technical components as decision variables in literature are substations, transformers and switchgear. Offshore substations, including transformers and switchgear, are included in all papers designing networks for offshore wind farms (Banzo & Ramos, 2011; Chen, Dong, Meng, Luo, & Yao, 2013; Dahmani et al., 2015; Hou et al., 2016). They also included as decision variables in some TN designs, such as in the European Supergrid by (Ergun, 2015) and the generic TN by (Sensarma et al., 2002). One DN design paper includes switching devices as a decision variable (Tang, 1996) (Explanation?). The other three DN design papers disregard all technical components in their designs (Carrano et al., 2006; Duan & Yu, 2003; Enacheanu et al., 2008).

One possible reason why technical components are more frequently included for TNs and offshore wind farms than DNs is that there is a difference in transmission distances. If the points of generation are far from the points of consumption, transmitting the electricity at higher voltages leads to lower power losses (Seifi & Sepasian, 2011). Transformers that can scale up or scale down the voltages at a certain point are therefore more applicable to long-distance transmission. DNs both operate at lower voltage levels and usually have lower voltage drops (Duan & Yu, 2003) and transformers therefore have limited importance compared to TNs and offshore wind farms.

The literature review has shown that technical components are more frequently included in electricity networks that transmit electricity over long distances and where scaling up or scaling down of the voltage levels is done strategically in order to minimise power losses. For DNs that usually transmit over shorter distances and experience smaller voltage drops, it is less important to include the use and the placement of technical components as decision variables. It should be noted that although technical components are disregarded simultaneously with the topology design, the appropriate technical components can still be determined and located at suitable locations in the network when the topology has been found.

2.2.7 Influence of alternating current and direct current

Electricity systems have two ways of transmitting electricity; with the use of alternating current (AC) or direct current (DC). From the papers reviewed, Ergun (2015) has included AC versus DC transmission as a decision variable when designing electricity grids and it is formulated. This is a paper specifically designing a European supergrid for transmission over long distances. By including this decision variable, the trade-off between minimising conversion losses and transmission losses with the use of DC transmission and the increased investment costs related to DC transmission can be explored (Elsayed, Mohamed, & Mohammed, 2015). For the reviewed papers aiming to design DNs, AC versus DC transmission has not been included as a decision variable.

When considering costs, DC is superior to AC for longer distances, whereas AC is superior for shorter distances (Rashid, 2017). The breakeven point, as shown in Figure 4, ranges from 500-800 km for overhead lines depending on the unit cable cost. For underground cables, the breakeven point occurs around 50 km (Rashid, 2017).

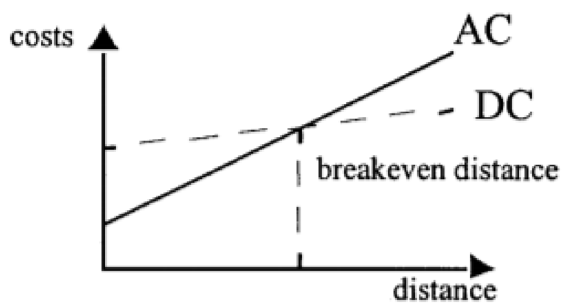


Figure 4 The trade-off between costs and transmission distance for AC and DC transmission is in equilibrium at the breakeven distance. Reprinted from (Rashid, 2017)

The literature review has shown that AC versus DC transmission has not been included in any of the DN network problem formulations. The only problem formulation including the variable aims to design a European supergrid with long transmission distances and deviations from the nominal voltage levels. With the future distribution systems in the Netherlands and their expected transmission distances being much shorter than 50 km, DC transmission is unlikely to be the preferred option and the two choices do not need to be considered explicitly as a decision variable.

2.2.8 Influence of underground and overhead cables

Electricity cables can either be underground, by digging a trench and laying and covering the cable, or overhead, suspended by electricity poles or towers. Installing underground is much more costly than installing distribution cables, with the costs estimated to equal four to twenty times that of overhead cables (Bumby et al., 2010). However, overhead cables are more prone to collisions with vehicles, live-wire contacts and are also more likely to be damaged in the event of a fire (Bumby et al., 2010). Due to the improved reliability, underground costs may decrease due to decreased need for maintenance. It should be noted that this advantage is to a certain extent constrained by the fact that maintenance takes longer for underground cables, as the cables are concealed and there is therefore no direct access to the cables. Additionally, there is a point of aesthetics, as overhead cables are more of a visual obstruction.

Similarly to the consideration of AC versus DC transmission, Ergun's (2015) European supergrid problem is the only paper considering underground versus overhead cables as a decision variable, having different costs associated to the two transmission concepts. From the most recent CEER benchmarking report on the quality of electricity and gas supply, it was presented that the Netherlands is the only country out of the 30 European countries surveyed with 100% use of underground cables in both LV and MV electricity grids (Council of European Energy Regulators, 2016) (Figure 5).

The fact that the LV and MV networks in the Netherlands are built completely underground indicates that underground cables are favoured in the country and that it is likely that future networks will also be built underground. Additionally, it has not been included as a decision variable by any of the DN papers. Underground cables versus overhead lines will therefore not be included in the problem formulation of new distribution grids in the Netherlands.

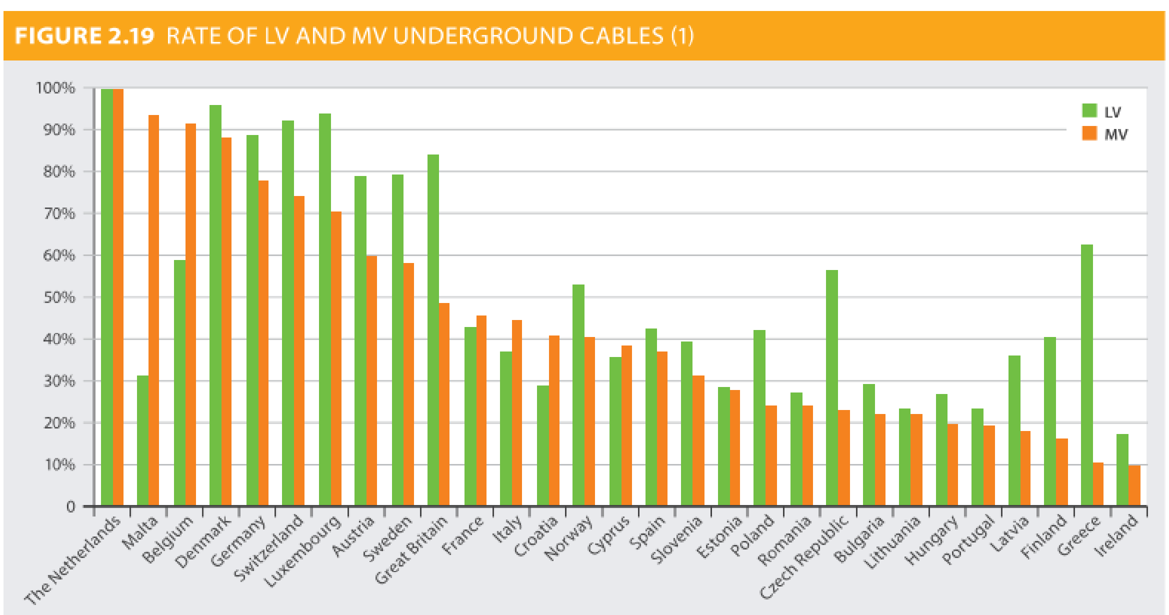


Figure 5 The Netherlands is the only out of the x surveyed countries that only uses underground cables for LV and MV transmission. Reprinted from Council of European Energy Regulators (2016).

2.3 Design constraints

2.3.1 Voltage levels and angles as design constraints

Voltage drop constraints are only included in one of the reviewed papers' problem formulation (Tang, 1996). Upper and voltage limits are in some cases also included (Carrano, Soares, Takahashi, Saldanha, & Neto, 2006; Duan & Yu, 2003; Hou, Hu, & Chen, 2016; Unsihuay, Lima, & de Souza, 2007). (Aghaei, Amjady, Baharvandi, & Akbari, 2014) also includes voltage angle limits in their TN design paper. (Duan & Yu, 2003) points out that the reason why many DN papers do not include voltage constraints could be due to the small differences in voltages as well as voltage angles in DNs compared to other electricity networks.

One of the papers designing DNs includes Kirchoff's Voltage Law (KVL) (Enacheanu et al., 2008). Because KVL is relevant only for networks with loops and in the case of opening and closing of switches, it should not be included for DNs with radial topologies when switches are not considered.

Due to the small differences in voltage drops and voltage angles for DNs, these aspects can be disregarded as constraints for the problem at hand. Similarly, KVL can be disregarded if the design has a radial topology and switches are disregarded.

2.3.2 Building large networks in spatially limited areas: taking spatial constraints into account

Electricity networks vary per country depending on population density, the country's topology and climate as well as the history behind construction and improvements of the electricity networks (Council of European Energy Regulators, 2016). In the large majority of cases when new electricity systems are designed, the grid topologies are limited by existing infrastructure or rules and regulations related to the concerned areas. If spatial properties are disregarded, this may lead to suboptimal designs as if the electricity design overlaps with existing infrastructure, the process can be both costly and timely depending on the land type. If areas are defined as unavailable due to existing rules and regulations, it may not just be costly, but illegal if special arrangements have not been made.

From the reviewed papers, a surprisingly low number of papers incorporate spatial constraints in their problem formulations and from the papers that include spatial constraints, the formulations vary significantly. The optimisation by (Carrano et al., 2006) starts with an initial set of available edges that can be used to connect a set of vertices. It is assumed that the set of included edges are all available to build on. However, the selection of available edges is done manually and there is therefore no specific formulation of which land types have been excluded. (Heijnen et al., 2014) takes spatial constraints into account by first creating an initial network before rerouting it until it lies within the allowed boundaries. For this approach, it is not defined which land types should be avoided. Instead, the allowable region is defined as a polygon, which makes it transferable to different network types as well as different areas.

The paper by (Ergun, 2015) explicitly states the considered land types and differentiating these by incorporating “spatial weights”. In Figure 6, the considered land types are presented as well as their corresponding cost coefficients, representing the costs associated with building on a certain land type. The cost coefficients are approximated for four categories, depending on transmission and cabling option. For the most probable category for distribution systems in the Netherlands, AC transmission with underground cabling (UGC), the reference cost is building on fields and on hills. Although not impossible to build on, prohibited areas are given a spatial weight corresponding to 40 times the cost of building on fields and hills. Additionally, cities of different sizes as well as mountains and offshore cables are considered. The spatial weights are incorporated in the design problem by discretising land points in a graph and adding horizontal, vertical and diagonal edges before adding weights from the land categories to the corresponding edges. It should be noted that the spatial weights are approximated specifically for Germany and that they may not necessarily reflect real-life costs.

Area	AC OHL	DC OHL	AC UGC	DC UGC
Field	1	1	1	1
Hill	2.5	2.5	1	1
Mountain	10	10	4.5	4.5
Sea	40	40	0.75	0.75
City	10	10	2	2
Big city	40	40	2.5	2.5
Prohibited area	40	40	40	40

Figure 6 Spatial weights differentiating between land types, as defined by Ergun (2015)

According to (Ongkiehong, 2006), the issue of building large infrastructures in a limited space is especially prevalent in the Netherlands due to the high ratio of built land and the general lack of space. It is therefore clear that spatial constraints are important for electricity design in the Netherlands. Further, as previously identified, the future electricity grids of the Netherlands are likely to be built underground. This should be reflected in the spatial constraints for the future Dutch grids.

In order to ensure that the grid topologies avoid unavailable plots of land, spatial constraints should be considered in the problem formulation. The challenge with the approach proposed by (Ergun, 2015) is the fact that it is difficult to quantify the costs of areas that will hold for all regions in the Netherlands. Instead, constraints can be made in such a way that the network completely avoids the unavailable areas.

2.3.3 Choice of system topologies

There are three main system topologies that exist for electricity networks. These topologies have different characteristics, advantages and disadvantages and their applicability therefore depends on the characteristics and requirements of the electricity grid.

2.3.3.1 Radial systems

Radial topologies are the most simple topologies with the lowest investment, maintenance and planning expenditure out of the three main topology categories (Schlabbach & Rofalski, 2008). Because the radial topology does not include cycles (Figure 7), the loading of the lines can reach 100%, meaning that the lines are used very efficiently. It is often used for LV and MV grids and predominantly in areas characterized by a low load density (Schlabbach & Rofalski, 2008). This is due to the system's main disadvantages, namely that there is no reserve in the case of faulty lines and that radial topologies are less flexible to changing loads. Radial topologies also have high system losses compared to the ring-main and meshed system (Schlabbach & Rofalski, 2008).

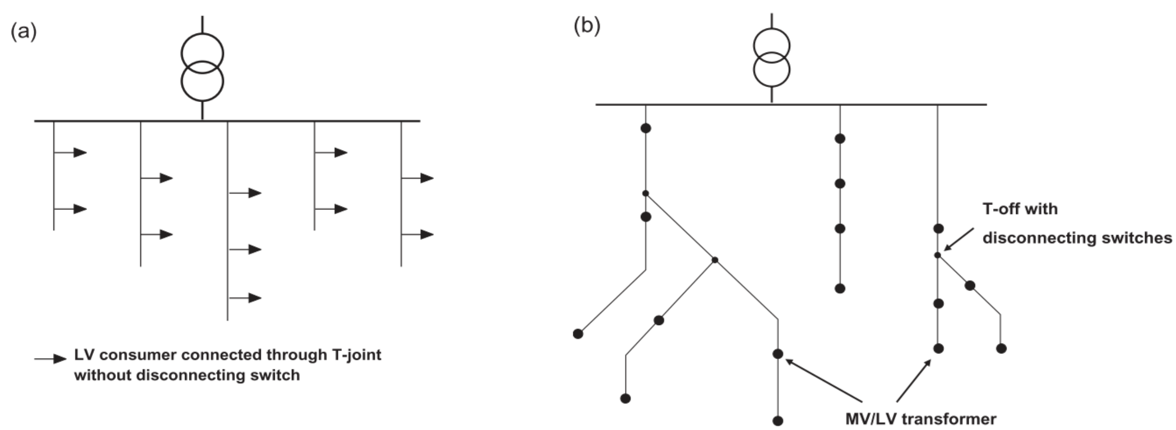


Figure 7 Radial systems (LV and MV). Reprinted from (Schlabbach & Rofalski, 2008)

In literature, all four of the reviewed papers designing DNs have included a radiality constraint (Carrano et al., 2006; Duan & Yu, 2003; Enacheanu et al., 2008; Tang, 1996). The method by (Tang, 1996) first finds an initial network before checking whether the radiality constraint is met. If loops are present, changes to the branches are made manually before re-checking that the radiality constraint is met. Radial systems have also shown to be the most common topology for electricity grids for connecting offshore windmills to the main grid due to its low cost and the lower required reliability levels for this network type (Banzo & Ramos, 2011; Chen et al., 2013; Dahmani et al., 2015; Hou et al., 2016). Due to the higher reliability requirements of TNs, it is not included as a constraint for such networks.

2.3.3.2 Ring-main systems

Ring-main systems in their simplest form are radial topologies where the branch ends are connected back to the feeder (Schlabbach & Rofalski, 2008). Ring-main systems include disconnection points that are normally left open in order to achieve simple operating conditions such as in radial systems (Figure 8). In the case of faulty lines or extreme load conditions, the disconnection points can be closed to utilize all the available lines, which increases the system reliability. The disadvantage of the ring-main system is a less efficient use of the lines compared to the radial system with a line loading of up to 50% and higher planning expenditure (Schlabbach & Rofalski, 2008).

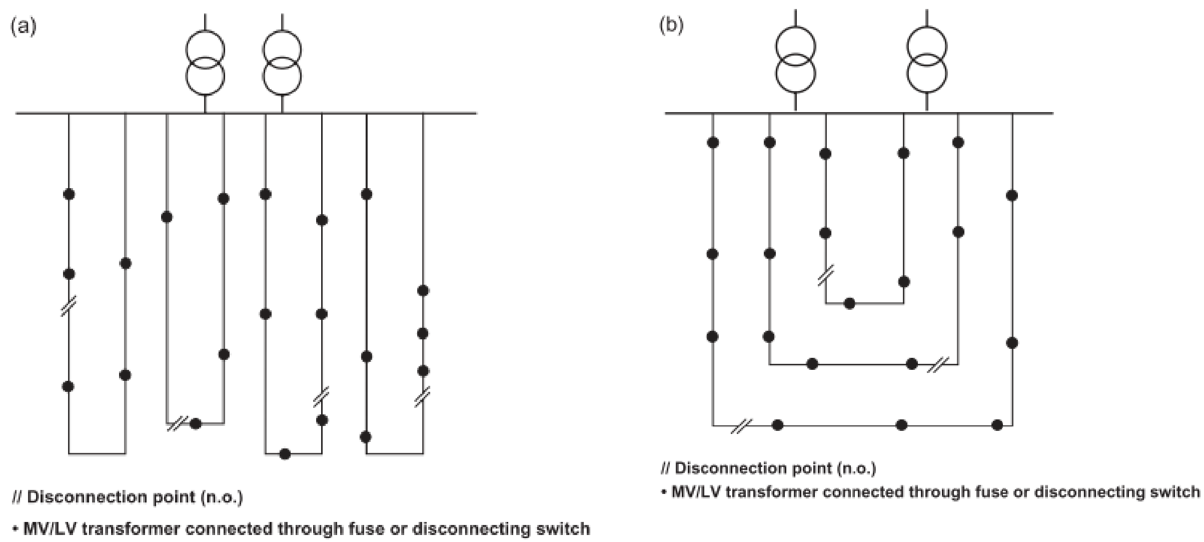


Figure 8 Ring-main systems. Reprinted from (Schlabbach & Rofalski, 2008)

Ring-main systems are not set as a design constraint for any of the reviewed papers. This indicates that for DN design, investment costs are valued more highly than the increased reliability and flexibility achieved by ring-main systems. For TNs, reliability is valued more highly than what the ring-main systems can provide.

2.3.3.3 Meshed systems

Electricity grids characterized as meshed systems can be ring-main systems where all disconnection points are closed during operation (Schlabbach & Rofalski, 2008) (Figure 9). This allows for several candidate lines to be used for transporting electricity, which leads to very high reliability and flexibility to changing load conditions and line failures. Meshed systems are also characterized by a very flat voltage profile, which allows for low system losses (Schlabbach & Rofalski, 2008). The disadvantage of this system is high investment and maintenance costs due to high material use, the need for a large number of technical components and high planning expenditure.

From the papered reviewed, several TN designs have a meshed topology (Aghaei et al., 2014; Ergun, 2015; Sensarma et al., 2002). It has not been the chosen topology for any DNs or offshore wind farm designs.

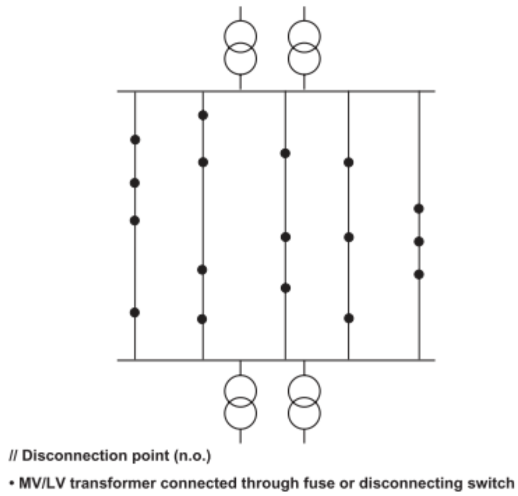


Figure 9 Schematic of a simple meshed system based on a ring-main system with closed switches. Reprinted from Schlabbach & Rofalski, 2008).

In order to conclude, it is found that radial systems are the most commonly used topology for DNs. This is because of its lower investment costs and the lower reliability requirements of DNs compared to TNs. A radial topology is therefore appropriate for the future DNs in the Netherlands and a radiality constraint should therefore be included in the problem formulation.

2.4 Designing static structures under time-varying conditions

One of the challenging characteristics of electricity grid design is the fact the electricity grid installations are fixed whereas the input conditions can vary greatly with respect to time. Although switches can be installed that modify the power flows in the system, the power cables are either fixed on utility poles or laid in a trench and then buried underground. At the same time, the electricity consumption varies depending on variables such as the time of day and the temperature whereas the electricity production depends on the wind speed for wind turbines and solar irradiance for PV modules. The issue that arises is therefore that different designs will be found for different time steps and choices need to be made in order to find a design that will be able to deliver electricity at varying conditions throughout its lifetime

In order to take time-varying conditions into account, (Dahmani et al., 2015) uses maximised generation and consumption data and makes 3000 iterations before choosing the cheapest network, only taking length into account. Capacities are thereafter assigned. (Hou et al., 2016) creates designs under varying conditions and simply chooses the favourite. 15 iterations are run before a final design is chosen. Ergun (2015) maximises the injection capability over the year and creates a meshed design using graph theory based on this. Finally, an N-1 analysis is performed and required changes are made. (Heijnen et al., 2014) use a somewhat different approach, using a time-averaged density graph. Designs for all iterations are added to the graph, and the more frequently chosen paths are given a higher weight in the density graph before the final network is found.

The literature review has shown that the ways of taking time into account vary greatly. In terms of topologies, instead of choosing a favourite or finding the shortest overall network, a choice based on frequency, like the density graph, gives better basis for choosing a good network topology over time. In terms of generation, maximisation of generation and demand data has shown to be used for finding the final cable capacities based on a worst-case scenario approach. By instead finding the maximum capacities needed for each cable during the time period, the robustness of the solution is further improved.

2.5 Methods used for designing electricity networks

2.5.1 Discretisation of land maps into grid graphs

With the use of graph theory, choices a required on whether cables can be built anywhere or whether they are restricted to an underlying set of allowable edges. (Ergun, 2015) approaches this by discretising land maps into a grid graph containing both horizontal, vertical and diagonal edges. This land discretisation is presented in Figure 10. The reason for the two grey tones in the figure is to differentiate between two areas of different spatial weights, as previously discussed. It should be noted that the mesh size is constant across the graph, but can be changed for each run.

Figure 10 Discretising map into a grid graph containing horizontal, vertical and diagonal edges. Reprinted by (Ergun, 2015)

2.5.2 Graph theoretical approaches searching for local optima

A common approach in electricity network design is performing local graph theory reconfigurations iteratively using Evolutionary Algorithms (EAs). The advantage of EAs is the fact that the algorithms can find a solution in a single run instead of having to run the method a large number of times and saving the outputs for each run (Carrano et al., 2006). This approach is used in two of the papers designing electricity grids for offshore wind farms. In both the cases, the vertices to be connected are added to the graphs before applying Prim's algorithm locally using an EA (Dahmani et al., 2015). In the other case, (Hou et al., 2016) uses an iterative MST approach, also using EAs, that was found to outperform Prim's algorithm. (Duan & Yu, 2003) has designed DNs using a similar approach. However, instead of finding an MST, the problem is formulated as a Steiner Minimum Tree (SMT), specifically a Capacitated Minimum Spanning Tree in order to take capacities into account. A disadvantage of EAs is the fact that it performs local searching. However, difficult to find a method searching for global optima that is within feasible computational complexities. It should be noted that many graph theoretical approaches also search for local optima, the so-called greedy algorithms. For large and design problems such as the ones for electricity network design, approaches searching for local optima may be appropriate options. (Ergun, 2015) manages to get close to a global optimum by iterating MILP as well as graph theory approaches. Both Dijkstra and A* have been performed, with A* giving the best results. (Tang, 1996) uses a Maximum Flow Algorithm to determine the optimal topology of a small DN. This is a method suitable for finding radial networks. However, it uses a linear cost function and is not suitable for very large networks.

2.5.3 Local reconfiguration procedures

It has previously been found that both lengths and capacities should be taken into account. However, the assignment of capacities at one point in time depend on changes and future capacity assignments made to the rest of the network. It is therefore difficult to create a network based on both lengths and capacities in on step. A network based on lengths does not change depending on the assignment of other edges. A shortest network can therefore be found using one step. However, this means that further procedures are required in order to take capacities into account.

(André et al., 2013) proposes an algorithm called Delta Change, which makes local reconfigurations based on an initial network. After identifying the closest vertex, an edge is created to make a cycle before another edge in the cycle is removed (Figure 11). It is thereafter checked whether the change makes cost savings. If savings are made, the local reconfiguration is applied to the network. In this way, the cost calculations can be based on both length and capacities. It should be noted that if the grid graph approach is applied, straight edges cannot be created as they do not follow the underlying grid graph. Paths following the underlying grid graph would have to be used instead.

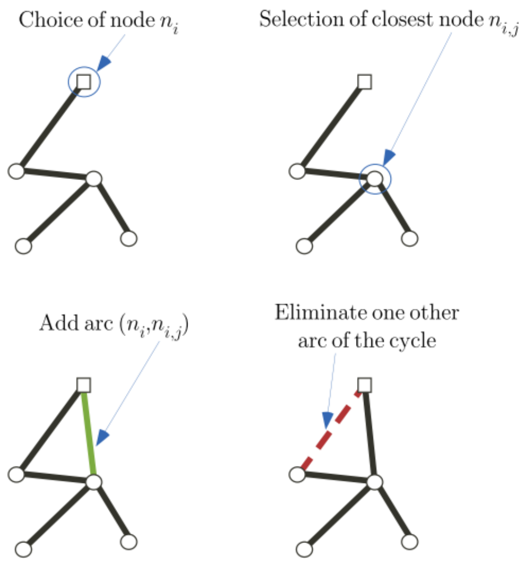


Figure 11 Demonstration of Delta Change. Reprinted by (André et al., 2013).

2.5.4 Conclusion of suitable methods for electricity distribution design in Dutch regions

The literature review has shown that it may be useful to discretise the land maps into grid graphs. By including horizontal, vertical and diagonal edges, the smoothness of the paths can be sufficient as long as the mesh size is chosen appropriately. Additionally, it can allow for spatial constraints to be taken into account, as in the paper by (Ergun, 2015). Another finding is the fact that in the design of electricity networks using graph theory, heuristics searching for local optima are often used in order to manage the high complexity of these problems.

Additionally, it has been found that it is difficult to take lengths and capacities into account in one step due to the assignment of edges depends on the assignments yet to be made. An approach to deal with this challenge is therefore to first find a shortest network before implementing a local reconfiguration procedure in order to take capacities and non-linearity into account.

2.6 Conclusions from literature review

From the study of how electricity networks have been designed in literature, it has been found that investment cost is the most widely used expression of costs, as it is often also the biggest cost associated with electricity networks. For simplicity, this should be the only cost expression included in the proposed method. All papers optimise based on network length, whereas only some papers also include capacity. If only length is considered, the network will be short. However, the overall network may be expensive if a large part of the network requires high capacities. If both length and capacity are included, a topology with a more efficient use of material will be found.

The exponent β is often used to represent the non-linearity of the investment cost function. With a β value of 0, capacities are not considered and with a value of 1, capacities are included but the cost function is linearised. Although several papers use a linearised cost function, this means that the final network is based on the assumption that building one line of capacity 2 is just as expensive as building two lines of capacity 1, which does not reflect reality. In order to incorporate the fact that investing in a short high capacity network may be cheaper than a long low-capacity network, a non-linear cost function should be included. Capacities can be either formulated as a continuous or discrete decision variable. Whereas discrete variables are more realistic as only certain capacities are available on the market, the computational complexity of the problem can be reduced by treating capacity as a continuous variable and instead rounding off to the nearest capacity available on the market if the solution were to be implemented.

In terms of electricity network topologies, three types have been identified; radial topologies, ring topologies and mesh topologies. For DNs, radial and ring topologies are appropriate, as in the trade-off between costs and reliability, meshed topologies are too expensive. In literature, radial topologies are often chosen due to their investment costs being the lowest and due to the lower reliability requirements of DNs. A radiality constraint can be met by chosen methods aimed specifically for creating trees, by preventing cycles or by ensuring that all cable costs are positive and minimising costs. Although radial topologies have lower reliability than other topologies, it is important that DNs have sufficient capacity to supply demand vertices with electricity during normal operating conditions.

It has also become apparent through the literature review that several decision variables that may add value for TNs are not as important in the design of DNs. Voltage levels can be disregarded in the design of DNs as voltage levels are restricted to an internationally standardised set of voltages and due to the final design being likely to be incorporated with the current networks in the Netherlands. Optimised voltage levels therefore have a limited importance to the future DNs. Additionally, voltage constraints in terms of amplitude and angles have also shown to be less important for DNs compared to other network types. For simplicity, they can be disregarded.

Finally, AC versus DC distribution should be disregarded as a design variable for the DN design problem due to AC being cheaper for short distances. Additionally, if the designed grid is to be incorporated with the current grid, it is an advantage that they are the same distribution type. Underground versus overhead cables can also be disregarded as a design variable, as the Netherlands has already chosen to invest in underground cables. This could be due to the interest in a high reliable network, the space scarcity and the high population density. It can therefore be assumed that the future grids should preferably also be underground cables.

Chapter 3: Methodology

3.1 Discretising regional maps in grid graphs

In order to differentiate between available and unavailable plots of land, a choice has been made to discretise the maps of land into grid graphs. The grid graphs are used as underlying networks of where electricity lines can be built. Vertices are added to each corner point of the graph. In this way, vertices corresponding to unavailable areas can be removed in order to prevent the final networks to be built on these plots of land. In order to increase the smoothness of the final networks, horizontal, vertical and diagonal edges are included in the grid graphs. For simplicity, space is considered in two dimensions and there is a consistent mesh size across the graph. Whereas the lengths of horizontal and vertical edges can be defined for each run, the lengths of the diagonal edges simply follow from Pythagoras' Theorem.

The method is created and run in Python using Networkx, a library specifically created for working with graphs and networks.

3.2 Electricity network design using a Minimum Steiner Tree in Graph approach

In graph theory, the problem of designing electricity grids based on connecting a set of defined vertices can be approached in several different ways. The simplest approach is the Minimum Spanning Tree (MST) approach, which connects all vertices in the cheapest possible way. However, for the design of the future Dutch electricity distribution networks, some plots of land are to be avoided. As the MST problem creates straight edges between the set of vertices, the final network is likely to violate the areas marked as unavailable. *Steiner vertices*, additional vertices that can be included in the final network, can be used in order to create paths that avoid the unavailable areas. Using Steiner vertices and taking the underlying grid graph into account, the problem can be formulated as a Minimum Steiner Tree in Graph (MSTG) problem. The MSTG problem aims to find the cheapest way of connecting a selected set of vertices, *terminals*, in a graph, possibly using Steiner vertices. The Steiner vertices are placed at the corner points of the grid graph (Winter, 1987). By definition, all terminals are to be connected to the final graph, whereas Steiner vertices can either be included or left out. The problem has similarities to the MST problem. However, the difference of only connecting a subset of vertices manifests itself in the increased complexity of the MSTG problem. Whereas the MST has a relatively low computational complexity, the complexity of the MSTG is high and, according to (Winter, 1987), it is difficult to solve a problem containing more than 30 points in less than an hour.

3.3 Problem formulation

The MSTG problem in an undirected graph is defined by (Winter, 1987) as follows:

Given: An undirected network G = (V,E,c) with n vertices, m edges, and the edge cost function c: E → R, a subset Z ⊆ V with p vertices (where V is a set of vertices, E is a set of edges and c is the edge-cost function).

Find: A subnetwork G_Z of G such that there is a path between every pair of Z-vertices, and the total cost of G_Z (i.e., the sum of its edge costs) is a minimum.

As investment costs are to be minimised, a non-linear cost function is formulated taking edge lengths and capacities into account:

$$min\ C_{inv} = \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} l_{ij} q_{ij}^{\beta} \qquad 3.1$$

Where l_{ij} is the length and q_{ij} is the capacity of the edge between vertices i and j and β is the exponent representing the economies of scale related to installing cables with high capacity compared to low capacity. The length and capacity variables are both continuous whether β is any number between zero and one, $0 \leq \beta \leq 1$. The costs are summed over all edges in the final network.

It should be noted that if the edge-cost function *c* is positive, the final network will always have a radial/tree topology (Winter & Smith, 1992). The network will therefore be a connected graph which does not contain any cycles.

Spatial constraints are also included in the problem and cables can only be built on land marked as available. This constraint is met using the removal of Steiner vertices in areas characterised as unavailable.

3.4 Methods to finding a Minimum Steiner Tree in Graph network

As the DN design problem can be described as an NP-hard problem for which the computational complexity increases exponentially with the scale of the problem, a well-chosen approach that both performs well for the problem at hand and that has acceptable computational time is needed. Whereas a brute-force method is guaranteed to find the globally optimal solution, it is too computationally complex for anything else than very small networks. Heuristics are therefore needed in order to decrease the computational time. It should be noted that a heuristic often just finds a local optimum and not the global optimum. If a well-chosen heuristic is chosen, the final network can be a good solution, although not necessarily the best solution.

There are a number of already formulated algorithms and heuristics in place that can be used to find MSTGs. These are presented in Figure 12. According to (Duan & Yu, 2003), mathematical algorithms such as Branch and Bound methods, Lagrange Relaxation, and Dynamic Programming will not be able to handle the computational complexity of DN design problems, especially if it is formulated as an MSTG. (Winter, 1987) further proposes that for MSTG problems that are not very small, heuristics should be used.

Path Distance Heuristics (PDHs) are a set of heuristics that can be used to find the MSTG. The PDHs all start with a graph consisting of isolated terminals before defining a way of adding paths between terminals until the graph is connected. An MST is thereafter computed and trimming is thereafter performed until the final tree is presented. In this subchapter, four common heuristics will be presented and their applicability is analysed.

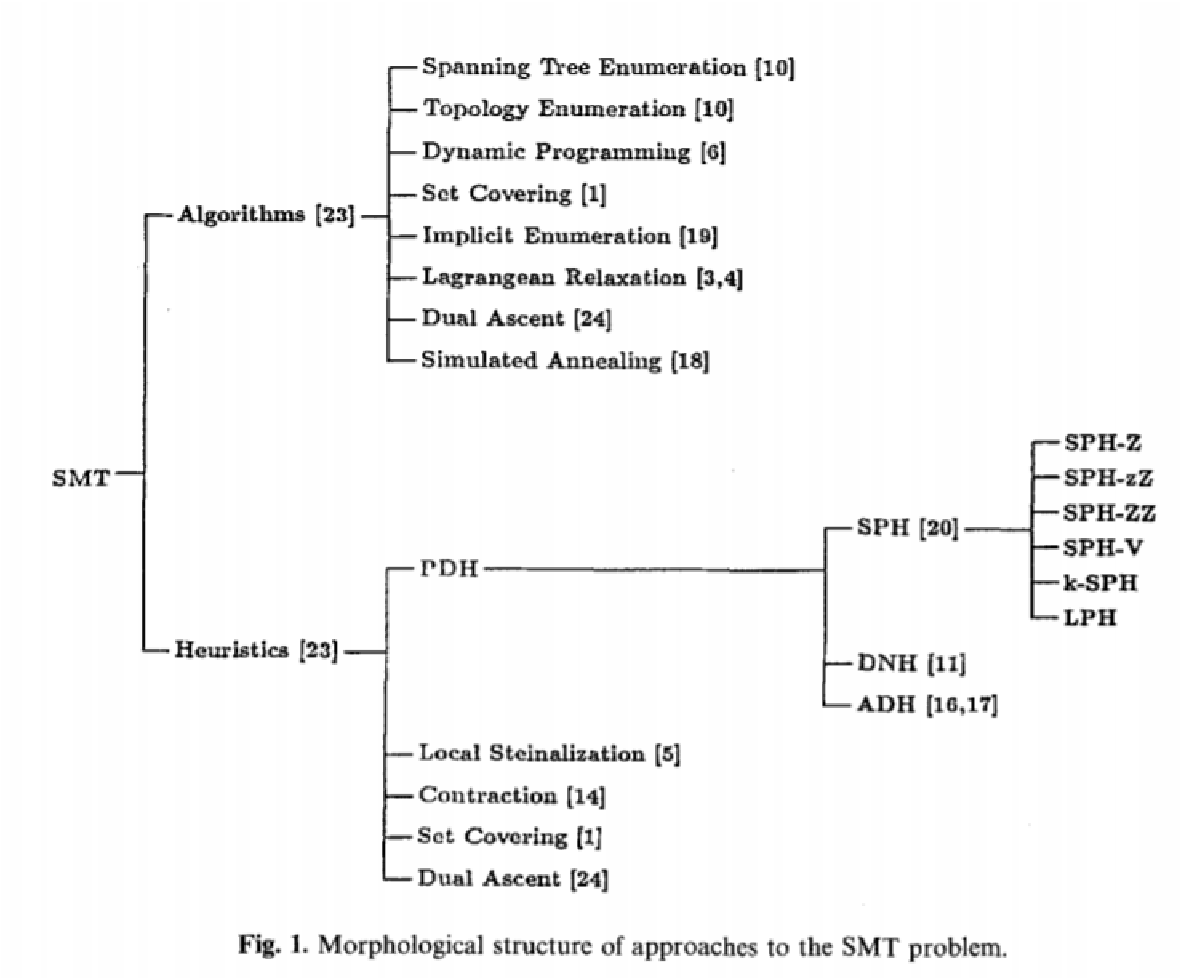


Figure 12 Minimum Steiner Tree in Graph approaches. Reprinted from (Winter & Smith, 1992)

3.4.1 The Shortest Path Heuristic and its repetitive applications

The Shortest Path Heuristic (SPH) is a heuristic with the rationale that incrementally adding shortest paths will lead to a short network. The heuristic starts by randomly choosing an initial terminal vertex and searching for the terminal vertex that will lead to the shortest connection path (Winter & Smith, 1992). In a grid graph as chosen in this method, Dijkstra's algorithm can be used to compute the shortest path and paths can either consist of a direct edge connection or with the use of Steiner vertices. After adding the shortest path to the subgraph, the search for another shortest path continues. This is done using a Prim's type search, adding the visited vertex found in the previous iteration to the set of vertices that can work as initial vertices. The computational time is $O(pn^2)$, with *p* representing the number of terminals to be spanned and *n* representing the total number of vertices in the graph (Winter & Smith, 1992). It is often a favoured approach as it is more accurate than the Distance Network Heuristic (DNH) (Winter & Smith, 1992). The error ratio is bounded by two, meaning that in the worst case, the solution is double the length of the globally optimal solution.

One of the disadvantages of the SPH is that the solution is very sensitive to the initially chosen terminal, which is in the original formulation chosen randomly (Winter & Smith, 1992). Repetitive applications of SPH are formulated in order to avoid this issue and thereby finding a shorter network. The iterative approaches will in this way never be worse than the original SPH formulation, but computational time will increase. One of these repetitive applications is the SPH-Z, which iterates over all initial vertices before choosing the network of shortest total length. The computational time is therefore multiplied by the number of terminals in the network. SPH-ZZ and SPH-V are two other repetitive applications of the SPH. In addition to iterating the initial vertices, they iterate the use of Steiner vertices. As a MSTG approach is chosen in this case, the Steiner vertices will be placed at each corner point and do not need to be iterated. SPH-Z is therefore a more appropriate method.

3.4.2 Distance Network Heuristic

(Winter & Smith, 1992) describes the Distance Network Heuristic (DNH) as the "iteration of Prim's algorithm for the MST problem of the distance network". The distance network consists of the set of terminals, Z, as well as edges between terminals represented by minimum length paths. Similarly to the SPH, the computational time of the DNH is $O(pn^2)$ and the worst-case error ratio is bounded by 2 (Winter & Smith, 1992). The DNH is not always, but often less accurate than SPH. In Winter & Smith's (1992) comparison of the PDHs performances for a grid graph. From Figure 13, it can be seen that both the Average Distance Heuristic (ADH) and SPH perform better than DNH.

3.4.3 Average Distance Heuristic

The Average Distance Heuristic (ADH) starts by choosing an initial vertex, either terminal or Steiner vertex, made based on a defined centrality measure (Winter & Smith, 1992). The rationale being that initiating the heuristic with the most central vertex is that with a larger number of candidate first paths, it is more likely to lead to a cheaper network. This partially overcomes the discussed disadvantage of the SPH. Both for random networks and for grid graphs specifically, the performance of ADH is superior to both the SPH and the DNH (Figure 13). However, when repetitive SPH approaches are included in the comparison for grid graphs, the repetitive SPH approaches have a higher best solution frequency. The ADH has a computational complexity of $O(n^3)$ (Winter & Smith, 1992). The computational time is therefore worse than the standard SPH and DNH approaches, but better than the repetitive SPH approaches.

3.4.4 Minimum Spanning Tree Heuristic

Finally, the Minimum Spanning Tree Heuristic (MSTH) computes the MST for all vertices before removing obsolete edges. The worst-case error ratio is n-p+1. Although the computational complexity is the lowest of the reviewed heuristics with a computational complexity of $O(n^2)$, it is inferior to the SPH and should therefore not be the chosen heuristic (Winter, 1987).

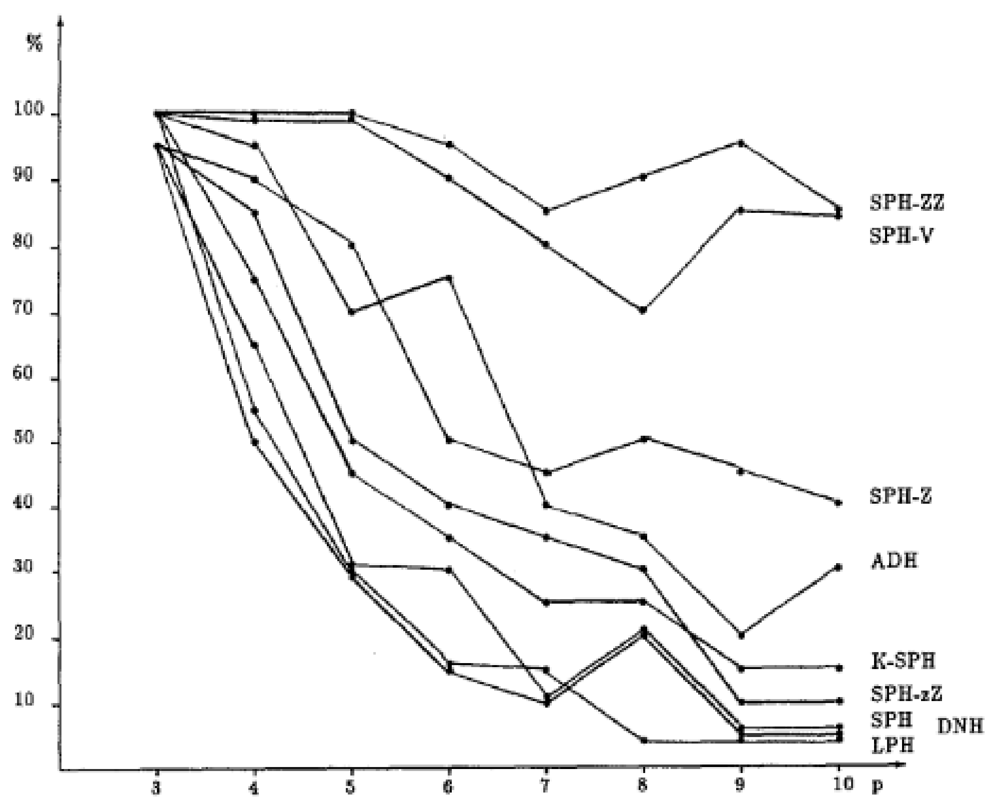


Fig. 6. Grid networks: best solution frequency.

Figure 13 Performance of path-distance heuristics, as found by Winter (1992). The iterative SPH approaches have the best solution frequency, followed by the ADH heuristic.

As a number of heuristics that can be used to solve the MSTG problem have been presented, a conclusion on which one to use for the future DNs in the Netherlands can be made. For grid graphs, the repetitive applications of the SPH have achieved the best solution frequency, followed by the ADH. Because the SPH-ZZ and SPH-V iterate over Steiner vertices, which is not needed in this case as Steiner vertices are placed at each corner point of the grid graph, the SPH-Z is chosen. The advantage of SPH-Z is that it overcomes the disadvantage of the SPH, namely that it is sensitive to the initial vertex. By iterating over all initial vertices, the shortest network can be used. However, it should be noted that this requires higher computational times. Because the heuristic is only applied once, the increased performance is valued more highly than the additional computational time.

3.5 Minimum Cost Flow algorithms for determining cable capacities

The objective of the Minimum Cost Flow (MCF) problem is to send flows from a set of source vertices to a set of sink vertices at the lowest possible cost. The MCF algorithms optimise which edges to use for the flow transportation and how much flow to transport through each edge, taking the underlying graph as well as the upper and lower capacity constraints of each edge into account. By setting the upper capacity constraint to infinity and the lower capacity constraint to zero, the algorithms can be used to allocate appropriate edge capacities according to the optimal flows of electricity. The algorithms can be used in many different applications, such as transportation problems and electricity flow problems, but it should be noted that they solve problems linearly. The benefit of the MCF algorithms is the fact that as long as opening or closing of disconnection points is considered, they will always satisfy KCL, in other words, the sum of incoming flows to a vertex will always equal the sum of outgoing flows. A constraint of the algorithms is the fact that they do not work during imbalances. The total supply of supply vertices in the graph must equal the total demand of demand vertices.

3.5.1 Max flow min cost algorithm

Max_flow_min_cost is a MCF function available in Networkx. The advantage of this function is the fact that it can be used for undirected networks, such as the one at hand. The disadvantage of this algorithm is that it only take one source vertex, *s*, and one sink vertex, *t.* As there are a large number of source and sink vertices needed in the design of distribution grid topologies, the *Max_flow_min_cost* algorithm can only be used if “Dummy sources” and “Dummy sinks” are implemented. Dummy sources and sinks are additional vertices added to the graph, connected to all the real sources and sinks respectively. The dummy vertices are given the demand attribute of all real terminals combined and edges connecting the dummy vertices to the real terminals are given capacities corresponding to their respective demands.

3.5.2 Network simplex method

Network simplex is a method based on the Simplex method, developed to solve linear problems in graphs (Cunningham, 1979). The working principle of the network simplex method is that it starts with an initial spanning tree. It then proceeds to the next one by adding a new edge that was initially not part of the spanning tree and thereafter deleting an edge part of the initial spanning tree

(Cunningham, 1979). This process is repeated until an optimal solution is found or it can be shown that no such solution exists. With this working principle, the network simplex method can be used to find an initial spanning tree in the graph based on a linear cost function. However, in this case MCF methods are to be used on an already defined tree network and only used for the optimum assignment problem.

A primal version of network simplex is available in Python library Networkx and can be used for edge capacity allocation. In practical terms, the method overcomes the limitation of Max Flow Min Cost, as it can take a set of sources and sinks as input. This is therefore the preferred solution for the proposed method. It should be noted the function can only take directed graphs as input. The graph will therefore first need to be transformed into a directed graph before network simplex can be used.

3.6 Cost improvement procedure

3.6.1 Rationale of cost improvement procedure

After applying the SPH-Z in order to find the MSTG and using the Network Simplex algorithm in order to define the required edge capacities, a feasible initial solution is found. However, the topology is optimised solely on length and on a linear cost function. The requirements set in the problem formulation were that the cost function should be a non-linear function, taking both lengths and capacities into account and these aspects have not yet been included in the method. Additionally, local reconfigurations can be used to further reduce the investment costs of the network. It should be noted that as the improvement procedure deals with optimisation of local configurations, the final solution is dependent on the initial network topology and the method does not necessarily lead to a global optimum. However, with the required capacities in the network depending on changes to the overall network layout, it is difficult to create a method that optimises both lengths and capacities of cables simultaneously.

The rationale of the chosen improvement procedure is the fact that when considering both cable lengths and capacities, it becomes expensive to use high capacity lines over long distances and the use of high capacity lines should therefore be minimised. By targeting local configurations of higher capacity lines, the procedure evaluates whether the use of the high capacity line can be shortened with the remaining terminals being connected using low capacity lines.

3.6.2 Working principle of cost improvement procedure

Three possible changes to the configuration are considered, as presented in Figure 14.When reconfigurations are made, the network becomes more of an “electricity highway” where the largest bulk of the electricity is transmitted. Connectedness is ensured with terminals being connected using lower capacity lines. In order to calculate the costs of the reconfigurations, the direction of the flow must be known. This can be done by finding the initial capacities flowing through each path as well as the net production of the corner terminal.

The goal is to find a configuration that, taking the non-linear relationship between length and capacities into account, gives the lowest total investment costs. In Figure 14, the original configuration as well as the three possible reconfigurations are presented. For all configurations, lengths are denoted by *l* and capacities are denoted by *q*. The diagrams are made for electricity flowing in the right direction, from Terminal 1 to Terminal 3. If the electricity is flowing in the opposite direction, the capacities change accordingly.

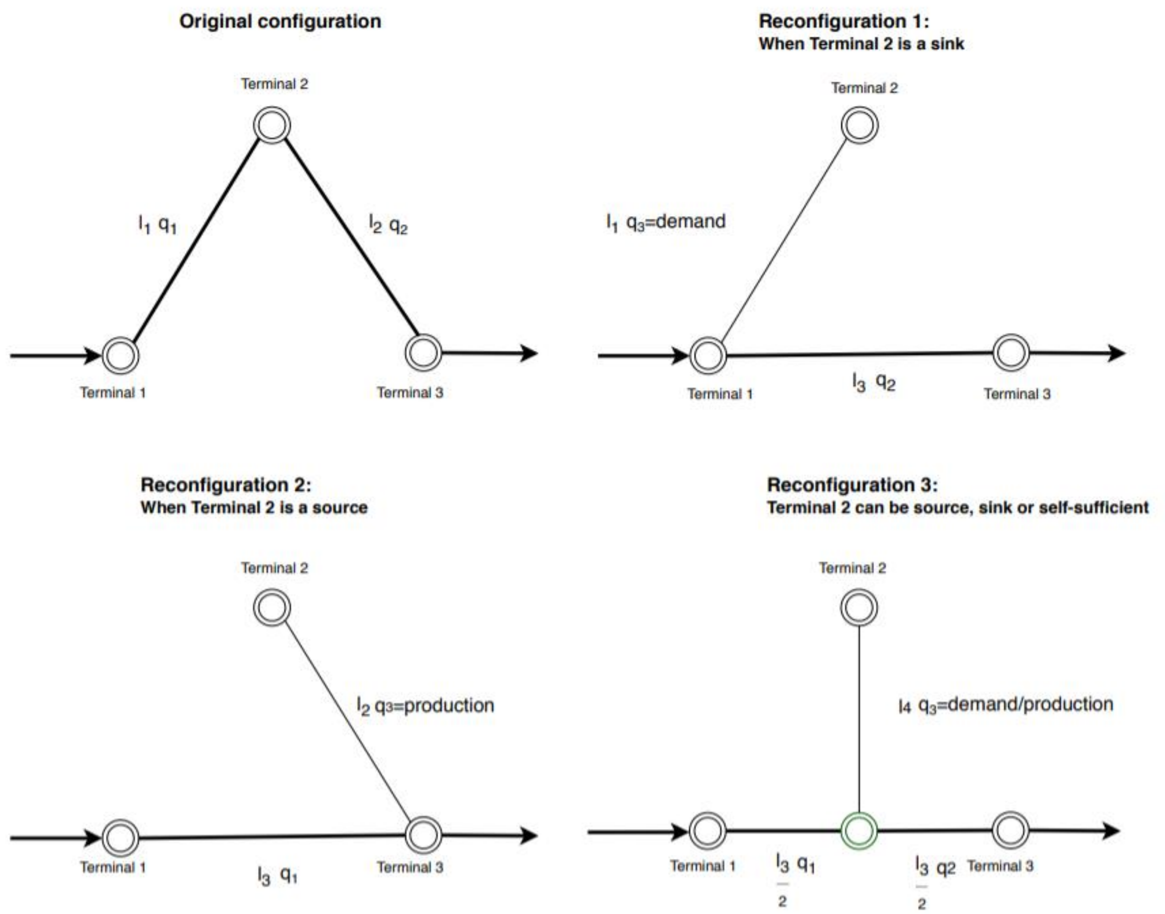


Figure 14 The three possible reconfigurations in the cost improvement procedure. The use of the different configurations depends on whether the corner terminal is a source or a sink and which direction the electricity is going in.

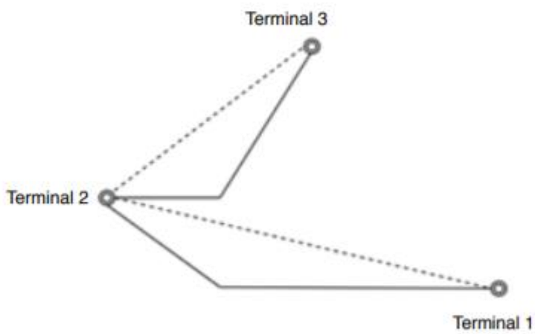
Configuration 1 is the original configuration consisting of Terminals 1, 2 and 3. The electricity is transmitted through the angle, visiting all three terminals. Initially, the capacity is denoted as q_1. After passing through Terminal 2, which is either a sink or a source, the capacity changes to q_2. The investment costs for this angle may be reduced by reconfiguring the angle into Reconfiguration 2. Instead of transmitting all the electricity through all terminals, the bulk of the electricity is passed directly from Terminal 1 to Terminal 3. In order to ensure connectedness, Terminal 2 is connected via Terminal 1 and the only capacity required is the demand of Terminal 2. This reconfiguration is suitable when Terminal 2 is a sink, as it prevents the electricity representing the demand of Terminal 2 from flowing through the path from Terminal 1 to Terminal 3. Reconfiguration 3 has the same working principle as Reconfiguration 2, but instead of connecting Terminal 2 to Terminal 1, it is connected to Terminal 3. This configuration is suitable when Terminal 2 is a source, as the electricity representing the production of Terminal 2 does not have to pass through the cable from Terminal 1 to Terminal 3.

Finally, Reconfiguration 3 is presented. Similarly to the other reconfigurations, the bulk of the electricity is transmitted directly through the new cable from Terminal 1 to Terminal 3. Instead of connecting Terminal 2 to one of the other terminals, it is connected to a Steiner vertex in the middle of the new cable, called a splitting point. This reconfiguration is suitable when Terminal 2 is both a source or a sink, depending on the relevant lengths and capacities of the angle. Although the splitting point could theoretically be placed on any Steiner vertex on the path between Terminal 1 and Terminal 3, it is assumed to be placed at the mid-point on the cable. This simplification is made in order for the improvement procedure to only test three reconfigurations per angle instead of for example 10 or 15.

In the search for improved local configurations, configurations of small angles are targeted first as, using this improvement procedure, the smallest angles have the highest potential for savings. This is because the new cable in the reconfigurations (Terminal 1 to Terminal 3) is likely to achieve larger reductions in the length of the high-capacity part of the network for smaller angles as the initial configuration created a long, high-capacity route. For large angles, the new cable makes less of an impact on the length that the high capacity flows have to be transmitted because the configuration is already close to a straight network and the new cable (Terminal 1 to Terminal 3) makes less of an impact. The Law of Cosines, as presented in Equation 3.2, is used in order to calculate the angle of each terminal with a degree of two.

$$A = \arccos\left(\frac{b^2 + c^2 - a^2}{2bc}\right) \qquad 3.2$$

Where *A* is the unknown angle created by the edges corresponding to lengths *b* and *c* (Figure 15). *a* is the length of the edge opposite to A. It should be noted that when calculating the angles, the paths between the terminals are assumed to be straight. In reality, due to a grid graph being used and due to spatial constraints being taken into account, the paths may have a more jagged shape. To the left in Figure 15, the actual paths of an angle are drawn using solid lines whereas the assumed paths are drawn using dotted lines.



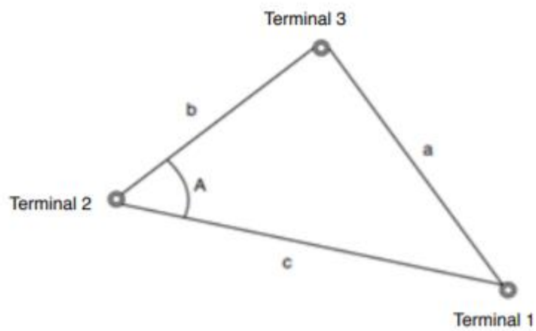


Figure 15 To the left: angle assumption. To the right: assignment of sides for law of cosines

After calculating the angles for all terminals with a degree of two, the vertex with the smallest angle is chosen. If savings are found, the angle is reconfigured with respect to the cheapest found reconfiguration for this exact case. Once an angle has been visited, it is added to a taboo list in order to prevent the improvement procedure from revisiting the angle. It should be noted that the angles need to be recalculated for each iteration due to possible local reconfigurations in the network. The overview of the steps required in the improvement procedure is presented in Figure 16.

In order to simplify the process slightly, certain conditions are applied before finding the lowest-cost configurations out of the four configurations possible. The cost of Reconfiguration 1 is only calculated and compared to the initial configuration when Terminal 2 is a Sink. Similarly, Reconfiguration 2 is only considered when Terminal 2 is a source. These simplifications are made because, taking the direction of flows into account, they are very unlikely to be the lowest-cost reconfiguration under these conditions. Additionally, if the terminal demand is found to be zero, only Reconfiguration 3 is compared to the original configuration. This is because for a demand of zero, the low-capacity connector connecting Terminal 2 will always have a capacity of zero. In other words, it is non-existing. The program can therefore check whether it is cheaper to connect Terminal 1 to Terminal 2 directly, but is not required to check all three reconfigurations as they will all have the same investment cost.

Finally, a flow diagram of the improvement procedure process is presented. It should be noted that, due to the fact that reconfigurations are only kept when savings are found, the final solution will never be more expensive than the initial solution.

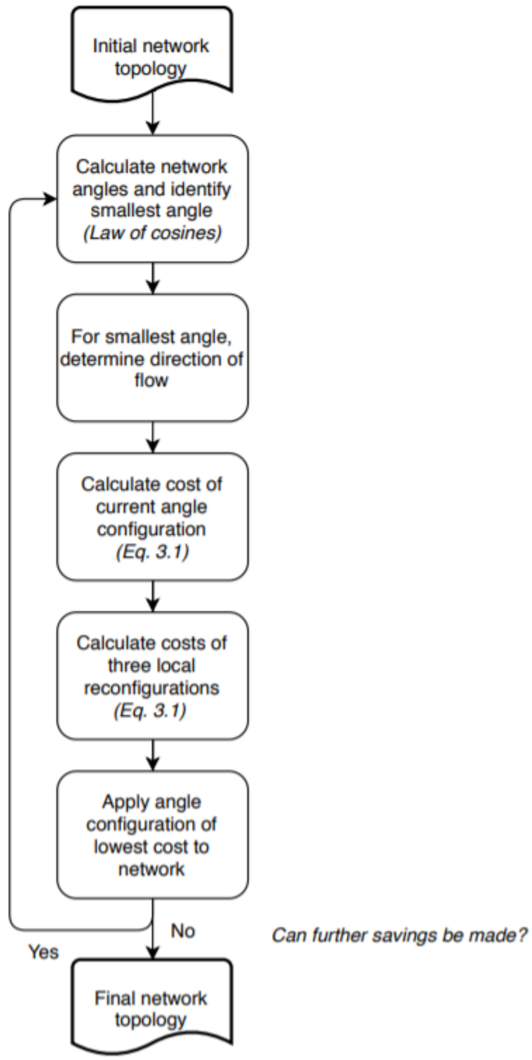


Figure 16 Steps included in cost improvement procedure in order to find the final network topology.

3.7 Determining the final network based on numerous time steps

In order to create a fixed network that can be used under changing operating conditions, choices need to be made on how to take time into account. The requirements of the final network are firstly that all terminals should be connected into one network. Although the graph may be disconnected for some time steps, the implemented final design should be a connected network in order to ensure flexibility under differing operating conditions by allowing electricity from all terminals to reach each other. As radial networks have shown to be the most appropriate topology for the future DNs in the Netherlands, it should also be ensured that the final network still meets the radiality constraint.

Because the initial network only depends on length, the initial network does not change with respect to time. The SPH-heuristic therefore only has to be run once. The improvement procedure should thereafter be run for a large number of time steps, either all time steps or a representative selection, in order to analyse how often each angle is reconfigured and which reconfiguration type (1, 2 or 3) is chosen the most often. Because the improvement procedure has a strong dependence on the initial network, the final network topology is based on the initial topology, reconfigured using often-occurring local reconfigurations from the improvement procedure.

3.7.1 Determining final edge capacities

When the final topology has been found, the required edge capacities are to be determined. As the network should not experience blackouts or faults during normal operating conditions, the cable capacities should be set sufficiently high to transmit electricity during every hour of the year.

For each hour of the year, the terminals should be given their appropriate production and demand value. By running the Network Simplex algorithm on the final network topology for each hour of the year, the flows through the network at each time step are found. Finally, the maximum flows through each edge experienced during the year are set as the fixed edge capacities for the final solution.

3.8 Graph reduction approaches

Previously in this chapter, the choice of discretising the regional maps as grid graphs has been presented. The grid graphs include horizontal, vertical and diagonal edges with Steiner vertices at each corner point in order to improve smoothness of paths and to prevent horizontal and vertical connections to be favoured over diagonally located connections. These choices lead to a large number of Steiner vertices and edges. As the chosen MSTG heuristic and the Network Simplex algorithm depends on the number of terminals, edges and Steiner vertices, the problem can reach very high computation times. The computation times can be reduced by applying appropriate reduction approaches for this case in order to simplify the graph.

3.8.1 Combining terminals in spatial proximity

As the computational complexity of the chosen MSTG heuristic, SPH-Z, depends on the number of terminals, it can be beneficial to reduce the number of terminals to be connected. As the location of terminals makes a big impact on the final network topology, this is an appropriate reduction only when two terminals are very close to each other as two very close terminals should always be connected by an edge. In the proposed method, this reduction approach is incorporated at the beginning of the approach, before the SPH-Z heuristic is run. The minimum distance that two terminals can have is set as an input parameter and can therefore be changed between iterations. Possible values could be 1500m or 2000m, but this of course depends on the network specific network. After targeting a pair of terminals in close spatial proximity, a new terminal is created in between the initial terminals. The net production of the new terminal is the two initial terminals' net productions combined.

3.8.2 Reduction of graph resolution

Another option for vertex reduction is to make the graph coarser. Instead of for example considering land data at 100m intervals, intervals of 200m can be considered. This significantly reduces the computational time. By halving the number of coordinates in x and y direction, the remaining number of vertices is a fourth of the initial number of vertices. It should be noted that the disadvantage of using this reduction approach is the fact that some of the land details may be lost (Figure 17).

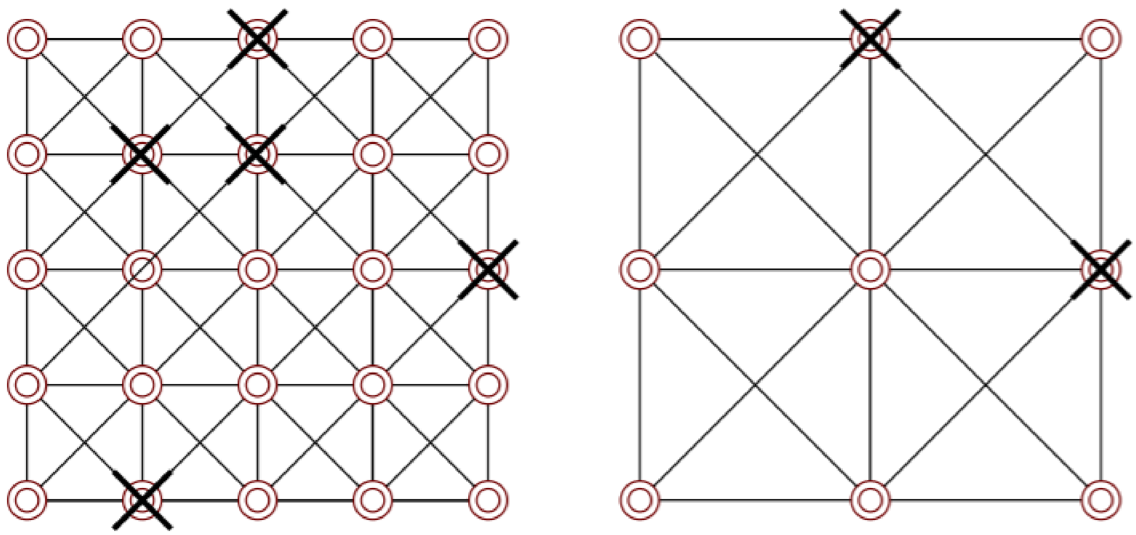


Figure 17 To the left: graph with high resolution. All vertices marked as unavailable are considered. To the right: graph with reduced resolution, leading to some of the data on unavailable vertices being lost.

The applicability of this approach is therefore more in line with regions that are characterised by a high ratio of available land compared to unavailable land. If applied in a densely built energy region such as Noord-Holland Zuid, which contains the municipality of Amsterdam, crucial land data could be lost. In the design of networks for the less densely built energy regions, making the grid coarser can be a very useful, while still appropriate technique. One way of overcoming this limitation is by first optimising the topology using the coarse graph and thereafter comparing the topology to the more detailed map in order to ensure that the lines are not built over unavailable plots of land. If the topology violates land that should be defined as unavailable, the vertices surrounding the unconsidered, unavailable land could be removed manually before re-applying the heuristic in order to ensure that the final network does not overlap with areas that have been defined as unavailable.

3.8.3 Steiner vertex reduction using a convex hull approach

Another way of reducing the number of vertices in a graph is by removing the Steiner vertices outside a certain area where they are very unlikely to be part of the final network. As previously pointed out, one of the characteristics of the defined grid graphs is the fact that all horizontal and vertical edges have the same length and that all diagonal edges have the same length, related to the horizontal and vertical through Pythagoras' Theorem. As the edge weights are defined by their lengths, all horizontal and vertical edges in the graph have the same weight. Similarly, all diagonal edges have the same weight. The total network cost therefore depends on the overall topology and whether horizontal, vertical or diagonal edges are used, but does not vary with respect to which edges are used.

This characteristic can be used to reduce the graph with the rationale being that paths do not need to cross the coordinates of the outermost terminals. A convex hull can be created between these outermost vertices in the graph and all vertices on the outside of the defined perimeter can be excluded as possible Steiner vertices. The working principle of the convex hull approach is presented in Figure 18.

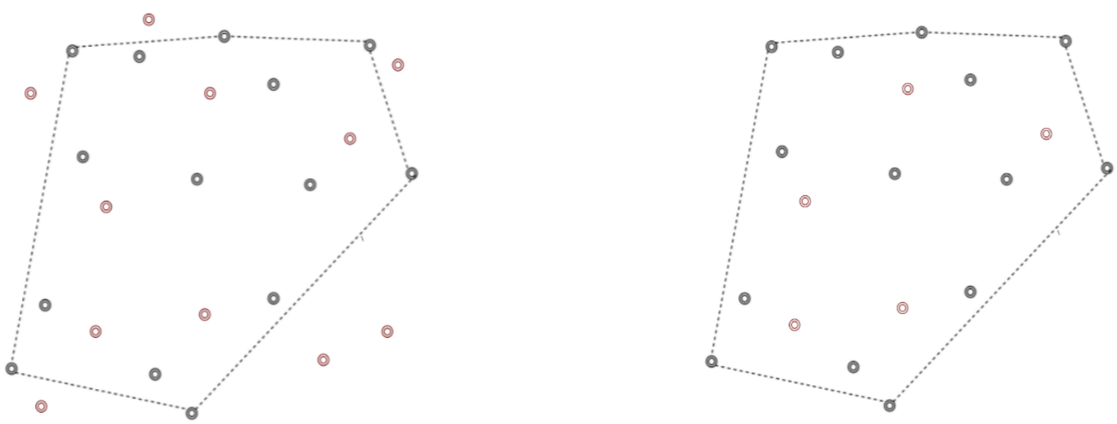


Figure 18 The working principle of convex hull reduction. The trace around the outermost vertices from a set of terminals are shown in black. If a Steiner vertex (red) is located outside the defined area, it will be removed from the graph.

If all the Steiner vertices were kept available, a zig-zag path crossing the perimeter could possibly be chosen by the heuristic as the shortest path. However, unless a large piece of land is made unavailable on the inside of the perimeter, a path with the same cost could be found within the polygon. This reduction approach is therefore both effective and valid in most instances. In the case that the reduction method would disconnect an energy region, the convex hull reduction method should be replaced simply by masking and removing coordinates outside the wanted region or increasing the area of the convex hull in order to ensure graph connectedness.

3.9 Model verification

As the steps included in the method have been finalised, evaluations should be made on whether the proposed method meets the specifications set in the problem formulation.

3.9.1 Avoidance of unavailable areas

Firstly, a constraint has been set in the problem formulation that land considered as unavailable should be avoided by the network. This constraint has been verified using a test network of 121 vertices in total, of which nine are terminals and the rest are characterised as Steiner vertices, as presented to the let in Figure 19. The terminals are displayed in red whereas the Steiner vertices are displayed in green. Horizontal, vertical and diagonal edges are created for vertices of a defined distance, as defined in the problem formulation. In this case, the distance is set as 200 meters. The initial test network is created for a grid graph where all Steiner vertices are defined as available. The shortest network as based on the SPH-Z heuristic is thereafter found, representing a local optimum in terms of length minimisation of the graph.

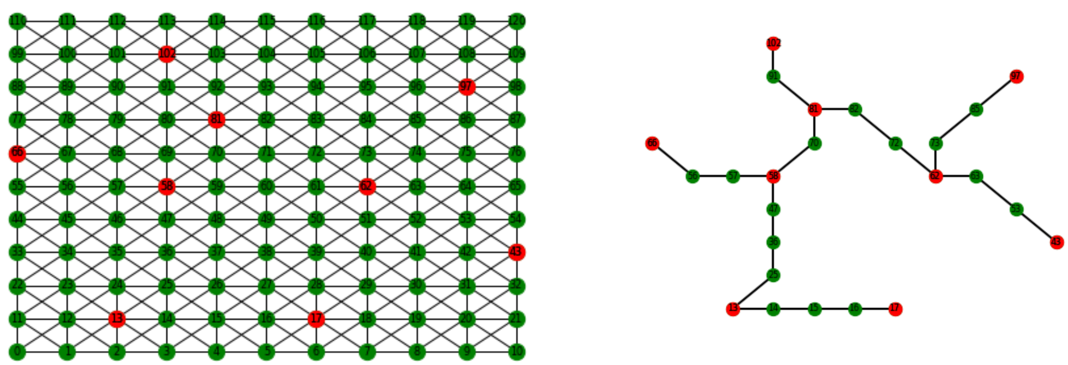


Figure 19 Minimum Steiner Tree in Graph network based on the SPH-Z heuristic. All land is assumed to be available.

After finding the MSTG for a graph where all Steiner vertices are characterised as available, vertices are removed in order to verify that the updated MSTG does not avoid these areas. Four patches of land that obstruct with the initial MSTG are removed. The results of the updated MSTG, taking spatial constraints into account, is presented in Figure 20. The results show that because the shortest path only uses available Steiner vertices to connect the set of terminals and no new edges are created over the unavailable areas, the spatial constraints are met.

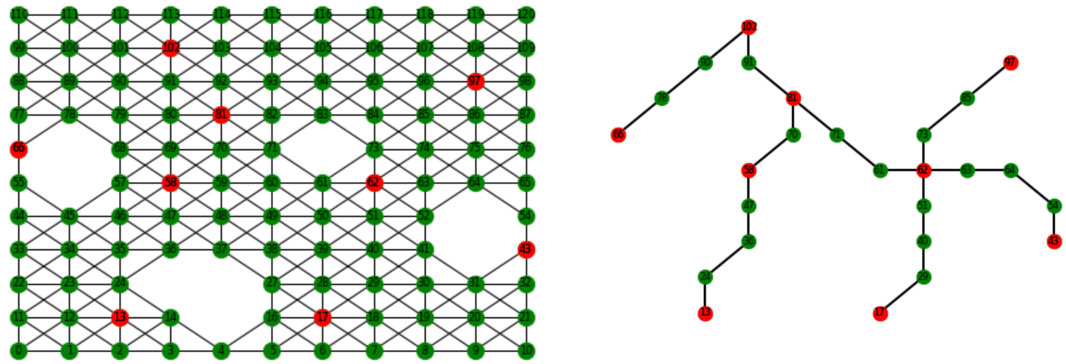


Figure 20 Updated Minimum Steiner Tree in Graph network after unavailable plots of land have been removed. The final network does not overlap with any unavailable areas.

3.9.2 Compliance with radiality constraint

In the problem formulation, it was also set that the electricity networks should have radial topologies. In order to comply with this, a taboo list with the visited terminals is used in the code of the SPH-Z heuristic in order to ensure that each terminal is only visited once. The arbitrarily chosen initial vertex is automatically added to the list. Thereafter, every time a shortest path is added to the graph, the connected terminal is added to the list. This process is iterated until the taboo list includes all the terminals.

This process ensures that each terminal will only be visited once, preventing cycles between terminals. Seldomly, cycles can occur due to two or more shortest paths using the same Steiner vertices. It is therefore not impossible for the SPH-Z heuristic to lead to cycles. However, with the use of the Network Simplex algorithm, the flows will be sent through the network in the cheapest possible way. As long as all edge costs are set as positive and there are no maximum edge capacity constraints, the flows being sent through the network will have a radial topology. As the unused edges are removed after the Network Simplex algorithm has been run, the final costs, including both length and capacities, will be based solely on a radial topology. The radiality constraint is therefore met.

3.9.3 Consideration of net production and demand of terminals

Finally, it has been decided that the networks should be designed with respect to the net production and demand of its terminals. In order to verify that the method actually does take production and demand into account, an extreme case is tested where all terminals are considered as electricity self-sufficient. To the left in Figure 21, the initial solution is found when all terminals are either sources or sinks. To the right, all terminals have a net production of zero and no connections are made between the terminals as in this case, a network is not needed. The requirement that the model is to take net production of terminals into account is therefore verified.

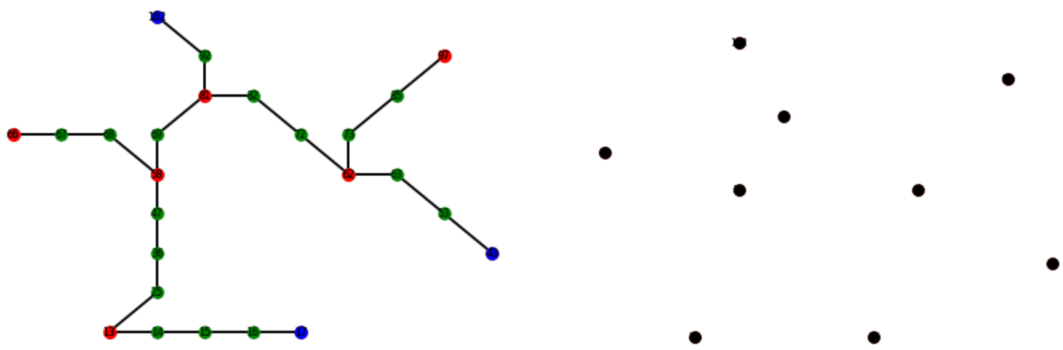


Figure 21 Demonstration of no network being created when all terminal locations are self-sufficient.

3.10 Overview of the proposed method

With the use of the literature review in Chapter 2, choices have been made so that the problem at hand could be formulated and appropriate methods have been chosen. An overview of the resulting steps in the method are presented in Figure 22.

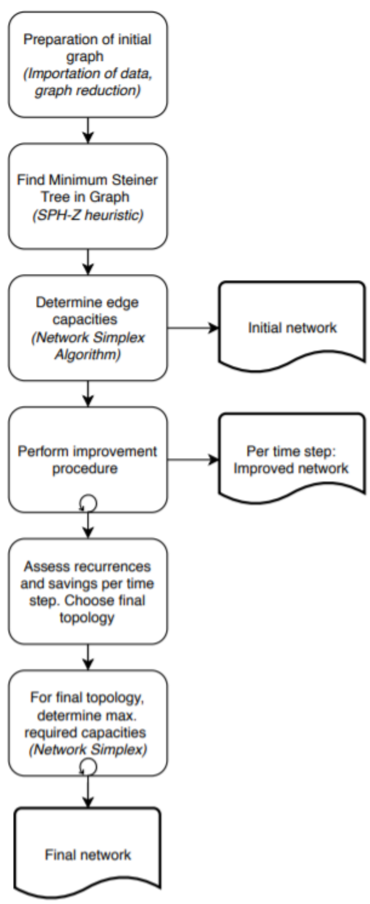


Figure 22 Process flow diagram of proposed method

Chapter 4: Input data

4.1 Land use data

In order to define available and unavailable vertices for energy regions in the Netherlands, data from CORINE Land Cover (CLC) database is used. CLC database is an inventory of free, open-access data on land use in Europe. The programme was initiated in 1985 by Copernicus Land Monitoring Service, an initiative partly by the European Union, in order to facilitate environmental decision-making (Copernicus Land Monitoring Service, 2019). The most recent data, CLC 2018, is from the time period 2017-2018 and includes data from 39 countries with land divided into 44 categories (Copernicus Land Monitoring Service, 2019). The land data is given in a resolution of 100 meters, so each square of 100x100 meters is given a land type label and all other details within the square are omitted. Points are set in the middle of each square, giving the land use coordinates as well as the land use type. The data is given in two dimensions, x and y, the spatial coordinate system, EPSG3035. The data files from CLC are very large and need to be processed before importation in Python. In this paper, already processed data from CLC 2012 is used. Although it is not the most recent datafile, the land use has not changed significantly. After implementation, the dataset may require further reductions in order to "zoom in" on the wanted energy region.

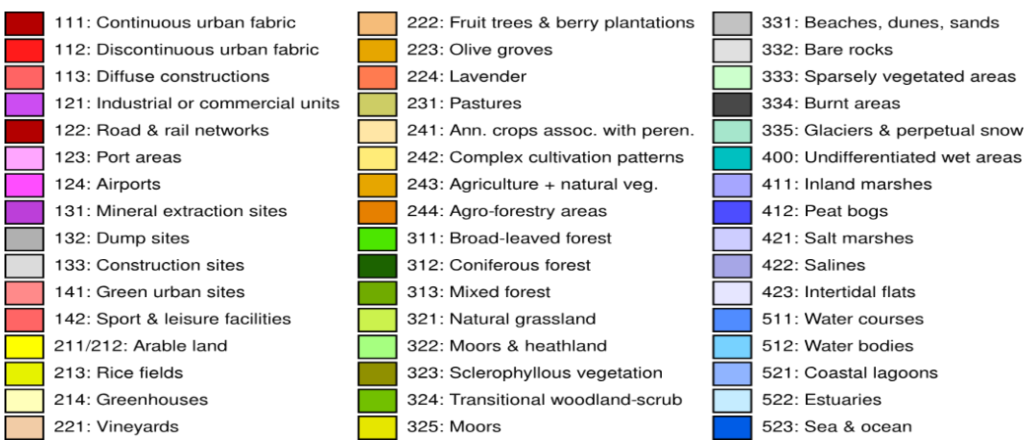


Figure 23 CORINE Land Class Categories. Reprinted from (Copernicus Land Monitoring Service, 2019)

The 44 included land categories are presented in Figure 23. The chosen excluded land types are airports, all categories of water bodies and protected areas such as sand dunes and national parks (Explain why). Airports and water bodies can directly be addressed using CLC database as these are explicitly stated in the land use types. The database does not include data on national parks or protected areas. Sand dunes are addressed in the category "beaches, dunes and sands" and land data in this category will therefore be removed. It should be noted that sand bodies that would otherwise be marked available will be removed in the process. In order to address protected areas or national parks as no-go zones, this will have to be done manually. If an output network overlaps with a national park or protected area, the specific range of vertices needs to be identified and removed manually before re-applying the method. The implementation of the manual removal be achieved by finding the coordinates of the no-go areas and converting them to EPSG3035 before removing the corresponding vertex ranges.

4.2 Annual production data and terminal coordinates

Supply and demand data as well as corresponding coordinates are needed in order to define the positions and net demands of each terminal. Although the production data is not considered in the process of finding a MSTG, it is considered both in the capacity allocation using the Network Simplex algorithm as well as in the improvement procedure.

The data is provided by PhD student at Delft University of Technology, Ni Wang. The production data is made on an hourly basis over a year, with electricity generated by PV modules, wind turbines and biomass. Estimations are based on historical wind and solar irradiation data. In other words, the regional production data consists of only renewable energy sources. An assumption is made that there is no storage options except for the storage capabilities of biomass. Another assumption is the fact that the sum of production and demand will always equal zero at each time step. Although this electricity balance may not always hold in real life, this assumption is needed for the Network Simplex algorithm to run.

The coordinates of each terminal are also needed in order to create the electricity distribution topology. As previously pointed out, terminals represent the vertices that contain generation or consumption data. Coordinates are assumed as the middle point of each town or city. In reality, electricity will be produced an consumed at several different locations and not necessarily at the middle point of a village. For simplicity, for each village or city, only one vertex is created. From the terminal coordinate data, the coordinates of the closest Steiner vertex is found and chosen as the location of the terminal (Figure 24). This simplification is performed so that all terminals will be part of the grid graph. An alternative approach would be to keep the original terminal coordinates for the vertex positions and thereafter connecting the terminals to the closest Steiner vertices. As the terminal coordinates are already approximated, placing the terminals in the graph corners is not going to make a big impact on the final solution.

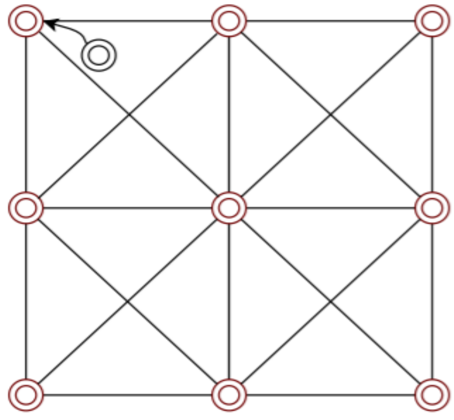


Figure 24 After importation of terminal coordinates, terminals are positioned at the closest Steiner vertex

It should be noted that as the terminal coordinates and their respective net demands are defined as inputs to the method, this data can be changed and the method will still work. The allocation of electricity generators per village is based on cost-efficiency, taking both resource availability, demand and the overall network topology into account. When time averaged, the terminals may therefore be more prone to being sources or more prone to sinks, with certain terminals having high magnitudes of net production or demand whereas others having low magnitudes of net production or demand. These differences will not affect the SPH-Z, but will have an effect on the capacity allocation from the Network Simplex algorithm in addition to having an impact on the cheapest configurations in the improvement procedure. It should also be noted that the data points for the terminal coordinates are given in two dimensions, latitude and longitude, in the spatial coordinate system EPSG4326. In order to link the terminal coordinates to the land type coordinates, the spatial coordinate system of the terminal coordinates needs to be converted to the EPSG3035 spatial coordinate system.

4.3 Value of β

As previously explained, the value of β represents the impact of the cable capacity with respect to the length in the total cost of purchasing an electricity cable. This value cannot be chosen, but is fixed. In the paper by (Heijnen, Stikkelman, Ligtvoet, & Herder, 2011), the value has been approximated to have a value of 0.6. This is therefore the approximation used in the design of the future DNs in the Netherlands.

Chapter 5: Experimental results

In order to assess the effectiveness of the proposed improvement procedure with respect to the initial network and the impact of input data on the final results, the proposed method is applied to 50 randomly generated networks. The test networks of varying input conditions are thereafter used to determine under which conditions the improvement procedure is most effective and under which conditions the improvement procedure does not make any local reconfigurations.

5.1 Experimental setup

In assessing the impact and sensitivity of input values, six different input variables are considered; the β exponent, the number and location of the terminals, net production and demand data, overall share of unavailable land and the location of the unavailable land. The ranges for which the random variables are created are presented in Table 2.

Table 2 Input variables are created randomly based on defined ranges.

Randomised input variable	**Range of input values**
β exponent	[0.0-1.0]
Number of terminals	[5-12]
Location of terminals	Position of any Steiner vertex in the graph
Production and demand data	[-100,100]
Share of unavailable land	[0-25]%
Location of unavailable land	Position of any Steiner vertex in the graph, if the Steiner vertex is not already set to be a terminal

One of the assumptions made in the proposed method is the fact that total network supply must meet total network demand. This is needed for the Network Simplex algorithm to run. In order to satisfy this condition, the sum of the network production and consumption data is set as the production or demand data of the final terminal in the list of terminals. It should be noted that due to this assumption, although production and demand data is taken from the range -100 to 100, the value for the final terminal may exceed the values in the input range. Additionally, it should be noted that for all test networks, the spatial resolution is set to 200 by 200 meters, with a minimum distance between vertices set at 300 meters. This implies that if two terminal vertices are immediate neighbours, they will be combined to one terminal in order to reduce the graph.

5.2 Effectiveness of improvement procedure

From the 50 random networks created, the improvement procedure makes reconfigurations in 40 cases with the maximum savings reaching 21.3%. The full overview of the experimental results are presented in Appendix C: Experimental results for improvement procedure.

5.3 Effect of β exponent

In the analysis of the effect of the β exponent, it should be noted that the value of the β exponent cannot be chosen in practice, but is a measure of the relation between length and capacity in the total cost of an electricity cable. However, it is still of interest to assess the sensitivity of the final solution to the variable, as the β exponent used in practice is approximated.

The experimental results have shown that the optimal local configurations and the possibility for savings depend quite strongly on the value of the β exponent. When the value of the β exponent is high, the improvement procedure is more likely to make local configurations and the savings in percent are also higher. This is due to the fact that the initial solution is based solely on length, with the value of the β exponent being equivalent to zero. With a higher deviation of β from zero, the capacity is given higher significance in the investment cost function and the resulting network is more likely to deviate from the initial solution.

In addition to randomly generated networks showing that a higher β value is more likely to lead to savings in networks, the effect of β can be further demonstrated by analysing a network that initially does not lead to savings. By increasing the value of β, the impact on the final results can be assessed. In Figure 25, a network that does not experience any reconfigurations is presented. In the upper, leftmost network, the β value is 0.1 and no local reconfigurations are made. The savings caused by the improvement are therefore 0%. By increasing the β exponent to 0.3, capacity is given higher importance in the calculation of total costs and local reconfigurations of two different angles occur. The savings due to the reconfigurations lead to total network savings of 1.22%. The value of β is further increased to 0.5 and 0.7. Although the increase does not lead to further reconfigurations in this case, the impacts of the improvement procedure are increased to 5.9% and 9.85% respectively. This demonstrates the high sensitivity of the final solution to changes in β, which is in line with the cost function as defined in Equation 3.1.

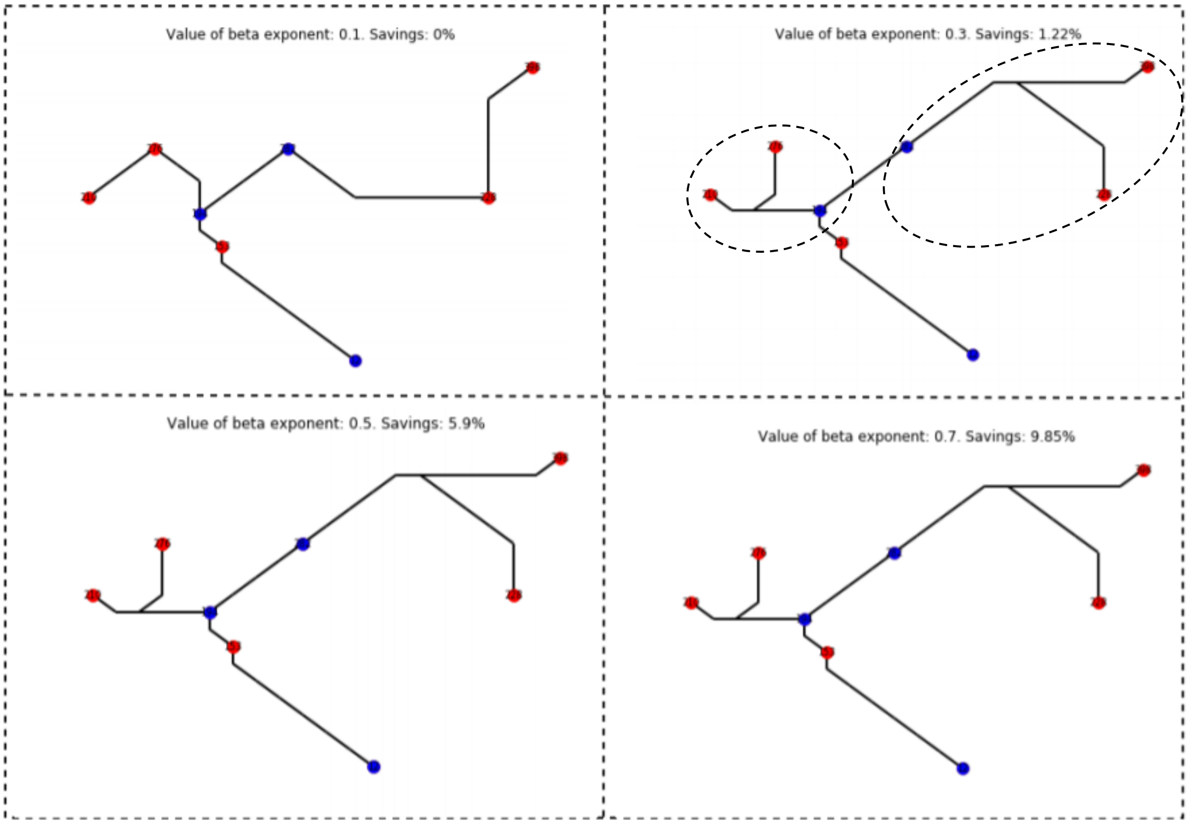


Figure 25 Final network results based on four different values of β.

5.4 Number of terminals

Because the improvement procedure targets terminal vertices with a degree of two, a network with a larger number of terminals is more likely to have terminals fulfilling this condition. A network with a larger number of terminals is therefore more likely to experience local reconfigurations. Although reconfigurations are more likely, the overall network savings in percent may be limited due to the fact that a higher number of terminals could indicate that the overall network is larger.

It should be noted that with the number of terminals ranging from five to twelve, large savings (in this case defined as savings exceeding 8%) are not limited to networks with a large number of terminals. Large savings can be found in the whole range of number of terminals, including networks of five and twelve terminals. The number of terminals therefore may have a certain effect on the expected network, but the final networks do not show to be highly sensitive to the number of terminals. The possibility of savings depends rather on how these terminals are connected in the initial network.

5.5 Terminal locations and initial network topology

Terminal locations have shown to have a big impact on the possibility for savings from the improvement procedure, both in terms of the general network topology and the specific angles created between a set of three terminals. The savings in percent due to the improvement procedure are high when the reconfigured angle is a large share of the total network length. This happens when there is a large distance between the terminals in an angle and the network is relatively small, such as in Figure 26. In large networks, network reconfigurations make less of an impact in percent.

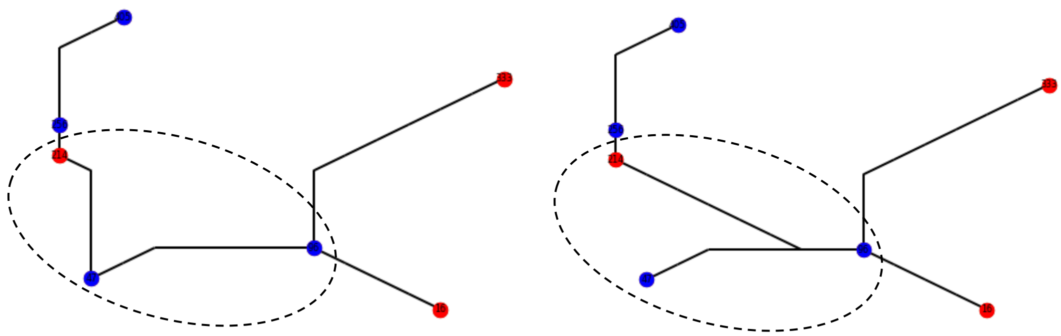


Figure 26 Large reconfigured angle compared to overall network size. The reconfiguration leads to an overall cost improvement of 8.68 %.

Additionally, there is a higher chance of savings where the initial network has a large number of vertices with a degree of two and when the relevant terminals are part of an angle which is relatively small. In addition to the smaller angles being reconfigured more often in the experimental results, it can also be seen that the reconfigurations most often occur during the first few iterations, as the improvement procedure starts by targeting the smallest angles.

Figure 27 gives an example of a reconfiguration of a small angle. In this case, only the first iteration of the improvement procedure is shown in order to highlight the relevant angle. By reconfiguring the angle, the total network costs are reduced by 18.5%. After running the improvement procedure until no more savings can be made, reconfigurations leading to savings of 21.3% are made, which is the highest savings found in the experimental results. It should be noted that the very high savings in this case both depend on the reduction in transmission distance for the bulk load in addition to depending on the production and demand data. Production and demand data as a variable will be further discussed in Chapter 5.7.

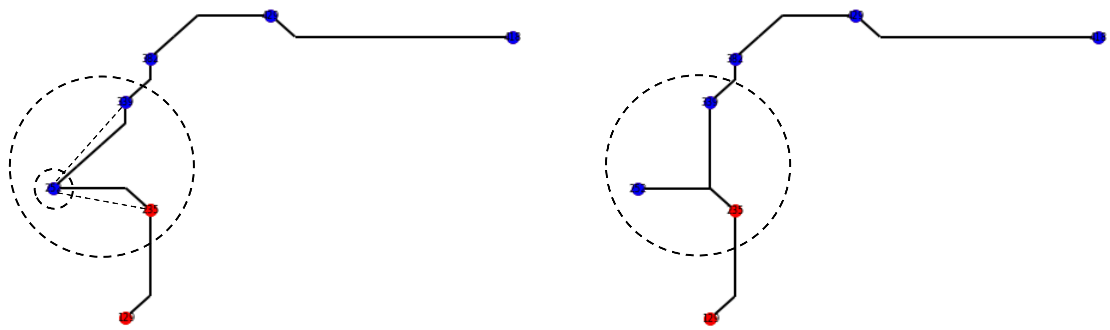


Figure 27 Demonstration of reconfiguration of small angle in the initial network. The reconfiguration leads to total network savings of 18.5%

For large angles, defined as angles closer to 180 degrees, the improvement procedure is not able to make improvements. This can be seen in Figure 28, where the angles of the three relevant terminals are shown as dotted lines.

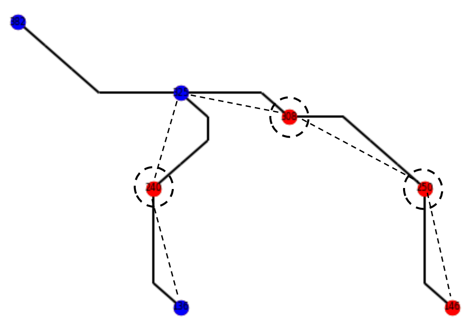


Figure 28 Demonstration of network with large angles. In this case, although β has a value of 0.7, no reconfigurations lead to savings.

5.6 Share and locations of unavailable land

The experimental results have shown that higher shares of unavailable land do not make it more or less likely for savings to occur. However, higher shares of unavailable land lead to more volatile results, depending on the location of the unavailable land. If the initial configuration consists of long paths in order to avoid unavailable land, in some cases higher savings can be achieved with the use of the improvement procedure, if the local reconfigurations are less constricted by unavailable land. Equally, if the initial configuration is unaffected by unavailable land but the local reconfiguration is affected by unavailable land, the savings of local reconfigurations may decrease or savings due to local reconfigurations may not even be possible.

A demonstration of the usefulness of the improvement procedure in cases of high shares of unavailable land can be seen in Figure 29. To the left, it can be seen that the initial network based on shortest paths is constricted by large patches of unavailable land. By performing the improvement procedure, the total network costs can be reduced by 8.34%.

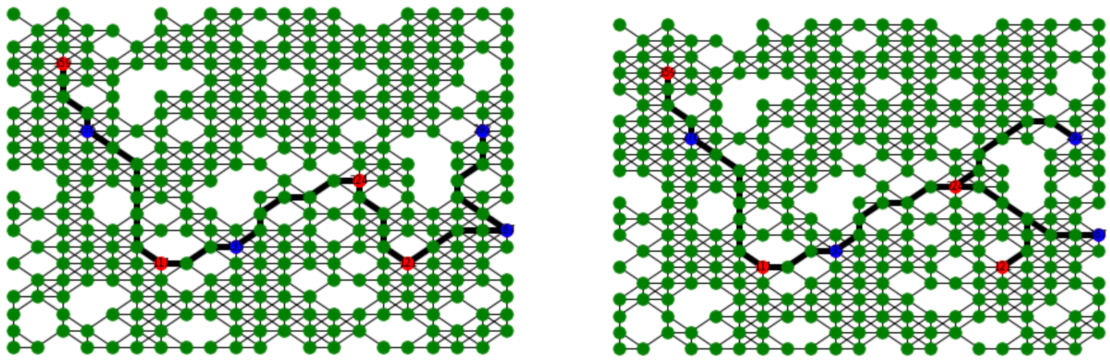


Figure 29 To the left: initial network with relatively long paths due to avoidance of unavailable land. To the right: local figurations lead to savings. (8.34%)

For the same input data, when all land is characterized as available, the initial solution is not constricted by unavailable plots of land (Figure 30). In this case, the improvement procedure does not lead to savings.

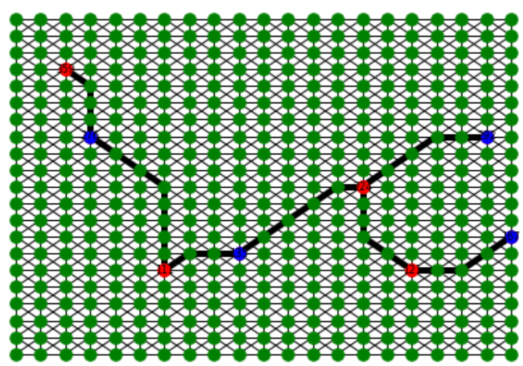


Figure 30 Network when all land is considered available. The improvement procedure does not lead to savings.

5.7 Net production and demand of terminals

The improvement procedure makes the biggest savings when the edge capacities are high. This happens when the production and consumption values have large deviations from zero, in other words when the terminals have a small degree of self-sufficiency and are either great net electricity consumers or exporters. Additionally, the edge capacities required increase when there are several sources or several sinks close to each other. This means that large electricity flows are transmitted further in the network. Due to the network requiring increased edge capacities, the improvement procedure makes bigger savings to the initial network.

5.7.1 Areas with large concentrations of sources or sinks

A demonstration of the effect of placement of sources and sinks is shown in Figure 31. To the left, half of the network consists of sinks and the other half consists of sources. High capacity edges are therefore required to transmit electricity between the two areas. The improvement procedure makes a local reconfiguration which leads to a 3.5% decrease in investment costs (with a β value of 0.3). To the right, the net production and demand values of two terminals are exchanged while all other variables remain the same. Supply and demand can in this case be supplied at shorter distances and less electricity has to be transmitted across the whole network. In this case, no local reconfigurations from the improvement procedure lead to savings. It should be noted that the jagged paths in both networks depend on the underlying distribution of unavailable land.

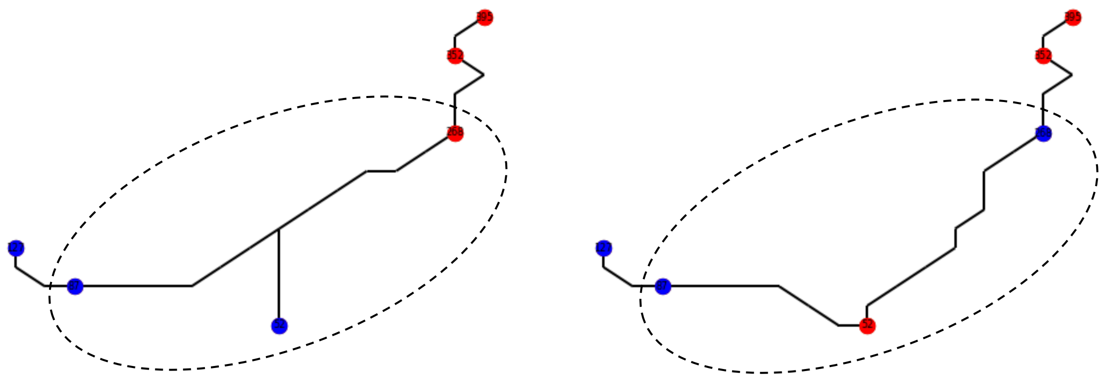


Figure 31 Demonstration of the effect of having several sinks in one part of the network and several sources in another part. To the left: three sinks to the left (blue) and three sources to the right (red) leading to high capacity edges and local reconfiguration. By changing the net production of a source and sink, the edge capacities are lowered and no reconfigurations are made.

5.7.2 No electricity flowing through corner terminal of angle

In some cases, there is no electricity flow being transmitted across the corner points of angles. In other words, the production or demand of what has previously been defined as Terminal 2 is supplied by its neighbouring terminals. In such cases, the experimental results show that there is a smaller possibility for savings using local reconfigurations. In Figure 32, an example is given for such a network. Although there are relatively small angles in the network where reconfigurations could lead to savings, all relevant terminals (highlighted using dotted lines) are supplied by their immediate neighbours. This reduces the problem of large flows being transmitted far in the network. Electricity is transmitted at the shortest possible distances and no reconfigurations can be made to decrease the investment costs of the network.

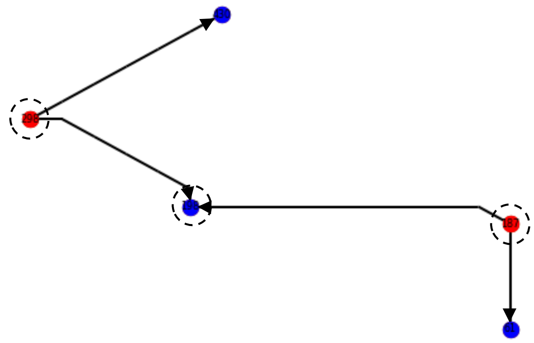


Figure 32 Demonstration of networks for which no electricity flows are transmitted though the three highlighted corner points. All production and demand is balanced by the corner points' neighbouring terminals.

5.8 Conclusion of experimental results

Firstly, the experimental results have shown that the improvement procedure is more likely to make reconfigurations when the β value is high, which is in line with Equation 3.1. The final solution is also quite sensitive to this value and a good approximation should therefore be used in the final networks. The results have also shown that the improvement procedure is more likely to lead to high savings when the initial network has a high number of terminals with a degree of two, as these are the relevant terminals for the improvement procedure. Small angles are more likely to be reconfigured, especially if the flows through the angle are of high absolute value. This has been found to be the case when the production and demand values of terminals have high absolute values, meaning that the terminals are either large net exporters or consumers. Additionally, edge capacities are high when there is a large concentration of either sources or sinks in an area of the graph.

There are little opportunities for reconfigurations when the network topologies resemble a straight line, as paths connecting terminals cannot be further combined to create a shorter or a lower capacity network. Additionally, if the β value or edge capacities are low, reconfigurations make little or no impact compared to the initial networks.

In addition to creating a higher possibility of reconfigurations, a higher β value also creates higher overall savings to the reconfigured network. If the relevant angles consist of long paths, the impact of reconfigurations in percent increase. Additionally, although there is a higher chance of reconfigurations for large networks as it increases the possibility to find relevant angles, the savings caused by reconfigurations in larger networks make a smaller impact on the overall network costs.

Chapter 6: Case study on designing a new electricity distribution network for Goeree-Overflakkee

In order to demonstrate the use and to evaluate the effectiveness of the proposed method, a case study is performed on Goeree-Overflakkee, one of the smallest of the 30 Dutch energy regions. In Figure 33, Goeree-Overflakkee is presented in light green with four surrounding energy regions to the North, West and the South. The region consists of one large, connected island and one smaller island as shown in. Only the main island is to be supplied with electricity. The region consists by a large part of agricultural areas such as non-irrigated arable land, followed by urban areas with a relatively low density of occupied space. The area is also characterised by pastures, grassland, crops, inland marshes, beaches and dunes (Copernicus Land Monitoring Service, 2019). Additionally, the island includes protected areas that are located along the Northern coast.

Figure 33 Energy region Goeree-Overflakkee (light green), as reprinted from Regionale Energie Strategie (2019). Surrounded by Rotterdam-Den Haag (grey-blue) to the North, Hoeksche Waard (purple) and West Brabant (dark green) to the East and Zeeland (violet) to the South.

6.1 Importation of land use data and preparation of initial graph

Initially, land use data from CLC database is imported from an already prepared csv file. From the minimum to the maximum x and y coordinates from the file, at a certain distance, a vertex is added to the graph. These represent the initially available vertices for the grid graph. As no reductions have been made yet, the graph is simply a green rectangle of data points including the chosen energy region, but also containing the surrounding water bodies and other energy regions in the vicinity. Horizontal, vertical and diagonal edges are thereafter created, based on a search for neighbouring vertices. Neighbouring vertices are initially defined as vertices that have a horizontal or vertical distance of 100m or a diagonal distance of 141.42m, considering that a spatial resolution of 100m is chosen. The diagonal distance is calculated simply using Pythagoras' theorem, in order to ensure that the vertices and edges will create a grid graph with vertices of equal spacing. Using this approach, all vertices are initially connected to eight other vertices.

6.2 Importation of net production and coordinates data for terminal vertices

The terminal points are plotted on top of the green grid graph containing the map of Goeree-Overflakkee. With production vertices in red, demand vertices in blue and self-sufficient vertices in black, the terminals are represented. The green background represent the Steiner vertices that can be used to connect the terminals. Due to the large number of Steiner vertices, the vertices cannot be seen individually, but as a fill colour of the available land (Figure 34).

6.3 Ensuring that network avoids unavailable land

As defined in the problem formulation, certain types of land are unavailable to dig in and lay cables on. The chosen unavailable categories are airports, all types of water bodies and national parks. From the CLC data, the vertices corresponding to the unavailable land types are removed from the map of available vertices. The edges connected to the removed vertices are also automatically removed in the process. As "national parks" is not a defined category in the CLC database, beaches and sand dunes are removed in order to capture some of these spaces. If the network overlaps with other protected areas, these Steiner vertices have to be removed manually in Python.

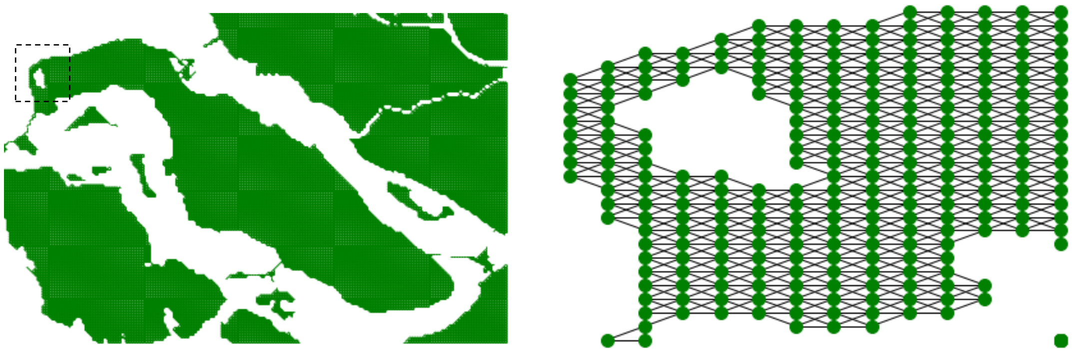


Figure 34 To the left: network of all available Steiner vertices and edges. Due to there being a large number of Steiner vertices (165 000), the details of the network cannot be seen. To the right: close-up of network showing Steiner vertices and edges around a water body in Goeree-Overflakkee.

6.4 Graph reduction

Although Goeree-Overflakkee is a small energy region, a large initial number of vertices is returned and reductions need to be made in order to reduce the computational time. With vertices plotted at every 100m, the initial map of data points contains approximately 165 000 vertices. The graph before reduction is presented in Figure 35.

Figure 35 Initial grid graph of all available Steiner vertices and edges (green background) and all input terminals highlighted in red, blue and black depending on whether they are sources, sink or self-supplied terminals respectively..

In order to reduce the graph, the number of Steiner vertices are firstly reduced by limiting the ranges of x and y coordinates to only including the square containing Goeree-Overflakkee. By reducing the resolution of the graph to data per 200x200 meters, the number of vertices is reduced to a fourth of the initial vertices. Terminals of high spatial proximity, in this case defined as 2000m, are combined in order to reduce the number of terminals. In this case, Sommelsdijk and Middelharnis are combined, resulting in one less terminal to be considered. Finally, the convex hull approach is performed. The results can be seen in Figure 36. After the application of reduction techniques, the number of vertices is less than 3500. Using reduction techniques, the number of vertices has in other words been reduced by 97%. It should be noted that this is partly due to the large area of the data at first and a large number of vertices are therefore removed during masking. However, this demonstrates how reduction techniques can be used to significantly decrease the computational time of the problem at hand.

Figure 36 . To the right: reduced graph using convex hull approach, graph coarsening approach and combination of terminals of high spatial proximity.

6.5 Determining the initial network of Goeree-Overflakkee

The initial solution is found by applying the chosen MSTG heuristic, SPH-Z. The resulting network is presented in Figure 37. The execution time of the SPH-Z heuristic shows to be 19902.96 ms. Because it is only run once, the execution time is within feasible limits. For each time step, the total investment costs of the initial solution are found by applying the Network Simplex algorithm to the initial network topology in order to determine the required edge capacities. The initial investment costs are thereafter calculated using Equation 3.1, taking both lengths, capacities and the β exponent into account.

Figure 37 Initial solution for the electricity network in Goeree-Overflakkee.

6.6 Determining the final network in Goeree-Overflakkee

6.6.1 Choice of timesteps to be considered

When the initial solution has been found, the improvement procedure is run. When the improvement procedure cannot make any further savings, the Network Simplex algorithm is re-run in order to update the edge capacities after possible reconfigurations. From running the file for an arbitrary time step, it has been found that the Network Simplex algorithm has a computation time of 34.47 ms whereas the improvement procedure has a computation time of 367.65 ms. It should be noted that the computation time of the improvement procedure varies slightly per run, depending on the reconfigurations made.

In order to take time into account, a subset of timesteps is selected from the complete set of annual production data. As there is a total of 8760 timesteps, production data for every first Tuesday and Sunday per month over a year is chosen as the included timesteps. In this way, consumption patterns both during a relatively normal weekday and during a day in the weekend are considered. In total, the number of selected timesteps is 576.

6.6.2 Electricity production in Goeree-Overflakkee

By finding the average electricity production over the year, it can be seen that a large share of the electricity in Goeree-Overflakkee is produced in Ouddorp, whereas the other 13 terminals are sinks on average (Table 3). This data shows that electricity is often produced in Ouddorp before being transmitted southwards in order to meet the other terminals’ demand. Additionally, several of the terminals are on average close to self-sufficient. Comparing to the full dataset, it can be seen that the Achthuizen and Den Bommel have a net production of zero relatively frequently. This will have an effect on the local reconfigurations made.

Table 3 Average net production data per terminal

Terminal name	**Average net production [MWh]**	**Terminal name**	**Average net production [MWh]**
Dirksland	-0.141	Stad aan ‘t Haringvliet	-0.106
Middelharnis	-0.004	Ooltgensplaat	-0.242
Sommelsdijk	-0.839	Den Bommel	-0.163
Herkingen	-0.093	Melissant	-0.039
Nieuwe-Tonge	-0.045	Stellendam	-0.489
Achthuizen	-0.046	Goedereede	-0.218
Oude-Tonge	-0.407	Ouddorp	2.832

6.6.3 Frequency of local reconfigurations

After performing the improvement procedure on the subset of timesteps, it is found that the most frequent reconfiguration occurs for the angle Dirksland, Middelharnis, Nieuwe-Tonge. A direct connection between Dirksland and Nieuwe-Tonge is made and a diagonal cable is created from Dirksland to Middelharnis. This reconfiguration is made in 79% of the cases. The reason for the reconfiguration is partly the position of Middelharnis, which deviates from the straight line in the networks and makes the angle a rather long high-capacity cable. By instead connecting Middelharnis using a lower-capacity line, savings can be made. It is also the smallest angle found in the network, which gives it further potential for savings. It should be noted that this reconfiguration only occurs when the combination of terminals of high proximity has been included. For a small number of cases, the reconfiguration is made using a splitpoint instead of a diagonal line. This occurs mostly for timesteps when Middelharnis is self-sufficient. Due to the assumption made in Chapter 3, this reconfiguration is the only one compared to the original configuration when the net terminal production is zero.

The second most common reconfiguration is a split point between Ouddorp, Goedereede and Stellendam (Figure 38). This reconfiguration occurs in 53% of the timesteps. Although the angle is relatively large, the high capacities of the cables lead to the high frequency of reconfigurations for this angle.

Thirdly, the angle Goedereede, Stellendam, Melissant is in 21% of the cases reconfigured using a splitpoint. Similarly to the split point connecting Goedereede, the interesting finding is that the network is already relatively straight with a large angle. Due to the high-capacity cables often being required in the North, it is still in some cases reconfigured.

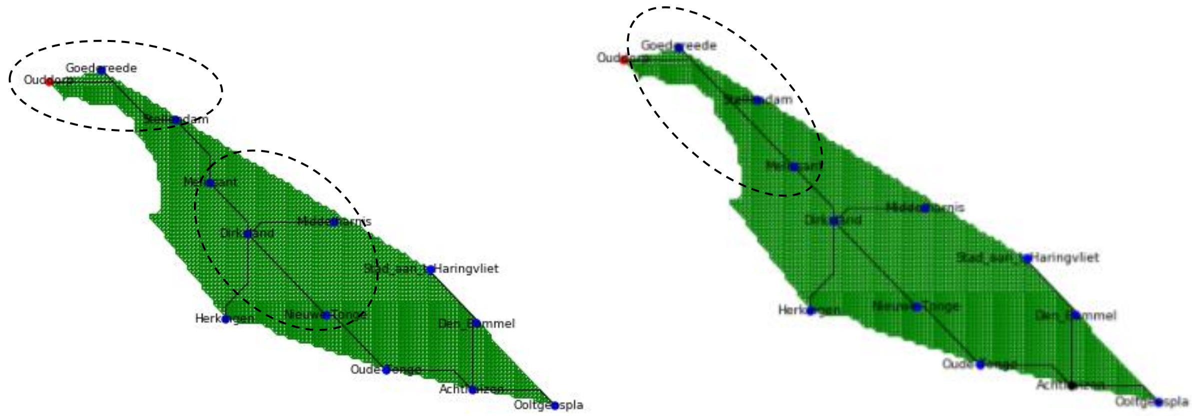


Figure 38 Overview of the three most common reconfigurations.

Another finding is that reconfigurations occur relatively seldomly in the South. This is due to several of the terminals often being self-sufficient or having small deviations from a net production of zero. Oude-Tonge and Den Bommel are also part of relatively large angles, which has been shown in Chapter 5 to reduce the possibility for savings. The reconfiguration with the highest frequency in the South is the angle Staad an 't Haringvliet, Den Bommel, Achthuizen, which was reconfigured in 11.5% of the cases. This reconfiguration is presented in Figure 39. Finally, the angle Dirksland, Nieuwe-Tonge, Oude-Tonge was reconfigured in 0.70% of the cases. This occurred when Middelharnis was not reconfigured, as the angle is otherwise 180 degrees.

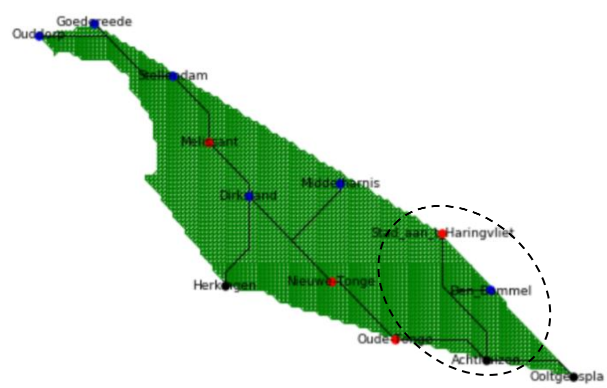


Figure 39 Reconfiguration of Den Bommel, which occurs relatively seldomly.

The final choice of topologies is to include two options; Option 1, including the angles reconfigured for Middelharnis and Goedereede, as these reconfigurations both had a frequency of more than 50%. Option 2 includes Stellendam, which was reconfigured in 21%. The reason for this is that the timesteps considered were only a subset from the whole year and the reconfigurations showed to depend strongly on the production data. Additionally, the savings in percent per timestep have not been considered. Overall, including the reconfiguration could lead to an overall cheaper network.

6.6.4 Determining the required edge capacities

In order to determine the required edge capacities of the final network, the Network Simplex algorithm is run. Because the Network Simplex algorithm has relatively low computation time, the algorithm is run for all time steps. Additionally, this ensures that the final network has sufficient capacity to operate during the year without any blackouts. The maximum electricity flow found for each edge over the year is set as the fixed capacities of the edges in the network.

Table 4 Comparison of two topology options for the case study of Goeree-Overflakkee

Method	**Total length [m]**	**Difference in total investment cost compared to final network [%]**
Network Option 1 (Goedereede, Middelharnis, Stellendam)	53 381	0
Network Option 2 (Goedereede, Middelharnis)	52 919	+2.07

By running the Network Simplex algorithm for all timesteps for both topology options, it was found that when including the reconfiguration at Stellendam, the overall network costs were reduced. This was therefore the chosen final topology for Goeree-Overflakkee.

6.7 Comparison of the proposed method to a simultaneous optimisation of electricity production and grid topology

For security reasons, information on the topologies and capacities of the DNs in the Netherlands is not open to the public. It is therefore not possible to compare the outputs of the proposed method to the current electricity grid in Goeree-Overflakkee. However, it can be compared to another available method that has created DNs for Goeree-Overflakke which includes both topology and generation in its optimisation.

6.7.1 Description of simultaneous optimisation

The simultaneous optimisation starts with an initial network of straight lines between terminals, disregarding unavailable areas. The initial network, which can be seen in Figure 40, is a meshed topology and therefore contains cycles.

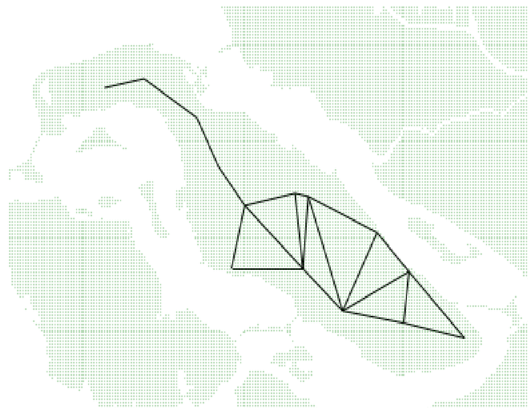


Figure 40 Initial set of edges for simultaneous optimisation of production and topology. Capacity has not yet been considered

The required capacities in the network are assigned in the same way as the proposed method; the maximum flows transmitted through each edge during a year is set as the final edge capacities. The outputs of the two methods can therefore be compared. The final network, taking capacities into account, is presented in Figure 41. The results show that two of the lines are assigned capacities of zero and can be removed from the network.

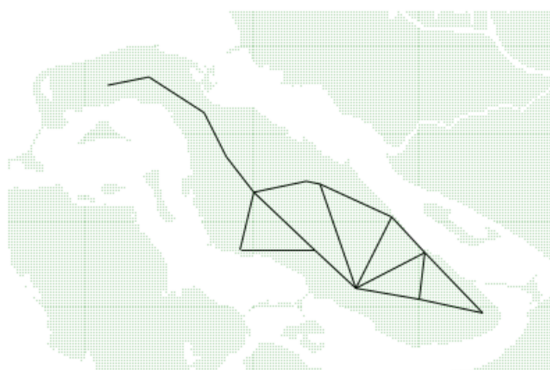


Figure 41 Final network for the simultaneous optimisation of production and topology. Two of the lines in the initial network have been removed as the required capacity was found to be zero.

6.7.2 Method comparison

A clear difference between the two methods is the fact that the simultaneous optimisation does not assume a specific grid topology and the resulting network therefore contains cycles. This generally leads to increased investment costs due to the increased number of cables. However, it increases reliability. If a fault occurs around one of the cables or maintenance is required, the grid may still be able to deliver electricity using an alternative route. Additionally, the simultaneous optimisation does not consider spatial constraints and all the lines are straight, in contrast to the proposed method. In Figure 40 and Figure 41, a background of the available land for Goeree-Overflakkee has been added to the graph. Although the background graph is not considered by the method, it can be used to check whether any cables are placed on spatially unavailable areas. In the case of

Goeree-Overflakke, most of the land is characterised as available and the simultaneous optimisation therefore does not violate any of the spatial constraints set in this paper. For other more spatially constrained energy regions, however, using this method could result in cables being placed in unavailable areas.

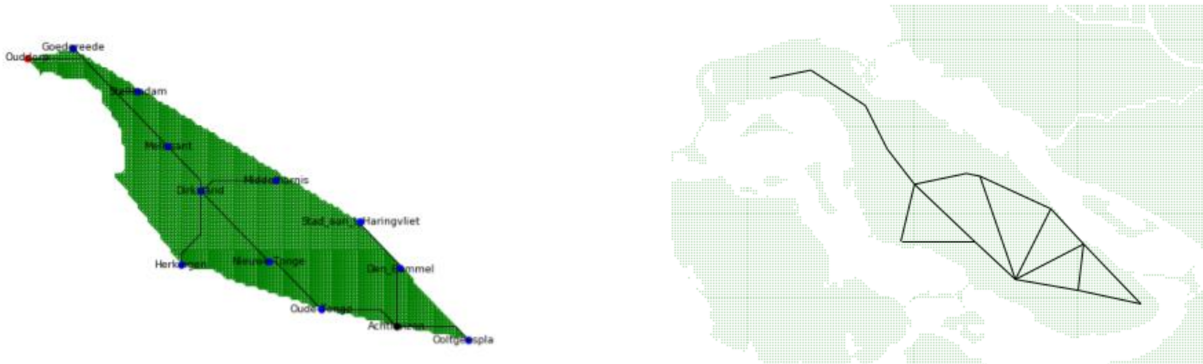


Figure 42 Comparison between final solution and alternative method

Table 5 Comparison of method performances for the case study of Goeree-Overflakkee

Method	**Total length**	**Difference in total investment cost compared to base case**
Simultaneous generation and topology optimisation	96 499m	-
Final network (Goedereede, Middelharnis, Stellendam)	53 381m	-13.1%
Initial network	51 593m	+5.3%

From Table 5, the differences in total costs between the different methods are presented. The total investment costs of the final network are 13.1% lower than the costs for the simultaneous optimisation. Additionally, the edges of the simultaneous optimisation are straight whereas the paths in the proposed method, and further savings are therefore expected if the paths were to be straightened. The reason for the savings is partly due to the radial topology and the fact that there are no cycles, as can be seen from the big difference in total length. By comparing to the initial solution based solely on length to the simultaneous optimisation, it can be seen that when the Network Simplex algorithm is run for all timesteps, it is more expensive than the simultaneous optimisation. This also demonstrates the importance of the improvement procedure, as total costs are decreased by 17.5%.

Discussion of results from case study of Goeree-Overflakkee

6.7.3 Effectiveness of the improvement procedure in the case of Goeree-Overflakkee

Firstly, the case study of Goeree-Overflakkee can be compared to the findings from the experimental results. Due to the long and slim shape of the island, the initial network already creates a long, and in some parts, straight network. As the improvement procedure aims to combine lines in order to limit the use of high capacity lines, the effectiveness of the improvement procedure is more limited in the Northern part of Goeree-Overflakke as it contains a straighter network. It can therefore be expected that higher savings can be found for energy regions with less straight initial networks. The case study of Goeree-Overflakkee also included seven relevant terminals as corner points of angles with a degree of two. The network therefore allows the improvement procedure to make reconfigurations for seven angles. Another finding is the fact that the reduction procedure of combining terminals of high spatial proximity has in this case not only reduced the set of terminals for reduced computation times. The reduction has also allowed for the improvement procedure to make larger savings.

The case study has also proved the importance of generation data for the effect of the improvement procedure. As Goeree-Overflakkee is characterised by generation in the North and consumption in the South, high capacities are needed, especially in the North. Although the network is relatively straight in the North, the production data leads to the improvement procedure still making reconfigurations for some of these angles, and the improvements show to have a large effect on the total costs of the network.

Finally, the case study has demonstrated the method's ability to avoid land areas characterised as available. In this case, the relevant land types were different types of water bodies. Although the initial and final networks avoid these land types, a low-cost solution is still found. This is found in comparison to an alternative approach which co-optimises network capacities with electricity generation. Calculation of the total costs of both methods show that the proposed method in this case creates a cheaper network, with a cost reduction of 13.1%.

Chapter 7: Discussion and conclusions

7.1 Discretisation of maps into grid graphs and reduction of mesh size

A resolution of 200m by 200m has been chosen for the implementation of spatial data in order to reduce the number of vertices to iterate through. The clear advantage of is that halving the resolution, the number of final vertices is the square root of the initial vertices. Computational time is therefore reduced significantly. However, this also means that some of the data of unavailable land may be lost and therefore not considered when finding cheapest paths. Increasing the distance between vertices also results in more jagged paths. If the final network was to be installed in real life, the jagged paths would of course be straightened and not installed with the jagged paths presented in the output of the model. The most important outputs of the model are the optimised connections and the routing of these connections. The jagged lines therefore do not pose any issues in the implementation phase. However, having a coarser resolution means that paths of an angle between that of horizontal/vertical and diagonal lines may become more expensive. A bias can therefore exist where straight and diagonal paths are favoured over paths of different angles.

In order to evaluate whether the resolution reduction still leads to valid outputs, the initial network of Goeree-Overflakke is used for demonstration purposes. The program is run for both resolutions, 100m by 100m and 200m by 200m, so that the resulting topologies can be compared. The results shown in Figure 43 show that the optimised connections in the two cases are exactly the same. This gives the insight that the total distances are large enough so that the change in resolution does not affect the final solution. The only difference between the networks, except for the fact that the higher resolution graph is aesthetically more pleasing, is the fact that the graph with reduced resolution has slightly more jagged lines. Additionally, some of the shortest paths between the connections vary slightly. It should be noted that due to the fixed distances of horizontal/vertical and diagonal edges, there are often several shortest paths between two connection points that have the same total lengths. The chosen paths may therefore vary between runs of same initial conditions, whereas the total cost of the network stays the same. Another insight is the fact that the paths in the reduced resolution case does not overlap with any unconsidered unavailable data. From this demonstration, it can be assumed that the distances in the Dutch regions are large enough to reduce the mesh size. However, the map containing the spatial constraints should be compared to the final topology for the reduced case for each energy region in order to ensure that the final network still meets all spatial constraints.

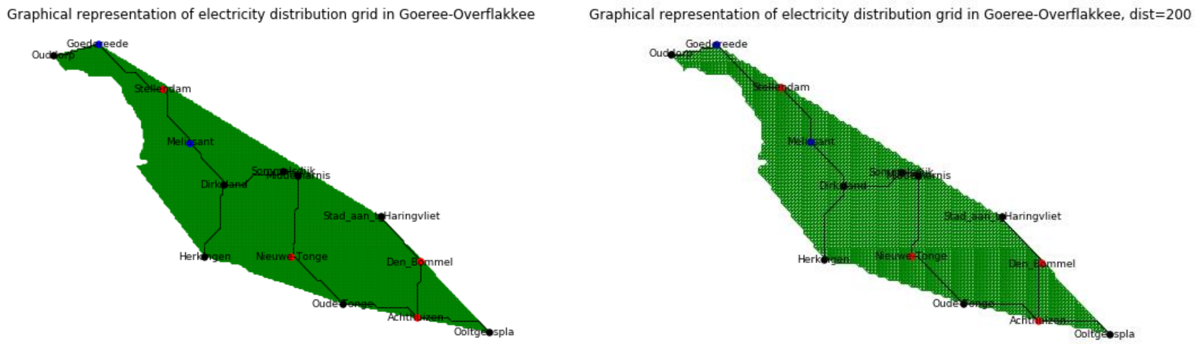


Figure 43 The initial solution is tested for two different resolutions (100m to the left and 200m to the right) in order to see how the difference in resolutions affects the final network topologies. Except for very slight changes in how jagged the paths are, the connections stay the same.

7.2 Designing new networks versus expanding existing networks

In the proposed method, an assumption has been made that the future DNs are to be designed from scratch. An advantage of designing electricity networks from scratch is the fact that it optimises the topology on a system level. In reality, the current grid will probably not be removed completely, as using the already existing grid can reduce investments costs. It is more likely that the existing networks will be expanded to meet the increasing capacities needed, in addition to upgrading and improving ageing parts of the grid.

One possibility to deal with this is by designing a network from scratch and comparing the outputs to the current network to look for similarities and differences. If there are similarities, upgrades from the final network could be made to the existing grid. However, the outputs of the method may be very different, which may make this a difficult approach. Additionally, data on the current DNs of the Netherlands is not available to the public for security reasons. This evaluation would therefore have to be performed by the distribution system operators. If one were to have access to data on the current network, another possibility could be to try to resemble the current grid in the graph used in the proposed method. The terminals and connection points could be resembled quite accurately, whereas the paths between the terminals would have to be resembled using the available edges. The terminals and Steiner vertices used could thereafter be added to the taboo list of the SPH-Z heuristic and the new terminals to be connected should be defined. The proposed method could thereafter be used for extension rather than for building a network from scratch.

7.3 Answering the research sub-questions

From the literature review performed, the proposed method and results from demonstrating the method, the sub-questions formulated at the beginning of the paper can be answered. Together, the seven sub-questions can answer the main research question of this research paper.

SQ1. What are the requirements of future regional electricity distribution networks in the Netherlands?

From this research paper, it has been found that the most important requirements of future regional electricity distribution networks in the Netherlands are low costs, in particular investment costs, and ensuring that the network can withstand the required flows of electricity. It has been found that on a general basis, the Netherlands is a country that values reliability highly. This can for example be seen with the Netherlands being the country in Europe that only build underground cables. However, it has also been found that there exists a trade-off between costs and reliability and that due to the perceived importance of electricity loads in DNs, a network with low investment costs is often preferred. This is in contrast to TNs, which are in most cases are designed as more expensive due to the use of more redundant lines. Networks in the Netherlands are not designed to never have blackouts. In fact, even with the Netherlands being a country characterised by high security of supply, it was found that the average Dutch electricity consumer experiences 15-38 minutes of blackouts on average per year. This is the outcome of the trade-off showing that it is more beneficial to allow for a certain rate of blackouts with the savings that can be made. It should also be noted that the investment costs in the end will be indirectly placed on the consumers and consumers may be content with half an hour unsupplied with electricity per year in order to spend less on electricity. However, due to the changing electricity market, the uncertainty and volatility of electricity production and demand is increasing and the general demand level is expected to increase as well. With the expected changes, the current DNs will not be able to meet the requirements. The trade-off now makes it beneficial to make investments in the grid in order to prevent much more frequent blackouts and even grid failure.

Another finding is that low electricity losses are also important due to the loss of electricity leading to the loss of revenue. It could also be argued that power losses should be avoided for environmental reasons, but this was not found to be a topic in focus in literature to date. Loss minimisation in general was found to be more important for transmission over long distances, such as in TNs and the European Supergrid, but was only in some cases for DNs. It was also found that minimisation of power losses were not valued as highly as investment costs. This is likely to be due to the costs of investing in networks being much more expensive than those of power losses. Additionally, although often not set as a requirement for the design problem of DNs, it is found to be a more common requirement for the operational problem of DNs, which becomes relevant at a later stage when the grid is built.

SQ2. Which network characteristics have an influence on the identified requirements?

From the literature review, it has been found that the most prominent characteristics influencing the identified requirements are edge lengths and edge capacities. Lengths and capacities are considered as important characteristics due to the most important requirement being identified as investment costs and due to the installation of the cables themselves having the biggest impact on the investments. The influence of lengths and capacities on investment costs is of non-linear character, as it is relatively cheaper to invest in a short network of high capacity cables than a long network of low capacity cables. In addition to having an effect on investment costs, increasing cable lengths also has a negative effect on the low power losses requirement as electricity is lost during transmission. For shorter networks, it can also be argued that there is a smaller chance of disruptions due digging accidents by third-parties, which has shown to cause a significant amount of disruptions. However, the effects of network length on cost minimisation and power loss minimisation are more directly related.

Another finding is that the use of technical components can have impacts on several of the defined requirements. Firstly, technical components require investments and the use of technical components is therefore positively correlated to investment costs. Additionally, the use of technical components can increase reliability as they in many cases are needed for the successful operation of electricity grids. Transformers can be used in order to change voltage levels, another characteristic of electricity grids. By increasing voltage levels, power losses can be minimised. Placement of technical components such as transformers in the network therefore also has an effect on power losses. However, the use of technical components can also have a negative effect on power losses and a trade-off therefore exists.

Different network topologies are also found to have an effect on several identified requirements. Whereas trees are the topologies of lowest investment costs, they have lower reliability which can lead to high maintenance costs or high societal costs during blackouts. Meshed grids are found to be the most reliable network type, although they require much higher investment costs, a longer planning horizon and a less efficient use of the installed cables.

AC versus DC transmission is also found to be network characteristics that influence the identified requirements. If electricity sources that are inherently DC, such as electricity from solar modules, are used, power losses can be minimised by using DC transmission in order to prevent the use of conversion. The effect of this is also larger if a large share of DC loads is used in society. For shorter distances, AC is superior to DC in terms of costs. For transmission over longer distances, DC is a cheaper alternative. The breakeven distance depends on whether the network consists of overhead or underground cables, with the breakeven distance being lower for underground cables. The use of underground and overhead cables also has a direct impact on the identified network requirements. Whereas underground cables have higher investment costs, they have higher reliability.

SQ3. Which aspects of costs should be considered for the electricity distribution networks?

As previously discussed, one of the most significant findings of the literature review is the fact that investment costs is the most included cost type in the design of electricity networks. This holds for DNs, TNs, multi-carrier systems and for offshore wind farms. It is also argued that for electricity networks, the investment costs are much higher than any other cost aspect. Investment costs should therefore be included in the objective function. For networks used for transmission over long distances, it may be beneficial to include power losses as part of the cost function. Power losses are in some cases also included for already existing networks that optimise the use of switches. However, for the relative short distances of distribution networks, power losses can be disregarded as it can be considered as significantly less important than investment costs and would lead to increased complexity of the problem.

SQ4. How should the objective function, decision variables and constraints be formulated for the distribution grid designs?

Length and capacity of electricity cables should be considered in order to optimise based on a more realistic cost function and therefore achieve networks of lower total costs. Although the investment cost function sometimes is linearised in literature, the cost function should be formulated as a non-linear function in order to incorporate the economies of scale of investing in higher capacity cables.

As the Netherlands is a country characterised by limited space, spatial constraints should be incorporated into the design problem. By discretising the regional maps into grid graphs with vertices at each corner point, vertices corresponding to unavailable land types can be removed from the graph. In this way, the final networks, which can only be built with respect to the underlying grid graph, will never be built on land characterised as unavailable.

Finally, a radiality constraint is formulated. Radial systems have the lowest investment costs in general out of the three topology types. The downside to this is that they also have lower levels of reliability as there are no redundant cables. However, due to DNs often having lower reliability levels than for example TNs, DNs are often designed with radial topologies.

SQ5. Which graph theory heuristics should be used for optimizing the electricity distribution topologies?

A choice has been made to discretise regional maps into grid graphs. On this grid graph, locations of electricity production or consumption, *terminals*, are assigned to their closest corner point location. Because of the underlying grid graph, the problem can be described as a MSTG problem, where the corner vertices not defined as terminals are defined as Steiner vertices. The MSTG problem aims to connect the terminals in a graph, possibly with the use of Steiner vertices.

Although both lengths and capacities of cables have been included in the problem formulation, it is difficult to create a final network based on both lengths and capacities in one single step as the assignment of cables depend on the cables yet to be assigned. It is therefore chosen to find an initial network based solely on length before incorporating capacities. The Shortest Path Heuristic, iterating over all initial vertices, is chosen as the most suitable graph theory heuristic, as it is shown to have a high performance for MSTG. The SPH-Z aims to find a network that connects all terminals and possibly also Steiner vertices, aiming to minimise length. A Network Simplex algorithm is thereafter applied to the initial network in order to assign cable capacities based on the net production of terminals.

SQ6. How can graph theoretical approaches be adapted to further improve the solution?

After using a Network Simplex algorithm in order to define cable capacities for the initial solution, an improvement procedure is included in order to take non-linear costs and both edge length and capacity into account. The improvement procedure uses local reconfigurations in the graph iteratively in order to reduce investment costs. The rationale of the improvement procedure is to limit the use of high capacity lines and instead use a short high capacity “highway” with lower capacity connectors ensuring that all terminals are connected to the electricity network.

SQ7. How effective is the model in doing what it is intended to do?

Firstly, the method was set to create networks of low investment costs. The proposed method is initially able to create networks of low total length. Using a case study of Goeree-Overflakkee, it was found that compared to an alternative network, the total length is decreased by over 40% and the investment costs are 13.1% lower.

The improvement procedure is at its most effective and makes the biggest savings when the graph consist of many small angles of high capacity, especially if the corner points of the angles have low magnitudes of supply and demand. In such networks, the improvement procedure is effective in shortening the high capacity cables and instead connecting some terminals using low capacity lines which may lead to lowered costs. The improvement procedure makes little savings if the high capacity part of the network is a straight line. In the case study of Goeree-Overflakke, it can be seen that due to the shape of the island as well as the placement of the terminals, most of the terminals can be connected using an almost straight line.

Additionally, the method intends to avoid unavailable plots of land. By verifying this constraint, it was found that the method does indeed avoid areas marked as unavailable. It is therefore shown that low-cost networks can still be found while taking spatial constraints into account.

SQ8. Does the model create valid electricity grid designs?

As previously pointed out, the planning of new electricity systems is characterised as both complex and long-term and the planning horizon is generally in the range of 10 to 20 years. Due to the extremely large investments and high uncertainties of such projects, it is not realistic to assume that the design outputs of a six month project should be ready for installation and several more factors would have to be taken into account before an electricity grid could be built. However, the method provides a good starting point and a flexible tool in in the design of electricity DNs for regions in the Netherlands.

Firstly, the validity of the model with respect to spatial constraints is higher than many reviewed papers, as a large ratio of designs do not consider spatial constraints at all. The proposed method has proved successful in rerouting networks with respect to unavailable land and due to the grid graph approach, it has been verified that the final networks never overlap with unavailable land. The method allows for land use categories to be incorporated, as has been demonstrated in the case of Goeree-Overflakkee. With the use of the CLC database, the spatial constraints can be considered at a resolution of 100m. Additionally, the method provides further flexibility by allowing for specific Steiner vertices or coordinate ranges to be removed manually. This allows for the possibility of even higher spatial validity using the proposed method. The validity of the cost function is also high as it takes both edge lengths, capacities and a non-linear function into account when designing topologies.

In real life, the spatial constraints are much more complex than what has been captured using the unavailable land. Although it is good that the most important unavailable areas have been excluded from the graph, it simultaneously creates an assumption that all Steiner vertices characterised as available are completely free to build on. This is of course a simplification, as social and political factors as well as who has the ownership of the land are disregarded. In reality, the availability of each plot of land would have to be thoroughly considered. The method is flexible as changes to the unavailable and available land can be made and the topology will change accordingly. By making more careful spatial considerations, the method can still be used.

Simplifications have also been made with respect to terminal locations, as the locations have been set as the middle point of each neighbourhood, village or municipality. In real life, generation facilities and consumption points would be much more numerous, with every wind farm, solar panel and household being connected to the DN. These smaller capacity connections have not been taken into account in this research paper. If the final network were to be implemented, further network design would be needed to connect all facilities to the bulk DN lines created in this research paper. This could be done locally for each terminal using the proposed method.

7.4 Answering the main research question

The main research question in this paper was defined as;

How to choose and adapt graph theoretical approaches in order to design cost-effective electricity distribution grids for regions in the Netherlands while taking spatial constraints into account?

The design of distribution networks (DNs) using graph theory is a complex task. Choices therefore need to make on which aspects to include in their design as well as choosing approaches that can further simplify the problem. In the design of future DNs for regions in the Netherlands, investment costs showed to be the most important objective function. By considering a non-linear cost function, the economies of scale of high-capacity lines is considered, which creates a more realistic network. Additionally, the final networks should have a radial topology and spatial constraints should be considered. The Netherlands is a spatially limited country and disregarding this aspect in electricity design could therefore lead to high unexpected costs upon implementation or sub-optimal rerouting. By discretising the land map into a grid graph, spatial constraints can be taken into account by removing Steiner vertices corresponding to unavailable areas from the grid graph. In this way, cables will never cross areas that have been defined as unavailable.

In the choice of methods to solve the problem, it has been found that a good approach is to start with a heuristic with relatively low computation complexity that can create an initial network based on length. This is because it is difficult to create a network based on both length and capacity in one run due to the choices to be made in the future having an impact on the current choices. A Network Simplex algorithm is thereafter applied to assign the required edge capacities. Afterwards, an improvement procedure should be applied that allows for reconfigurations performed locally in order to take the non-linear cost function into account. By making reconfigurations locally, the improvement procedure is able to deal with the high computational complexity of the problem. Additionally, the use of reduction techniques are crucial in order to lower the computational time. For this problem, the most appropriate reduction techniques have shown to be combining terminals in close proximity, reducing graph resolution and removing all Steiner vertices outside a defined convex hull. Finally, the most often occurring local reconfigurations from the improvement procedure should be used in the final network. Capacities should thereafter be assigned using the Network Simplex method over a large number of time steps, assigned to the highest flow found. Demonstration of the approach has shown that the method can find networks that take spatial constraints into account, while still finding a low-cost network.

In an industry where networks are often designed by expert intuition and using incremental steps that do not necessarily take the whole system into account, the proposed method provides system-level analysis based on scientific, repeatable methods. Choices have been made explicit and the steps have been explained so that they can be evaluated and altered. The data inputs and tools used are also both open source and free. In addition to creating new DN designs for the Netherlands, it has also been explained how the proposed method can be used to expand existing network instead of building from scratch.

7.5 Implications for practice

The proposed method provides a simple and flexible way of taking spatial constraints into account in the design of new and in the expansion of existing networks. For grid planners, the method can be used to provide more realistic final networks with higher implementability. If compared to a method where spatial constraints are not considered, the proposed method may prevent the need for legal rounds or expensive compensation to land owners. Considering unavailable land in the topology optimisation approach may also lead to a reduction in total investment costs, as there is a smaller possibility for unforeseen costs related to unavailable land. Additionally, the alternative of first finding the lowest cost network without taking spatial constraints into account and then rerouting at a later stage may lead to sub-optimal designs.

Because the method is made using a flexible approach, it can both be used to avoid land types and to avoid certain coordinates or coordinate ranges of land. The proposed method can therefore also be used as a decision-making tool by grid planners by first assessing the added investment costs of routing with respect to an unavailable area or land type. The investment costs of the output can then be compared to the expected costs of building in the area. If rerouting is cheaper, the particular plot of land should be avoided. If rerouting is found to be more expensive than cutting across an area, the assessment can be used in order to formulate a suitable compensation to the land owner or in the assessment of whether it is worth participating in a legal process in order to be able to build on this plot of land.

From the experimental results, it has also been found that the investment costs based on required cable capacities depend on the degree to which the net production of terminals deviate from being electricity self-sufficient. From a solely electricity network perspective, the costs of the future DNs in the Netherlands can be lowered by ensuring that electricity is generated and consumed locally instead of requiring large electricity flows on the grid, for example with the use of flexible demand and local storage. Having a region with net electricity generators in the North and net electricity consumers in the South has in this paper shown to lead to high capacity lines being required across the region, which in turn leads to high investment costs. If neighbouring villages could instead supply each other during changing weather conditions and demands, investment costs of the electricity grids can be reduced. It should be noted that these cost-saving procedures are based solely on a grid-cost perspective, disregarding the optimal generation locations within a region.

The proposed method can also be used for other electricity network. Due to the method having a radiality constraint, it is mostly suitable to DNs. However, with respect to different locations and sizes, the method is flexible and can be changed to incorporate different types of spatial constraints.

7.6 Recommendations for further work

Firstly, in terms of the proposed method, the concept of taking spatial constraints into account could be further enriched by incorporating edge weights, as used by (Ergun, 2015), in conjunction with the avoidance of areas. This would create even more realistic spatial characteristics, for example by incorporating the increased costs related to building cables in highly dense cities at an increased edge cost. This land data type could not be incorporated in the proposed method, as in some cases, the terminals will be positioned in areas characterised as highly dense cities. By removing these Steiner vertices from the grid graph, it might not be possible to ensure connectedness of the graph. The integration of the edge weight approach with the proposed method is rather simple if done using the CLC database categories, as used in this research paper. The challenge, however, is determining suitable standardised coefficients to represent building on different land types.

Following this first recommendation, it would also add value to analyse the relevant social, legal and political restrictions related to building the future DNs in regions in the Netherlands. In the demonstration of the method proposed in this research paper, the input data used to set the spatial constraints has been based on land use categories. This also means that graph vertices not included in the unavailable land categories have been assumed to be fully available. Because the proposed method is very flexible, the final networks could benefit greatly in terms of validity and implementability by additionally analysing the social, legal and political factors related to design of DNs in the Netherlands and incorporating this data in the spatial constraints.

From the experimental results and the case study on Goeree-Overflakkee, points of improvement have also found for the cost improvement procedure in order to further increase the possibility of savings using this approach. In this research paper, local reconfigurations have been set to only target terminals with a degree of two. However, it is also possible to make savings using reconfigurations of terminals with a degree higher than two. By increasing the number of relevant angles in the search, the local reconfigurations in the improvement procedure could to even higher total network savings compared to the initial network design.

The experimental results have also shown that in some cases, the assumption of placing the splitting points in the middle of the new cable in local reconfigurations creates sub-optimal results. The investment costs of local reconfigurations could be further reduced by checking the investment costs of the connection cable with the use of every Steiner vertex in the cable as a splitting point and choosing the splitting point that leads to the cheapest overall results. This would of course increase the computational complexity of the improvement procedure, so evaluations should be done on whether the increased savings make up for the increased computational time.

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Appendix A: Scientific Article

Designing the Future Electricity Distribution Network in Goeree-Overflakkee using Graph Theoretical Approaches

Ine Bjørkmann Rasmussen

Abstract

During the next few decades, a significant increase in the use of intermittent renewables is expected in the Netherlands which will lead to a more uncertain, volatile supply. A general increase in electricity demand is also expected and substantial upgrades and redesign of the current Dutch electricity networks is therefore needed. These upgrades will inevitably require great investments as the design and installation of electricity grids is costly. Additionally, the investments are lumpy and irreversible. It is therefore important that the investments will be made in such a way that the future grids will operate successfully, supplying consumers with the demanded electricity at sufficient quality with a low rate of interruptions. The aims of this paper has been to design the future electricity distribution grids for Goeree-Overflakkee, taking local spatial constraints into account. In comparison to an alternative method, the results have shown that the proposed method creates relatively shorter networks with lower investment costs, taking both lengths and capacities into account. Additionally, significant improvements in computational time have been achieved by the use of appropriate reduction techniques.

Keywords

Graph theory, electricity distribution, cost minimization, Minimum Steiner Tree in Graph, network design

1. Introduction

Recently, the Netherlands has been divided into 30 energy regions, which allows the Netherlands to work on its climate agreements both from a regional and a national level (Regionale Energie Strategie, 2019). These regions will work on generation and consumption of electricity and heating as well as on the energy infrastructures needed to supply this energy. Goeree-Overflakkee is an island in the Netherlands and one of the smallest of the energy regions. The region consist by a large part agricultural areas and villages.

Figure 1 Energy region Goeree-Overflakkee (light green), as reprinted from Regionale Energie Strategie (2019).

2. Literature review

For the suitable design of the future DNs for this region, the most important characteristics and requirements are identified using a literature review. Well-suited problem formulations and methods are also analysed.

2.1 Objective function

The most commonly included objective function in electricity network design is cost minimization. Costs can be divided into investment costs and operational costs, with investment costs to a high degree being to most common cost type to be included. In terms of operational costs, costs of running production plants were often included simultaneously with the topology optimisation (Aghaei et al., 2014; Chaudry et al., 2014; Tang, 1996; Unsihuay et al., 2007). Minimisation of power losses were in some cases also included, especially for transmission over long distances such as in transmission networks (TNs) (Sensarma et al., 2002) and offshore wind farms (Banzo & Ramos, 2011; Chen et al., 2013). Power losses have also been including for DN design, but in contrast to TNs and offshore wind farms, power losses are included for DNs when considering an already existing network and optimizing the opening and closing of switches (Carrano et al., 2006; Enacheanu et al., 2008). For building new networks, power losses were often disregarded in DN design.

2.2 Decision variables

The most commonly included decision variables in electricity grid design are cable length, calculated in two-dimensional space, followed by cable capacity. If only cable lengths are included, the final solutions may be sub-optimal in the way that high loads may have to travel far in the network. In most electricity designs, including DNs, both length and capacities are therefore included (Carrano et al., 2006; Duan & Yu, 2003; Enacheanu et al., 2008; Tang, 1996). A decision variable that is only sometimes included in electricity grid designs is the use of technical components. Although often included in the design of offshore wind farms, TNs and multiple energy carrier systems (Banzo & Ramos, 2011; Chaudry et al., 2014; Dahmani et al., 2015; Ergun, 2015; Hou et al., 2016; Hu et al., 2016; Sensarma et al., 2002), technical components are only included in one of the papers designing DNs (Tang, 1996). This may be due to the lower changes in voltage levels in DNs compared to other grids. It should also be noted that although they are often excluded as a decision variable, they can still be added to the final solution in order to ensure successful operation of the network.

2.3 Constraints

In the large majority of cases when new electricity systems are designed, the grid topologies are limited by existing infrastructure or rules and regulations related to the concerned areas. If spatial properties are disregarded, this may lead to costly and timely implementations. In DN design, the optimisation by (Carrano et al., 2006) starts with an initial set of edges that are all available to build on. The selection of available edges is done manually and may therefore be time consuming for larger networks. (Heijnen et al., 2014) defines the allowable region as a polygon which ensures that the final network avoids the areas outside the polygon. The paper by (Ergun, 2015) uses a different approach by including "spatial weights" edges in a grid graph corresponding to the costs of the land type. The spatial weights are incorporated in the design problem by discretising land points in a graph and adding horizontal, vertical and diagonal edges. It should be noted that the spatial weights are approximated specifically for Germany and that they may not necessarily reflect real-life costs. According to (Ongkiehong, 2006), the issue of building large infrastructures in a limited space is especially prevalent in the Netherlands due to the general lack of space. It is therefore clear that spatial constraints are important for electricity design in the Netherlands.

DNs are often designed using radial topologies (Carrano et al., 2006; Duan & Yu, 2003; Enacheanu et al., 2008; Tang, 1996), as this is the topology with the lowest investment costs. Additionally, it has the highest efficiency of material use. Although ring and meshed topologies have higher reliability, the reliability of DNs if often valued lower than the reliability of TNs and radial topologies are therefore appropriate.

3. Proposed methodology

3.1 Discretisation of regional maps into grid graphs

In order to differentiate between available and unavailable plots of land, a choice has been made to discretise the maps of land into grid graphs. The grid graphs are used as underlying networks of where electricity lines can be built. Vertices are added to each corner point of the graph. In this way, vertices corresponding to unavailable areas can be removed in order to prevent the final networks to be built on these plots of land. In order to increase the smoothness of the final networks, horizontal, vertical and diagonal edges are included in the grid graphs. For simplicity, space is considered in two dimensions and there is a consistent mesh size across the graph. Whereas the lengths of horizontal and vertical edges can be defined for each run, the lengths of the diagonal edges simply follow from Pythagoras' Theorem. The method is created and run in Python using Networkx, a library specifically for working with graphs and networks.

3.2 Electricity design using Minimum Steiner Tree in Graph approach

In graph theory, the problem of designing electricity grids based on connecting a set of defined vertices can be approached in several different ways. The simplest approach is the Minimum Spanning Tree (MST) approach, which connects all vertices in the cheapest possible way. However, for the design of the future Dutch electricity distribution networks, some plots of land are to be avoided. As the MST problem creates straight edges between the set of vertices, the final network is likely to violate the areas marked as unavailable. *Steiner vertices*, additional vertices that can be included in the final network, can be used in order to create paths that avoid the unavailable areas. Using Steiner vertices, the problem can be formulated as a Minimum Steiner Tree in Graph (MSTG) problem. The MSTG problem aims to find the cheapest way of connecting a selected set of vertices, *terminals*, in a graph, possibly using Steiner vertices. The paths can only be chosen from the descritised grid graph. By definition, all terminals are to be connected to the final graph, T, whereas Steiner vertices can either be included or left out. The problem has similarities to the MST problem. However, the difference of only connecting a subset of vertices manifests itself in the increased complexity of the MSTG problem due to the possible use of Steiner vertices (Winter, 1987).

3.3 Problem formulation

The MSTG problem in an undirected graph is defined by (Winter, 1987) as follows:

Given: An undirected network G = (V,E,c) with n vertices, m edges, and the edge cost function c: E → R, a subset Z ⊆ V with p vertices (where V is a set of vertices, E is a set of edges and c is the edge-cost function).

Find: A subnetwork G_Z of G such that there is a path between every pair of Z-vertices, and the total cost of G_Z (i.e., the sum of its edge costs) is a minimum.

As investment costs are to be minimised, a non-linear cost function is formulated taking edge lengths and capacities into account:

$$min\ C_{inv} = \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} x_{ij} l_{ij} q_{ij}^{\beta} \quad (3.1)$$

Where l_{ij} is the length and q_{ij} is the capacity of the edge between vertices *i* and *j* and β is the exponent representing the economies of scale related to installing cables with high capacity compared to low capacity. The length and capacity variables are both continuous and β is restricted to values between zero and one, $0 \leq \beta \leq 1$. The costs are summed over all edges in the final network.

It should be noted that if the edge-cost function *c* is positive, the final network will always have a radial/tree topology (Winter & Smith, 1992). The network will therefore be a connected graph which does not contain any cycles.

3.4 Choice of MSTG heuristic

According to (Winter, 1987), the MSTG problem is extremely complex, with only small networks (characterised as a network of less than 30 vertices) being solvable in an hour. For larger networks, heuristics that find local optima are needed. From a survey by (Winter & Smith, 1992) on the performance of heuristics on the MSTG problem, it was found that the repeated Shortest Path Heuristics (SPH) perform the best. SPH-ZZ and SPH-V iterate over different Steiner vertices. As the MSTG sets Steiner vertices at every corner point of the graph, this iteration is not needed in this case. The SPH-Z that iterates over initial vertices is therefore chosen.

The generic SPH heuristic starts by randomly choosing an initial terminal vertex and searching for the terminal vertex that will lead to the shortest connection path. In a grid graph as chosen in this method, Dijkstra's algorithm can be used to compute the shortest path and paths can either consist of a direct edge connection or with the use of Steiner vertices. After adding the shortest path to the subgraph T, the search for another shortest path continues. This is done using a Prim's type search, adding the visited vertex found in the previous iteration to the set of vertices that can work as initial vertices. The computational time is $O(pn^2)$, with *p* representing the number of terminals to be spanned and *n* representing the total number of vertices in the graph (Winter & Smith, 1992). The error ratio is bounded by two, meaning that in the worst case, the solution is double the length of the globally optimal solution. One of the disadvantages of the SPH is that the solution is very sensitive to the initially chosen terminal, which is in the original formulation chosen randomly. SPH-

Z deals with this disadvantage by iterating over all initial vertices before choosing the network of shortest total length. The computational time is therefore multiplied by the number of terminals in the network.

According to (Winter, 1987), the MSTG problem is extremely complex, with only small networks (characterised as a network of less than 30 vertices) being solvable in an hour. For larger networks, heuristics that find local optima are needed. From a survey by (Winter & Smith, 1992) on the performance of heuristics on the MSTG problem, it was found that the repeated Shortest Path Heuristics (SPH) perform the best. SPH-ZZ and SPH-V iterate over different Steiner vertices. As the MSTG sets Steiner vertices at every corner point of the graph, this iteration is not needed in this case. The SPH-Z that iterates over initial vertices is therefore chosen.

3.5 Determining cable capacities

When the shortest network is found, the required edge capacities are determined using the *network simplex* algorithm. Network simplex is a method based on the Simplex method, developed to solve linear problems in graphs (Cunningham, 1979). The working principle of the network simplex method is that it starts with an initial spanning tree. It then proceeds to the next one by adding a new edge that was initially not part of the spanning tree and thereafter deleting an edge part of the initial spanning tree (Cunningham, 1979). This process is repeated until an optimal solution is found or it can be shown that no such solution exists. With this working principle, the network simplex method can be used to find an initial spanning tree in the graph based on a linear cost function. However, in this case MCF methods are to be used on an already defined tree network and only used for the optimum assignment problem. The method so far creates the initial design. However, procedures can be defined in order to further reduce the investment costs of the network and take non-linear costs into account.

3.6 Cost improvement procedure

In order to take non-linear costs int account and to create further savings, a cost improvement procedure is formulated and applied. The procedure starts with the smaller angles as these have the biggest potential for savings. The smallest angle, consisting of two edges that are rooted in the same vertex, is found and it is checked whether a smoother curve will lead to a cheaper network. If it leads to an improvement, the network is updated using the Network simplex algorithm over the three vertices in focus and repeating the search for the smallest angles. By iterating through all terminals in the network, the smallest angle is found and it is checked whether a smoother curve will lead to a cheaper network. If it leads to an improvement, the network is updated using the Network simplex algorithm over the three vertices in focus and repeating the search for the smallest angles. The Law of Cosines is used in order to calculate the angle of each terminal with a degree of two.

$$A = \arccos\left(\frac{b^2 + c^2 - a^2}{2bc}\right) \qquad (3.2)$$

Where A is the unknown angle created by the edges corresponding to lengths b and c. a is the length of the edge opposite to A. It should be noted that for simplicity, when

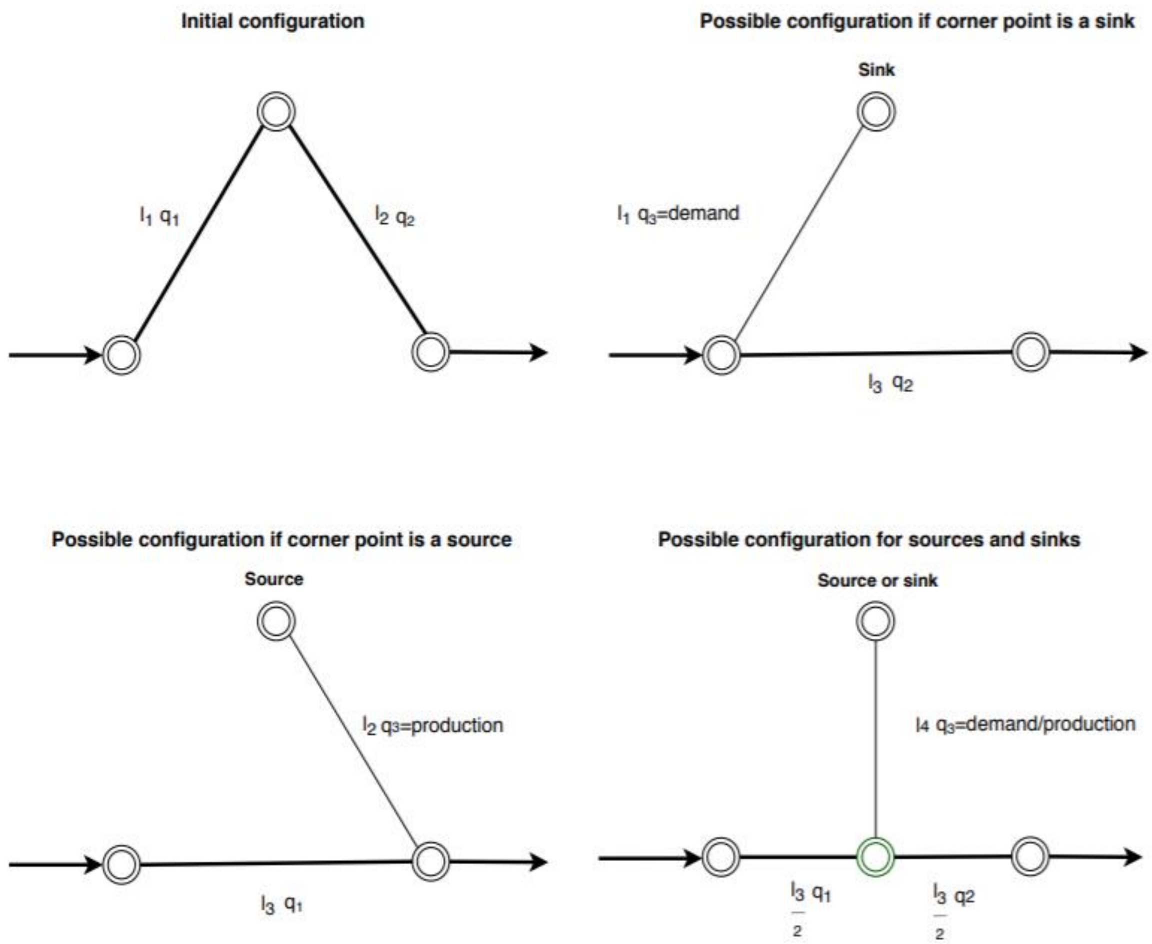

Figure 2 Overview of four possible configurations, including lengths and capacities that together make the configuration costs.

calculating the angles, the paths between the terminals are assumed to be straight.

After calculating the angle of all vertices, the vertex with the smallest angle is chosen. The paths connecting to this vertex are removed and a new path is created between its two adjacent vertices. The final step is to create a path that connects the vertex to the newly created path between its neighbours. The point where the vertex is connected to the path is called a splitting point. This procedure explores whether a splitting point can be used to limit the length of expensive high capacity lines and instead use low capacity lines to connect to this short high capacity “highway”. After changing the network configuration, the network costs need to be re-calculated. This is done locally by calculating the new edge lengths and defining new required capacities using the Network simplex algorithm. If the procedure leads to a cheaper network, the procedure is repeated. It should be noted that the angles need to be recalculated due to the reconfiguration. The procedure is repeated until no further savings can be made.

3.7 Graph reduction approaches

As the computational complexity of the chosen MSTG heuristic, SPH-Z, depends on the number of terminals, it can be beneficial to reduce the number of terminals to be connected. As the location of terminals makes a big impact on the final network topology, this is an appropriate reduction only when two terminals are very close to each other as two very close terminals should always be connected by an edge. The minimum distance that two terminals can have is set to 2000m. The net production of the remaining terminal is the two initial terminals' net productions combined.

Another reduction approach used is the convex hull approach, with the rationale that paths do not need to cross the coordinates of the outermost terminals. A convex hull can be created between these outermost vertices in the graph and all vertices on the outside of the defined perimeter can be excluded as possible Steiner vertices. If all the Steiner vertices were kept available, a zig-zag path crossing the perimeter could be chosen by the heuristic as the shortest path. However, due to the spatial topology of Goeree-Overflakkee and due to the large ratio of available land, a path with the same cost could be found within the polygon and the approach is therefore both effective and valid.

Thirdly, a spatial resolution of 200m is chosen instead of the minimum resolution of 100m that can be achieved with the use of the CLC database. It should be noted that the disadvantage of using this reduction approach is the fact that some of the land details may be lost. As Goeree-Overflakkee has a high ratio of available land compared to unavailable land, it is valid to reduce the spatial resolution of the graph.

4. Input data

4.1 Land use data

In order to define available and unavailable vertices for Goeree-Overflakkee, data from CORINE Land Cover (CLC) database is used. CLC database is an inventory of free, open-access data on land use in Europe, with land data divided into 44 categories. The land data is given in a resolution of 100 by 100 meters with points set in the middle of each square, giving the land use coordinates as well as the land use type. The data is given in two dimensions, x and y, the spatial coordinate system, EPSG3035. The data files from CLC are very large and need to be processed before importation in Python. In this paper, already processed data from CLC 2012 is used. Although it is not the most recent datafile, the land use has not changed significantly. After implementation, "zooming in" on the wanted area was needed in order to reduce the number of Steiner vertices.

The excluded land types are water bodies, wetlands and protected areas such as sand dunes and national parks. Water bodies, wetlands and sand dunes can directly be addressed using the CLC database as these are explicitly stated in the land use types. The database does not include data on national parks or protected areas. For Goeree-Overflakkee, the national parks are located along the coast in the north. By removing sand dunes, some of the no-go zones are removed. An initial solution can therefore be found, which should be evaluated whether the network overlaps with any of the defined national parks in the north. If an output network overlaps with a national park or protected area, the specific range of vertices needs to be identified and removed manually before re-applying the methodology.

4.2 Annual production data and corresponding coordinates

The production data for Goeree-Overflakkee is created on a yearly basis, in total including 8760 hours. The electricity is produced using the renewable energy sources wind, solar and biomass. For each hour, the generation is assumed to equal demand. The terminals are initially defined as the mid-point of each village, with the generation being optimised with respect to location. The terminal coordinates are thereafter approximated to have the location of the closest Steiner vertex. It should also be noted that the data points for the terminal coordinates are given in two dimensions, latitude and longitude, in the spatial coordinate system EPSG4326. In order to link the terminal coordinates to the land type coordinates, the spatial coordinate system of the terminal coordinates needs to be converted to the EPSG3035 spatial coordinate system. When time averaged, the terminals may therefore be more prone to being sources or more prone to sinks, with certain terminals having high magnitudes of net production or demand whereas others having low magnitudes of net production or demand. The average net production data for Goeree-Overflakkee is presented in Table 1.

Finally, the value of β is set to 0.6, in accordance with the estimate found by (Heijnen et al., 2011). It should be noted that the value of β cannot be chosen, but is a fixed exponent representing the impact of cable capacities compared to cable lengths in the total purchase price of the cable.

Table 1 Average net production data per terminal

Terminal name	**Average net production**	**Terminal name**	**Average net production**
Dirksland	-0.141	Stad aan ‘t Haringvliet	-0.106
Middelharnis	-0.004	Ooltgensplaat	-0.242
Sommelsdijk	-0.839	Den Bommel	-0.163
Herkingen	-0.093	Melissant	-0.039
Nieuwe-Tonge	-0.045	Stellendam	-0.489
Achthuizen	-0.046	Goedereede	-0.218
Oude-Tonge	-0.407	Ouddorp	2.832

5. Results

Using the chosen heuristic to find the Minimum Steiner Tree in Graph and the Network simplex algorithm in order to define capacities, an initial network for Goeree-Overflakkee was found (Figure 3).

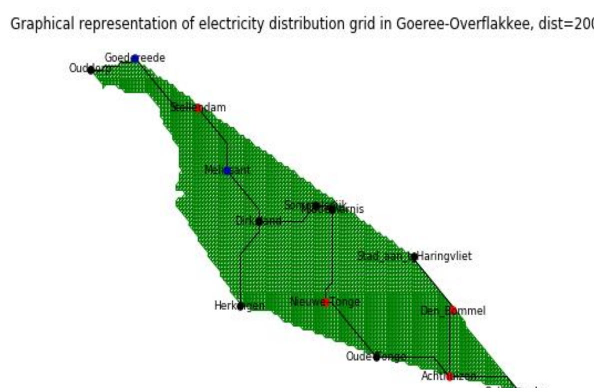

Figure 3 Initial network for Goeree-Overflakkee

After implementing the improvement procedure, it was found that the procedure did indeed make local reconfigurations by considering a non-linear cost function taking both length and capacity into account. After performing the improvement procedure on a subset of timesteps including every first Tuesday and Sunday of each month in a year, it is found that the most frequent reconfiguration occurs for the angle Dirksland, Middelharnis, Nieuwe-Tonge. This reconfiguration is made in 79% of the cases. The reason for the reconfiguration is partly the position of Middelharnis, which deviates from the straight line in the networks and makes the angle a rather long high-capacity cable. By instead connecting Middelharnis using a lower-capacity line, savings can be made.

The second most common reconfiguration is a split point between Ouddorp, Goedereede and Stellendam (Figure 38). This reconfiguration occurs in 53% of the timesteps. Although the angle is relatively large, the high capacities of the cables lead to the high frequency of reconfigurations for this angle.

Thirdly, the angle Goedereede, Stellendam, Melissant is in 21% of the cases reconfigured using a splitpoint. Similarly to the split point connecting Goedereede, the interesting finding is that the network is already relatively straight with a large angle. Due to the high-capacity cables often being required in the North, it is still in some cases reconfigured.

These are the three reconfigurations to be included in the final topology. The network simplex algorithm is thereafter run for 8760 hours during a year and the maximum flow found during the year is set as the edge capacities.

Figure 4 Final network for Goeree-Overflakkee

6. Discussion

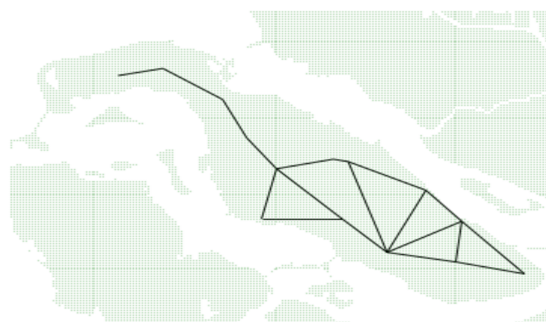

Figure 5 Final network for the simultaneous optimisation of production and topology. Two of the lines in the initial network have been removed as the required capacity was found to be zero.

In order to demonstrate the effectiveness of the proposed methodology for the design of future DNs for Goeree-Overflakkee has been compared to a simultaneous optimisation of both electricity production and grid topology. The simultaneous optimisation starts with an initial network of straight lines between terminals, disregarding unavailable areas. In order to assign capacities, flows through the network are calculated on an hourly basis. The net production data is the same as used in the proposed methodology. The maximum flow found for each line over 8760 hours is thereafter set as the capacity of the line. The final network, taking capacities into account, is presented in Figure 5. The results show that two of the lines are assigned capacities of zero and can be removed from the network.

The total investment costs of the simultaneous optimisation have been compared to the costs of the proposed methodology. The total costs of the proposed method are 13.1% lower than those of the alternative method. This is likely due to the radial topology of the proposed methodology which results in no cycles being present in the final network and due to the reconfigurations made using the improvement procedure. It should also be noted that the edges of the simultaneous optimisation are straight whereas the paths in the proposed methodology, and further savings are therefore expected if the paths were to be straightened. With the use of the proposed reduction techniques, the number of Steiner vertices were reduced by 97%. The number of terminals were also decreased from 14 to 13, which further decreases computational complexity.

Table 2 Overview of method results

Method	**Total length [m]**	**Difference in total investment cost compared to final network [%]**
Final network (Goedereede, Middelharnis, Stellendam)	53 381	0
Simultaneous generation and topology optimisation	96 499	+15.18
Initial network	51 593	+21.28
Alternative network (Goedereede, Middelharnis)	52 919	+2.07

7. Conclusion

The proposed methodology has been created based on the identified requirements of the future DN of Goeree-Overflakkee. By using a repeated Shortest Path Heuristic, assigning capacities using Network Simplex and applying a cost improvement procedure locally, a low-cost network that avoids spatially constrained areas is found. By comparing the proposed methodology to an alternative approach, the methodology has shown to return shorter DNs for the region as well as networks with lower investment costs based on a non-linear cost function.

Further work should incorporate spatial weights in conjunction with the avoidance of unavailable land in order to create even more realistic spatial constraints.

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Appendix B: Results from literature review on mathematical formulations of electricity network optimisations

Author (year)	Degrees of freedom	Method	Objective Function	Constraints	Contribution	Assumptions and shortcomings	Network
(Ergun, 2015)	**Physical** (capacities, edges, AC vs. DC, underground vs. overhead, flows) **Network layout** **Technical components** **Investment time**	MILP using graph theory (Dijkstra and A*)	**Min cost** (investment)	**Physical** (power, capacity), **costs** (average costs per MW), **spatial** (big cities and prohibited zones, incl. spatial cost), **soft** (social, environmental),	Transmission route and technology optimized together. Gets close to global optimum by iterating MILP and graph theory approaches	Soft constraints are difficult to quantify, static nature (assumes transmission grid to be built at once), fixed average costs per branch	**Transmission** - European supergrid
(Aghaei et al., 2014)	**Physical** (Investment in candidate lines, voltage phase angle at each vertex) **Network layout** (whether to invest in units)	MILP	**Min cost** (investment (edges and units) + operation and maintenance of units + VoLL (reliability)	**Physical** (generator capacities, flow constraints, line capacities, voltage angle limits)**, spatial** (candidate generators)	Efficient linear formulations for decreased complexity, multi-objective problem, deals with both generation and transmission planning	Only tested on smaller networks (up to 118 bus system) Does not optimise capacity and length of lines, only chooses the most appropriate lines from a given set	**Transmission** - generic
(Che et al., 2017)	**Physical** (Whether to remove edges)	Probabilistic iterative methodology	**Max reliability**	**Physical, spatial** (candidate edges), **reliability** (min microgrid reliability),	Increases reliability and economics of a community of microgrids	Assumes that all participating microgrids are already connected	**Interconnection** - microgrids
(Chaudry et al., 2014)	**Physical** (edges, flows, compressors, storage) **Network layout**	MINLP	**Min cost** (Investment, operation of units, VoLL)	**Physical** (flow, pressure, compressor and storage constraints)	Allows for interactions between gas and electricity sectors. The model is also creates specifically for Great Britain		**Multiple Energy Carrier System (electricity and gas) –** Great Britain

(Carrano et al., 2006)	**Physical** (edges (length, capacity))	Evolutionary Algorithm	**Min cost** (Investment, power losses, faults (occurrence and duration)) **min system failure index**	**Physical** (edge capacity, min voltage), **spatial**, **reliability**	Can be used for both greenfield design and for system expansion. Useful for decision-making in Investment policy	Tested for 20-100 buses and only finds a Pareto-optimal solution	**Distribution** - Generic (radial)
(Geidl & Andersson, 2006)	**Physical** (Edges, flows)	NLP	**Min total energy cost** (only optimises hubs, not the network itself)	**Physical** (Min and max power in vertices and edges, conservation laws (gas))	Connects electricity, natural gas and district heating	Assumes system operates in steady state. Does not consider constitutional laws (relation between voltage and current)	**Multiple energy carrier system** - generic
(Banzo & Ramos, 2011)	**Physical** (Edges, transformers, power flows)	MINLP	**Min cost** (Investment, power losses, VoLL)	**Physical** (Power flow, only one transformer and cable type allowed)	Includes stochasticity of wind, can be used both onshore and offshore	Assumes wind speed to be spatially uniform and Rayleigh distributed. Does not include other forms of renewable energy sources	**Power system for offshore wind farms**
(Hou et al., 2016)	**Physical** (edges, capacities, voltage level, substation locations) **Network layout**	Graph theory (improved MST) solved using Evolutionary Algorithm	**Min cost** (Investment)	**Physical** (Power flow, cable size constraints)	Optimises wind turbine and substation locations as well as topology. Improvement from MST, as capacities are included.	Varying foundation cost with water depth, cable installation cost, operation and maintenance cost not considered. Does not consider spatial constraints (MST)	**Power system for offshore wind farms (radial)**
(Unsihuay et al., 2007)	**Physical** (flows)	MINLP	**Min cost** (operational)	**Physical** (active and reactive power flow, voltage limits, capacity limits, mass balance equations (gas) and pressure constraints)	The hybrid approach increases precision and decreases computational time. The model is also able to find the neighbourhood of the optimal point instead of just a local	Computationally complex and includes several non-linear and non- convex terms (Partly improved by the hybrid approach). Optimises flows through an existing network only	**Multiple energy carrier system** (electricity and gas) - tested on Belgium gas network

					optimum		
(Hu et al., 2016)	**Physical** (edges, compressors) **Network layout**	MINLP, solved using Evolutionary Algorithm	**Min cost** (Investment, production and CO2 emission cost, load shedding)	**Physical** (Compressor operation constraints, pressure, supply, mass balance, generation, **reliability (N-1))**	Effective way of integrating uncertainty into optimisations. As it is a general approach, it can be further used for other uncertainties than wind speeds, as used here	Finds only Pareto optimal solutions	**Multiple energy carrier system** (electricity and gas)
(Tang, 1996)	**Physical** (edges, flows), **Technical components**	MINLP (solved using flow algorithm)	**Min cost** (Investment, operational, energy losses, outages, maintenance, cost of switching devices)	**Physical** (flows, capacity constraints, radiality constraint, voltage drop), **Reliability**	Includes formulation of how to convert from MINLP to MILP, suitable for large scale problems and especially for developing cities	Limited availability and accuracy of data – may be errors, does not consider spatial constraints	**Distribution** – developing City (radial)
(Chen et al., 2013)	**Physical** (edges (length and capacity))	Fuzzy C-Means (FCM) and Binary Integer Programming (BIP)	**Min cost** (Investment, power losses)	**Physical** (active and reactive power flow constraints, capability limits of the cables, voltage limits for all the buses, radiality constraints)	Reliable way of allocating wind turbines to nearest substations and obtaining the topology structure of cables	Wind turbine locations in the wind farm are assumed available	**Power system for offshore wind farms (radial)**
(Dahmani et al., 2015)	**Physical** (edges, cable sizing) **Technical components (**sub-stations, switchgears)	Evolutionary Algorithm	**Min cost** (Investment)	**Physical** (power limits, placement of sub-stations, discrete sizes), **Spatial** (limited search space**)**	Simplification introduced by removing potential edges with crossing cables	Direct current solution is not included in paper and vertices are assumed given, reliability not considered	**Power system for offshore wind farms (radial)**
(Sensarma et al., 2002)	**Physical** (edges, power) **Technical components Network layout** (Vertices)	Evolutionary Algorithm	**Min cost** (Investment, power loss)	**Physical** (Power flow, security limits), **Spatial** (lakes)	Includes security limits	Effect of deviation of bus voltages are approximated. Further investigation required	**Transmission** – generic
(Enacheanu et al., 2008)	**Physical** (edges,	MINLP using	**Min power losses**	**Physical** (KCL, KVL)	Valid for both planar and		**Distribution** - generic (radial)

	flows)	Evolutionary Algorithm			non-planar graphs		
(Heijnen et al., 2014)	**Physical** (edges, capacity),	MINLP using graph theory	**Max Present Worth Ratio** (Investment, income)	**Physical** (flow constraints), **Spatial**	Simple assumptions and ease of use, incorporates uncertainties using scenarios, uses a density graph in order to take time into account	Does not include specific constraints for electricity networks as it is created on a general basis, does not differentiate between spatial costs	**Generic energy infrastructure**
(Duan & Yu, 2003)	**Physical** (edges (length, capacity))	Evolutionary Algorithm (local CSMT reconfigurations)	**Min cost** (Investment)	**Physical** (no neg. cycles, voltage constraints)	Global searching	Assumption: fixed voltage and no angle when representing demands	**Distribution – generic (radial)**

Appendix C: Experimental results for improvement procedure

Test no.	No. of terminals	List of terminals	Production and demand data	β exponent	Share of unavailable land [x/440]	Improvement [%]
1	9	[431, 122, 74, 323, 433, 317, 151, 113, 319]	[-96, 22, 73, -7, 69, -42, 48, 85, -152]	0.8	60	10.83
2	6	[167, 279, 213, 189, 41, 191]	[66, -20, 16, 94, -41, -115]	0.6	110	0
3	8	[320, 351, 231, 283, 107, 301, 234, 2]	[-16, 55, -71, -76, 22, 65, 88, -67]	0.8	30	1.47
4	9	[198, 115, 366, 305, 260, 53, 375, 412, 116]	[-80, -21, -48, 4, 59, -41, 74, -63, 116]	1.0	50	5.65
5	7	[129, 418, 235, 429, 339, 252, 382]	[-59,45,-100,27, 4, 35, 48]	1.0	70	21.26
6	7	[357, 221, 199, 340, 65, 22, 189]	[86, -43, -11, -16, 0, 52, -68]	0.2	100	0
7	11	[312, 358, 392, 195, 208, 257, 157, 226, 33, 21, 283]	[-41, 8, -34, -19, -37, 33, 54, -70, -90, -77, 273]	0.1	50	0.74
8	7	[265, 88, 397, 296, 9, 158, 27]	[-97, 86, -80, 35, -11, 79, -12]	0.4	10	4.99
9	5	[221, 106, 25, 62, 314]	[98, -29, 65, -100, -34]	0.2	50	9.39
10	12	[352, 34, 40, 73, 335, 148, 20, 182, 154, 285, 94, 159]	[-73, -67, 67, 84, -50, -87, 82, -23, 64, -64, -11, 78]	0.9	10	6.1
11	11	[272, 151, 268, 156, 65, 400, 172, 316, 261, 290, 31]	[-4, 55, 65, -40, 58, -87, 85, 45, -18, 37, -196]	0	20	0
12	7	[49, 363, 22, 29, 316, 63, 382]	[90, -19, -48, -99, 93, -62, 45]	0.8	80	0.09
13	10	[275, 136, 383, 382, 251, 102, 231, 97, 66, 81]	[39, -79, -75, 70, -77, 37, -68, 41, 24, 88]	0.9	20	2.96
14	9	[194, 302, 130, 278, 411, 432, 273, 1, 214]	[-82, -75, 72, 22, 84, -74, 95, -43, 1]	0.8	80	2.78

15	5	[351, 247, 136, 413, 113]	[72, 44, 68, 39, -223]	0.1	30	0
16	9	[389, 39, 361, 271, 145, 309, 344, 156, 222]	[-4, -32, 59, -97, 2, 57, -44, -67, 42, 84]	0.2	80	1.14
17	11	[241, 350, 269, 179, 194, 174, 321, 39, 430, 243, 6]	[60, 51, 16, -39, 27, -88, 12, -72, 40, -56, 49]	0.4	100	5.68
18	7	[417, 418, 66, 39, 8, 234, 313, 186, 380, 93]	[79, -58, 79, -87, 6, 9, -49, 2, 66, -47]	1.0	100	4.53
19	5	[295, 121, 1, 274, 96]	[-54, 11, 34, 17, -8]	1.0	50	5.41
20	5	[201, 154, 357, 282, 72]	[-88, 16, -38, 31, 79]	0.3	40	6.4
21	11	[174, 188, 340, 122, 348, 396, 142, 284, 308, 15, 304]	[-54, -33, 51, -57, -11, -2, 59, 1, 68, -8, -14]	0.9	90	0
22	11	[428, 148, 260, 263, 120, 294, 287, 305, 311, 301, 376]	[-63, 83, -10, -28, 16, 81, 64, -67, -4, 74, -146]	0.1	60	1.57
23	5	[228, 203, 238, 17, 114]	[-98, -81, -28, 69, 138]	0.1	0	12.32
24	8	[206, 389, 120, 130, 54, 413, 40, 262]	[-60, -42, -60, 69, -19, 72, -78, 118]	0.6	50	5.64
25	6	[260, 293, 366, 176, 116, 54]	[55, -89, -35, 84, -69, 54]	0.8	50	0
26	5	[424, 73, 360, 429, 141]	[88, 66, -20, -15, -119]	0.4	100	6.59
27	11	[183, 396, 35, 197, 315, 352, 432, 434, 364, 339, 223]	[12, -14, -22, 68, 51, 75, -21, -91, 83, -98, -43]	0.8	90	8.65
28	6	[352, 395, 268, 52, 87, 127]	[47, 78, 30, -53, -70, -32]	0.3	60	3.5
29	10	[225, 33, 99, 100, 297, 142, 308, 340, 342, 20]	[92, 45, -88, 16, -92, -40, 73, 65, 53, -124]	0.7	60	3.53
30	5	[30, 409, 250, 92, 254]	[21, -62, 56, -84, 69]	0.4	70	0

31	7	[226, 422, 368, 315, 212, 186, 59]	[-29, 59, -67, -98, 31, -11, 115]	0.7	60	9.64
32	12	[257, 133, 383, 137, 298, 365, 174, 143, 78, 113, 185, 319]	[76, -38, 93, -32, 67, -88, 65, -32, 51, 27, -54, -135]	0.1	80	2.07
33	7	[416, 34, 298, 431, 405, 184, 380]	[51, -88, -63, 90, -34, -68, 112]	1.0	70	0.69
34	12	[2, 261, 73, 393, 271, 143, 315, 438, 407, 409, 346, 91]	[-90, -99, 38, 93, -63, -47, -97, -7, -72, 70, 80, 194]	0.6	50	3.71
35	9	[109, 302, 239, 82, 277, 55, 249, 27, 183]	[35, -35, -97, 90, 31, 11, -78, 88, -45]	0.1	90	0
36	8	[199, 266, 171, 333, 270, 82, 251, 316]	[84, -66, 32, -70, 24, -5, 88, -87]	0.2	50	4.24
37	10	[103, 218, 138, 74, 394, 10, 398, 335, 341, 58]	[65, 91, 93, 64, 10, 31, -11, -21, -27, -295]	1.0	40	4.84
38	9	[193, 202, 75, 300, 270, 60, 376, 120, 221]	[-25, -49, 23, -38, 51, 78, 21, -91, 30]	0.2	30	0
39	7	[256, 96, 333, 47, 16, 405, 214]	[-84, -88, 71, -99, 84, 68, 48]	1.0	80	8.68
40	9	[129, 98, 440, 16, 113, 371, 373, 408, 249]	[-52, 87, -60, -18, -57, -46, 63, 6, 77]	1.0	80	4.84
41	8	[71, 295, 73, 426, 106, 221, 25, 285]	[-22, 46, 82, 22, -89, -34, 100, -105]	0.2	100	1.96
42	12	[97, 1, 34, 422, 368, 275, 151, 440, 281, 88, 253, 287]	[65, 40, 13, 88, 15, 18, 62, 52, -60, 74, 16, -383]	1.0	50	10.3
43	8	[322, 38, 361, 107, 336, 304, 49, 31]	[-73, 85, 11, 66, -94, -63, -31, 99]	0.5	10	2.79
44	5	[175, 114, 214, 407, 152]	[-23, 69, -16, -14, -16]	0.7	90	11.95
45	10	[196, 132, 166, 8, 139, 82, 55, 312, 412, 188]	[95, -4, -47, -54, 35, -42, -99, 23, 29, 64]	0.4	10	1.06

46	6	[232, 250, 334, 177, 212, 410]	[76, 6, -51, 44, -36, -39]	0.7	10	11.74
47	10	[390, 137, 329, 234, 429, 143, 148, 213, 381, 95]	[-87, 6, 96, 40, 86, -45, 86, 27, 57, -266]	0.3	20	2.25
48	7	[198, 8, 49, 278, 23, 218, 348]	[-60, -38, -41, -93, 19, -79, 292]	0.7	100	0
49	7	[352, 5, 204, 372, 23, 314, 156]	[-4, -54, 70, -38, 47, 99, -120]	0.6	100	17.3
50	11	[384, 65, 99, 325, 264, 204, 239, 369, 146, 19, 409]	[384, 65, 99, 325, 264, 204, 239, 369, 146, 19, 409]	0.6	90	3.95

Appendix D: Occurrence of land use types in Goeree-Overflakkee

Grid Code	CLC Code	Land Category	Land type
1	111	Artificial surfaces	Continuous urban fabric
2	112	Artificial surfaces	Discontinuous urban fabric
3	121	Artificial surfaces	Industrial or commercial units
4	122	Artificial surfaces	Road and rail networks and associated land
5	123	Artificial surfaces	Port areas
6	124	Artificial surfaces	Airports
7	131	Artificial surfaces	Mineral extraction sites
8	132	Artificial surfaces	Dump sites
9	133	Artificial surfaces	Construction sites
10	141	Artificial surfaces	Green urban areas
11	142	Artificial surfaces	Sport and leisure facilities
12	211	Agricultural areas	Non-irrigated arable land
13	212	Agricultural areas	Permanently irrigated land
14	213	Agricultural areas	Rice fields
15	221	Agricultural areas	Vineyards
16	222	Agricultural areas	Fruit trees and berry plantations
17	223	Agricultural areas	Olive groves
18	231	Agricultural areas	Pastures
19	241	Agricultural areas	Annual crops associated with permanent crops
20	242	Agricultural areas	Complex cultivation patterns
21	243	Agricultural areas	Land principally occupied by agriculture, with significant areas of natural vegetation
22	244	Agricultural areas	Agro-forestry areas
23	311	Forest and semi natural areas	Broad-leaved forest
24	312	Forest and semi natural areas	Coniferous forest
25	313	Forest and semi natural areas	Mixed forest
26	321	Forest and semi natural areas	Natural grasslands
27	322	Forest and semi natural areas	Moors and heathland
28	323	Forest and semi natural areas	Sclerophyllous vegetation
29	324	Forest and semi natural areas	Transitional woodland-shrub
30	331	Forest and semi natural areas	Beaches, dunes, sands
31	332	Forest and semi natural areas	Bare rocks
32	333	Forest and semi natural areas	Sparsely vegetated areas
33	334	Forest and semi natural areas	Burnt areas

34	335	Forest and semi natural areas	Glaciers and perpetual snow
35	411	Wetlands	Inland marshes
36	412	Wetlands	Peat bogs
37	421	Wetlands	Salt marshes
38	422	Wetlands	Salines
39	423	Wetlands	Intertidal flats
40	511	Water bodies	Water courses
41	512	Water bodies	Water bodies
42	521	Water bodies	Coastal lagoons
43	522	Water bodies	Estuaries
44	523	Water bodies	Sea and ocean
48	999	No data	No data
49	990	Unclassified	Unclassified land surface
50	995	Unclassified	Unclassified water bodies
255	990	Unclassified	Unclassified