University of Zurich^UZH

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

MASTER'S THESIS

GEO 511

A Novel Approach to the Routing Problem of Overhead Transmission Lines

Department of Geography
Geographic Information Science
University of Zurich

Institute of
Cartography and Geoinformation
ETH Zurich

Submission Date: April 21, 2017

Author:
Nadine PIVETEAU
Student-ID: 10-726-776

Advisors:
Prof. Dr. Robert WEIBEL
Prof. Dr. Martin RAUBAL
Joram SCHITO

Faculty Representative:
Prof. Dr. Robert WEIBEL

Contact

Author:
Nadine Piveteau
Alte Landstrasse 158
8800 Thalwil - Switzerland
`nadine.piv@gmail.com`

Advisors:
Prof. Dr. Robert Weibel
Geographic Information Science (GIS)
Department of Geography
University of Zurich
Winterthurerstrasse 190
8057 Zurich - Switzerland
`robert.weibel@geo.uzh.ch`

Joram Schito
Geoinformation Engineering
Institute of Cartography and Geoinformation
ETH Zurich
Stefano-Franscini-Platz 5
8093 Zurich -Switzerland
`jschito@ethz.ch`

Prof. Dr. Martin Raubal
Geoinformation Engineering
Institute of Cartography and Geoinformation
ETH Zurich
Stefano-Franscini-Platz 5
8093 Zurich - Switzerland
`mraubal@ethz.ch`

Abstract

The current Swiss electricity grid is facing major challenges. It is out-dated and thus urgently in need of renewal and modernization. Despite the pressing problem, the expansion and modernization of the Swiss electricity grid is proceeding slowly due to the lengthy and complex planning procedure of transmission lines. GIScience can contribute to the acceleration of this process by providing decision support techniques.

The objective of this Master's thesis is to develop a novel approach to model the optimal route for overhead transmission lines. Previous work mainly applied raster-based methods, which aimed at determining the optimal route from a spatial planning, environmental and landscape protection perspective.

By contrast, the approach of this Master's thesis additionally integrates technical criteria into the route computation of transmission lines. To that end, an algorithm based on graph theory has been implemented. The vertices of the graph represent the transmission towers and the edges the conductors between two consecutive towers. The optimal route corresponds to the path in the graph that optimally respects spatial planning, environment as well as landscape criteria and also considering technical aspects of transmission lines. The technical aspects have been incorporated into the graph as both, constraints and optimization criteria.

The novel approach was tested by computing the optimal route in a mountainous terrain between two places that are located about 60 kilometers away from each other. In order to quantify the improvements of the novel approach, its results have been systematically compared to the ones obtained from the baseline method. The baseline method is raster-based and represents the current state-of-the-art approach to model transmission lines. Both approaches are contrasted with each other by means of a quantitative and a qualitative evaluation. The outcomes show that there are major differences between both approaches and that in many respects, the novel approach provides better results. As the main difference between both methodologies is the inclusion of the technical aspects, the impact and importance of the criteria considered in route computation are analyzed by means of a sensitivity analysis. Furthermore, the applicability of the novel approach in practice has been addressed. Examinations have revealed the potential of the novel approach to contribute to the planning procedure of transmission lines.

Acknowledgements

First and foremost, I would like to thank my advisor Joram Schito for the invaluable support and his encouraging words. Our long brainstorming sessions helped me a lot to bring structure into my work. Another big thank you goes out to my main advisor Prof. Dr. Robert Weibel. He gave me regularly precious advices and shared his knowledge during struggles. I also want to thank Prof. Dr. Martin Raubal for his support in the problem formulation. Further, I'm also grateful for the precious hints and feedbacks provided by Dr. Stefano Grassi und René Buffat.

I would also like to thank the experts from Swissgrid AG, BKW and AF-Consult AG, who spent ample time responding to my questions. They had a strong contribution to the evaluation of the results. Thus, a big thank you to Martin Weber, Marcel Stöckli, Thomas Lustenberger, Marc-André Hunziker, Thomas Segura and Jürg Morgenegg.

My special thanks go to Laura Piveteau, Christophe Piveteau and Sandro Felicioni, who supported me throughout this last year. Thank you for the proof reading, for helping me out when my hard disk failed, for your support with programming-related problems and for your continuous encouragement in difficult times.

Last but not least, I want to thank the rest of my family and my friends helping me throughout my years of study!

To all of you (and those who I have forgotten), a big thank you!

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List of Abbreviations

BAFU	Federal Office of the Environment (**B**undesamt **f**ür **U**mwelt)
BFE	Federal Office of Energy (**B**undesamt **f**ür **E**nergie)
BLN	Federal Inventory of Landscapes, Sites, and Natural Monuments of National Importance (**B**undesinventar der **L**andschaften und **N**aturdenkmäller von nationaler Bedeutung)
BUWAL	Swiss Agency for the Environment, Forest and Landscape (**B**undesamt für **U**mwelt, **Wa**ld und **L**andschaft)
ElCom	Swiss Federal **El**ectricity **Com**mission (Eidgenössische Elektrizitätskommission)
ESTI	Federal Inspectorate for Heavy Current Installations (**E**idgenössische **St**arkstrom**i**nspektorat)
GSchV	Water Protection Ordinance (**G**ewässer**sch**utz**v**erordnung)
ISOS	Federal, Inventory of Valuable Sites of Local Character (Bundes**i**nventar der **s**chützenswerten **O**rtsbilder der **S**chweiz von nationaler Bedeutung)
IVS	Inventory of the Historical Traffic Roads (Bundes**i**nventars der historischen **V**erkehrswege der **S**chweiz)
LCP	**L**east **C**ost **P**ath
NISV	Ordinance on Non-Ionising Radiator (**V**erordnung über den Schutz vor **n**ichtion**i**sierender **S**trahlung)
OMEN	Places with sensitive use (**O**rte **m**it **e**mpfindlicher **N**utzung)
RQ	**R**esearch **Q**uestion
SÜL	Transmission Lines sectoral plan (**S**achplan **Ü**bertragungs**l**eitungen)
SEN	Energy Network sectoral plan (**S**achplan **E**ergie**n**etze)
WaG	Federal Law on Forests (**Wa**ld**g**esetz)
WZVV	Ordinance on water bird and migratory bird reserves of international and national importance (**V**erordnung über die **W**asser- und **Z**ug**v**ogelreservate von internationaler und nationaler Bedeutung)

Chapter 1

Introduction

1.1 Motivation

The current Swiss electricity grid is facing major challenges in terms of planning transmission lines[1]. It is out-dated and thus urgently in need of renewal and modernization. Almost two thirds of the existing transmission lines were built in the 1950's until 1960's (Swissgrid AG 2017*c*). Many of them do not meet present-day standards since they were designed for lower voltage and aimed to transport electricity produced in centralized power plants (Bundesamt für Energie BFE 2016). Considering the continuously increasing electricity consumption, the Swiss electricity grid is about to reach its saturation point and several transmission lines are concerned by electricity supply bottlenecks. Furthermore, the current electricity grid will have to adapt to new circumstances given changes expected in the electricity production in the near future. Today, two thirds of the electricity is produced in centralized nuclear and storage power plants. Regarding the energy revolution and the ongoing nuclear phase-out, renewable energy will become increasingly important. Renewable energy is typically produced in small-scaled energy generation plants, which, in contrast to centralized large-scaled power plants, feed the produced electricity into the distribution grid. In addition, it is produced on an intermittent base, i.e. it is not continuously available due to external factors. Measures need to be taken in order to prepare the electricity grid to the new requirements of decentralized electricity production systems based on renewable energies. Moreover, in the last couple of years Switzerland has become increasingly dependent on electricity import and thus, the Swiss electricity network needs to meet requirements prescribed by the European Union. In the next decades, a smart and modern electricity grid is necessary to tackle these challenges.

Despite the urgency of this problem, the expansion and modernization of the Swiss electricity grid is proceeding slowly. From the launch of a transmission line project until its actual realization it takes on average 9 to 12 years. Objections from the population or decisions of the Federal Supreme Court can entail drastic changes at a late stage in the transmission line project and thus lead to delays of up to 30 years (Swissgrid AG 2017*c*). Furthermore, the planning pro-

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[1] When speaking about transmission lines, overhead transmission lines are meant.

cedure has become more complex. In the last decades numerous laws and ordinances have been issued that prescribe measures to protect the environment and landscape. Thus, in addition to the technical and financial aspects, criteria concerning the environment and landscape have to be respected in a transmission line project.

In order to reduce the duration required to build transmission lines, it would therefore be beneficial to optimize the planning procedure. GIScience can contribute to the acceleration of this process by providing decision support techniques and hence allow a transparent, sustainable and faster planning process of electric supply grids.

1.2 Scientific Motivation

The scientific motivation of this Master's thesis is to introduce a novel approach of modeling the optimal route for overhead transmission lines. Previous work mainly applied raster-based methods, which aimed at determining the optimal route from a spatial planning, environmental and landscape protection perspective. So far, technical aspects such as the type of transmission towers or the terrain situation have only been taken into account once the route was determined and the exact position of the towers had to be fixed. In contrast to previous work, this Master's thesis introduces a novel approach, which integrates technical criteria into the route computation of transmission lines while still considering spatial planning, environment and landscape criteria.

This Master's thesis is integrated in the research project *Application of 3D Geographic Information Systems for transparent and sustainable planning of electric power systems* at ETH Zurich. This project aims at developing a 3D GIS web-platform on which the optimal route of a transmission line can be modeled. It should promote negotiations among all involved stakeholders and enhance acceptance in the population for electric linear infrastructures.

1.3 Problem Definition

Determining optimal routes for transmission lines is a challenging task. The optimal route corresponds to the transmission line whose construction causes minimum costs. These costs are not necessarily of monetary nature, but are to be understood in an abstract sense. They rather express the impact and conflicts transmission lines cause and can be described based on three dimensions:

- *Spatial planning dimension*: This dimension describes how the human and urban environment is affected by transmission lines in terms of proximity and visibility. Transmission lines need to comply with the distance limitations defined by the Ordinance on Non-Ionizing Radiation (Verordnung über den Schutz vor nichtionisierender Strahlung NISV (1999)) in order to protect the population against established health hazards caused by exposure to electric and magnetic fields (Bundesamt für Umwelt, Wald und Landschaft BUWAL 2005). Furthermore, Bevanger et al. (2014) and Grassi et al. (2014) found evidence that high visible impact of transmission lines often incite citizens to object and thus, impede a transmission line project. Due to the low public acceptance of transmission lines, this dimension is of great importance for the planning of the transmission grid.

- *Environment and landscape dimension:* According to the assessment scheme of transmission lines (Bundesamt für Energie BFE 2013), various environmental legislations must be taken into account. There are clear specifications how forests, biotopes and the aquatic environment should be dealt with. Furthermore, it is important to guarantee that transmission lines affect the landscape as little as possible.
- *Technical implementation dimension:* This dimension involves criteria which characterize the technical implementation of the transmission lines and is closely coupled with the economic drivers of transmission lines. The angle of deflection as well as the subsoil, for instance, influence which type of tower and foundation is needed, respectively. Moreover, the transmission towers have to be placed such that the terrain is optimally considered and the sag of the conductor respects the ground clearance stipulated by law.

By optimizing the above-mentioned dimensions, the impact on the landscape, the urban and the natural environment should be minimized and the technical implementation of transmission lines optimized. The aim of this Master's thesis is to combine these three dimensions in order to compute the optimal path for transmission lines. The focus lies on the implementation and investigation of the additionally defined technical criteria.

1.4 Objective and Research Questions

In order to tackle the problem defined above, a novel approach based on graph theory and GIS techniques will be introduced. The insights gained in the analysis of the newly integrated technical properties are expected to improve the modeling of the optimal route and thus the improvement of the transmission line planning process. In order to identify and analyze the added value of the novel approach, it will be systematically compared to a baseline method, which corresponds to the state-of-the-art approach for modeling transmission lines. The following research questions will be addressed and answered in this Master's thesis.

> ***RQ1:*** *How do the baseline method and the novel approach differ in terms of the three dimensions (1) Spatial Planning, (2) Environment and Landscape as well as (3) Technical Implementation?*
>
> ***RQ2:*** *How and to which extent do the integrated technical criteria impact the course of the route?*
>
> ***RQ3:*** *To which extent is the novel approach applicable in practice and how does it contribute to the planning procedure of transmission lines?*

The first two questions aim at comparing the state-of-the-art method and the novel approach. It is expected that the novel approach will shorten, smoothen and thus, reduce the construction costs of transmission lines while considering aspects from both dimensions, spatial planning as well as environment and landscape. It is anticipated that technical criteria have a significant impact on the computation of the optimal route.

In order to answer *RQ1*, the resulting routes of the baseline method and the novel approach will be evaluated in a quantitative and qualitative analysis. Properties of the routes are captured in the form of indicators, which allow to quantitatively compare the baseline method with the novel approach. In order to complete the results of the quantitative analysis, inputs from interviews, which have been conducted with experts from the energy sector, are included. *RQ2* will be tackled by performing a sensitivity analysis.

Given that the scientific motivation is to contribute to the improvement of the planning procedure of transmission lines, the third question addresses the applicability of the novel approach in practice. It is expected that the modeled route computed by the novel approach will provide new insights for the planning procedure of transmission lines thanks to the newly integrated technical criteria. The experts with whom interviews are conducted are expected to provide answers to this question.

1.5 Thesis Organization

In order to answer the above formulated research questions, this Msc thesis will be structured as follows: Chapter 2 gives a general overview of transmission lines in Switzerland. The literature review in Chapter 3 provides a theoretical background to the routing problem for transmission lines. In Chapter 4, the methodology is discussed. To that end, the transmission line routing problem tackled in this Master's thesis is defined and both approaches, the baseline method and the novel approach, are introduced. The results of both methods are presented in Chapter 5.1 and evaluated quantitatively and qualitatively in the Chapters 5.2 and 5.3. The insights gained from the results and their evaluation are then used to discuss the research questions in Chapter 6. The main findings are summarized and an outlook for further research is provided in Chapter 7.

Chapter 2

The Swiss Transmission Network

The future development of the Swiss transmission network is a subject of wide-ranging debate, due to the energy revolution and the ongoing nuclear phase-out. This chapter provides a brief overview of the transmission network of Switzerland and its situation today. The challenges encountered by the Swiss transmission network are summarized. The suggested federal program to tackle these challenges, i.e. the *Strategic Network 2025*, is introduced. Smart grids are objectives of the Swiss transmission network and will be introduced in Section 2.4.

2.1 The Current State of the Electricity Supply System

The Swiss electricity grid links the electricity production and consumption. Its proper functioning preserves the Swiss population and the economy from harmful consequences, which a power failure would engender. The Swiss electricity grid encompasses 250'000 kilometers of lines and is organized hierarchically in seven grid levels (see Figure 2.1). The grid levels 1, 3, 5 and 7 represent the actual network and cover each a certain voltage range. They can be subdivided into the transmission and the distribution network. The sequence of the different transmission systems and transformers represent the course of electricity from the suppliers to the households.

This thesis will focus on the transmission network. It encompasses transmission lines at voltages from 220 to 380 kV, summing up to a total length of 6'700 km (see Figure 2.2) (Swissgrid AG 2017*c*). This type of transmission lines corresponds to the network level 1.

In 2013, the national grid operator Swissgrid AG became the official owner of the Swiss transmission network taking along-going responsibilities for the maintenance, the modernization as well as the demand-oriented expansion of the transmission network. Since 2012, Swissgrid is owned in its totality by the following shareholders: the electricity companies Alpiq AG, Alpiq Suisse AG, Axpo AG, Axpo Trading AG, BKW Energie AG, Zentralschweizerische Kraftwerke AG (CKW), Elektrizitätswerk der Stadt Zürich (ewz) and Repower AG (Swissgrid AG 2016).

The Swiss transmission network evolved from the necessity to transport electricity produced at centralized power plants in the Alps and at the rivers, to the consumers, who have been

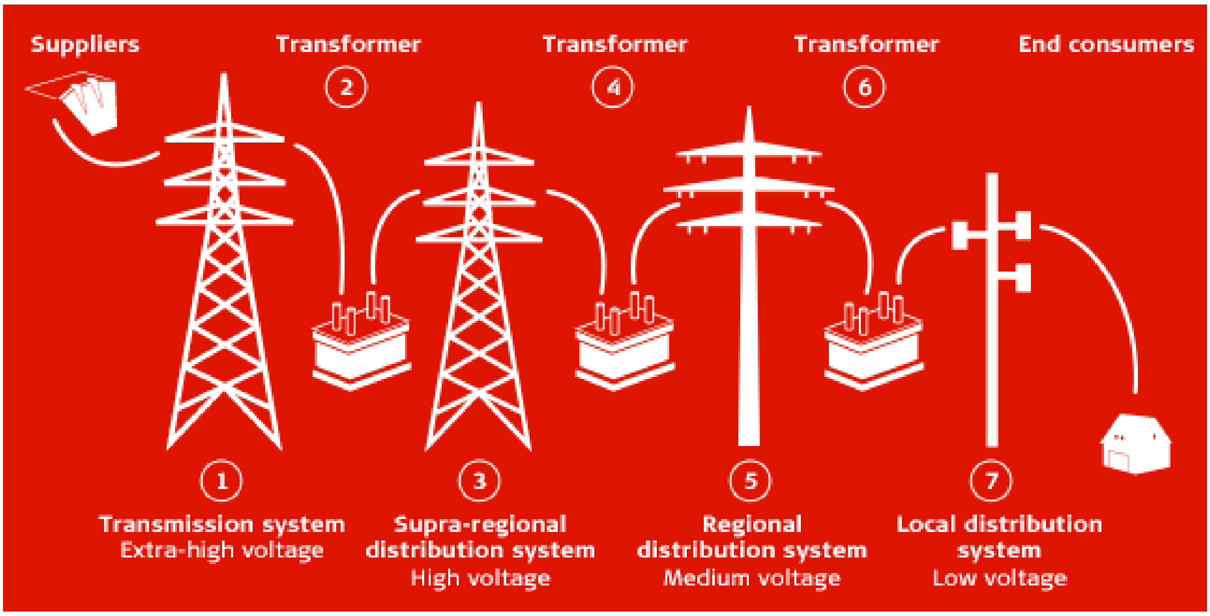

Figure 2.1 – Grid levels 1 to 7 of the Swiss electricity grid: The odd numbers represent the actual transmission network, whereby each level covers a different voltage range. Grid level 1 encompasses the transmission network, whereas the grid levels 3,5 and 7 build the distribution system. Grid levels with even numbers correspond to the transformers which convert high-voltage electricity produced in power plants into low-voltage electricity for use at the consumption point (Swissgrid AG 2017*d*).

living mainly in the Swiss central plateau (Akademien der Wissenschaften Schweiz (Ed.) 2012). In 1953, the first transmission lines at voltages of 220 kV have been built. Only twelve years later, the first 380 kV transmission line was commissioned. As the expansion of the hydropower production slowed down and the electricity demand continuously increased, the first nuclear power stations were built. First, Beznau 1 was constructed in 1969, then, Benznau 2 in 1971 and one year later followed Mühlenberg in 1972. Six and eleven years later, respectively, the nuclear power plants at Gösgen and Leibstadt were erected (Haemmerle 2001). During this period of nuclear power plants construction, two thirds of the transmission lines of today's grid were built (Swissgrid AG 2017*c*). The objectives pursued at that time were on the one hand, that transmission lines should be as cheap as possible regarding the growing economy and population and on the other hand, that they should ensure a high level of supply security (Akademien der Wissenschaften Schweiz (Ed.) 2012).

However, since then the value system considered during the planning process of transmission lines has changed. Human intervention in the landscapes as well as the impact on conservation areas is attempted to be kept as low as possible. To that end, new laws have been enacted such as the Spatial Planning Act or the Environmental Protection Act. Today, a compromise is sought, which takes into account economic aspects but at the same time considers urban and environmental issues.

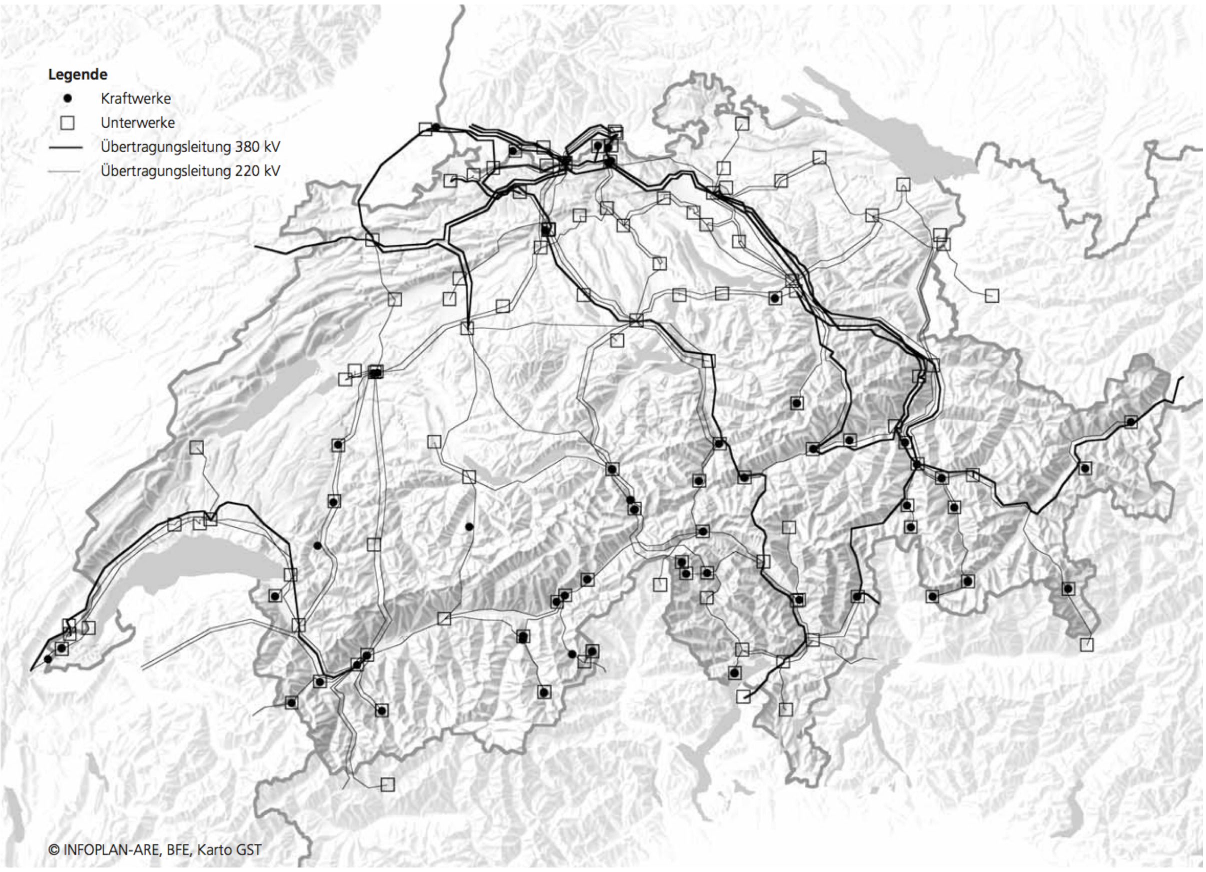

Figure 2.2 – The Swiss transmission network, which consists of transmission lines at a voltage of 220 (grey) to 380 kilo volts (black) (Bundesamt für Energie BFE 2001).

2.2 Challenges of the Swiss Transmission Grid

Today's transmission network in Switzerland is facing major challenges. As mentioned before, almost two thirds of the existing transmission lines were built in the 1950's and 1960's. Furthermore, they were designed for lower voltage. As the transport capacity of electricity is larger than the technically limited capacity of transmission lines, bottlenecks in the electricity supply arise. The red thick lines in Figure 2.3 correspond to transmission lines with high risk of bottlenecks which Swissgrid is about to remove by modernizing and expanding today's transmission network. Causes for these bottlenecks are the increasing electricity consumption due to liberalization of the electricity market and the delayed grid construction, which is lacking in efficiency and suffers of poor coordination in the planning procedure (Akademien der Wissenschaften Schweiz (Ed.) 2012). Despite this precarious situation of the Swiss transmission network, its renewal and expansion is progressing slowly (Swissgrid AG 2012). This is due to the challenges described in the following sections.

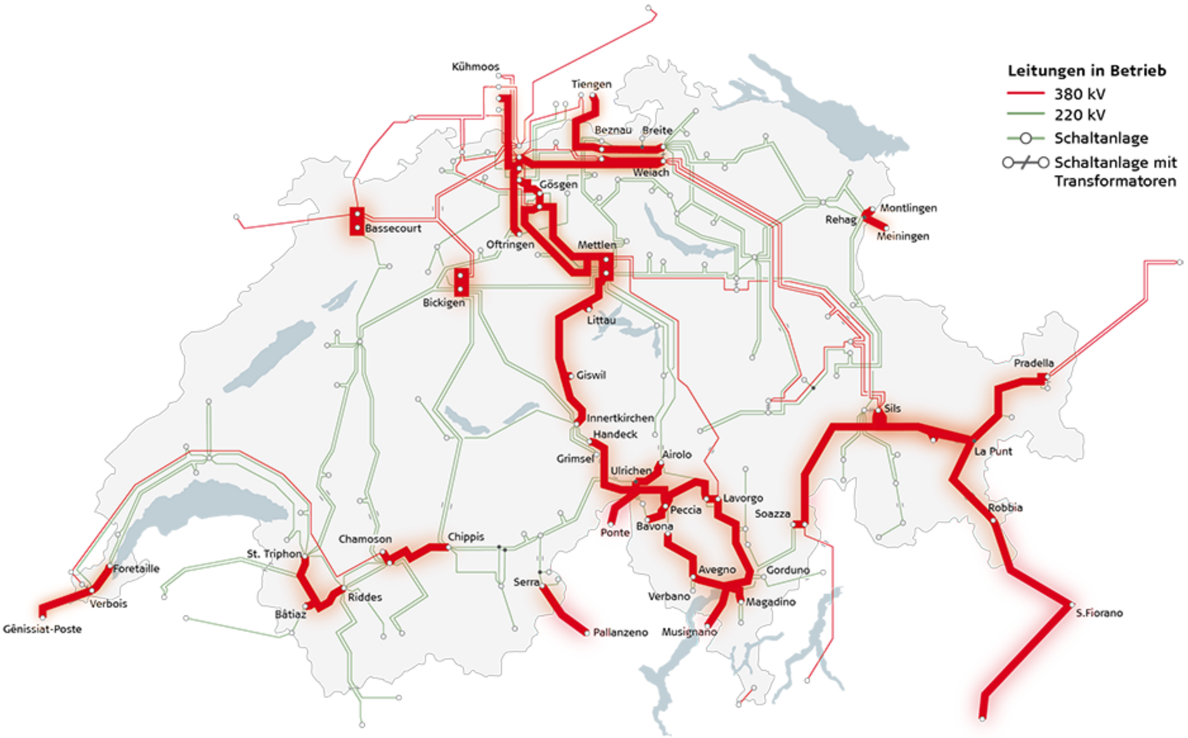

Figure 2.3 – The bottlenecks in the Swiss transmission network according to Swissgrid AG (2012) are represented as thick red lines. They have to be eliminated in order to enhance the security of supply in Switzerland.

2.2.1 Challenge 1: Project Planning of Transmission Lines

One reason for the slow progress of the renewal and expansion of the Swiss electricity network is the lengthy process from the launch of a transmission line project until its actual realization. The planning procedure consists of the following stages (Rendigs 2016):

1. The planning procedure starts with the **sectoral plan** of transmission lines (Sachplan Übertragungsleitungen SÜL), the main planning and coordination tool to realize a transmission line project. Its primary goal is to determine a suitable corridor[1] for transmission lines based on aspects regarding settlements, landscape and the environment (Bundesamt für Energie BFE 2001).

2. Once the sectoral plan is established, the concrete transmission line is developed in the **detailed plan**.

3. The transmission line and the corridor are then the subject of the **environmental impact assessment** by the Swiss Agency for the Environment, Forest and Landscape (Bundesamt für Umwelt, Wald und Landschaft BUWAL).

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[1] The corridor corresponds to the surface most suited for siting new transmission lines. Within this area, the route is defined.

4. The Federal Inspectorate for Heavy Current Installations (Eidgenössisches Starkstrominspektorat ESTI) examines the legality of the construction project in terms of technical aspects as well as environmental concerns leaning on BUWAL's environmental impact report. They determine the final transmission line, which is realized by the project applicant Swissgrid.

The entire procedure takes on average 5 to 13 years as a consequence of the lengthy approval procedure (Swissgrid AG 2017*c*). Due to objections from affected citizens or judgments of the Federal Supreme Court at a late stage of the project, several years can elapse (Bundesamt für Energie BFE 2015*b*, Elektrizitätskommission ElCom 2016). Delays of 30 years can be the consequence when in the course of the planning process unplanned changes are made, such as switching from a transmission line to a cable solution. In such cases, the project planning goes back to square one (Swissgrid AG 2012).

In addition to the lengthy approval process, another reason for the slow progress of transmission line projects is the low acceptance for network infrastructure projects among the population (Bundesamt für Energie BFE 2015*b*). In the Swiss population, a *Not-In-My-Backyard* (NIMBY) attitude can be observed (Wohlfahrtstätter & Boutellier 2010). People want to benefit from the stable energy supply guaranteed by a well-functioning grid but at the same time refuse to accept any restrictions caused by transmission lines (Devine-Wright 2013). Some of the appeals against the transmission line projects are due to the impact on the landscape. In this context Gill et al. (2006) differentiate between the visual impact and the negative effect on property values caused by transmission lines. On the one hand, people complain about transmission lines altering the scenery of a region. On the other hand, the construction of transmission line has a negative impact on property values. Other appeals are lodged against the exposure to electromagnetic fields. The electric and magnetic fields can be summarized as non-ionising radiation, also colloquially called *electrosmog* (Akademien der Wissenschaften Schweiz (Ed.) 2012). In Switzerland, the Ordinance on Non-Ionising Radiation (Verordnung über den Schutz vor nichtionisierender Strahlung NISV (1999)) aims at protecting the population from adverse health effects caused by transmission lines.

2.2.2 Challenge 2: Decentralized Electricity Production

Nowadays, electricity is produced in large centralized power plants. Nearly 59.9% of the electricity is being produced in hydroelectric power plants and 33.5% in atomic power stations. This generated energy is introduced into the transmission system of the electricity grid in order to be transported to the households. Of the remaining 6.6 % only 4.3% is generated from renewable energies. The remainder corresponds to the electricity production in conventional thermal district heating plants (Bundesamt fur Energie BFE 2015*a*).

Considering the ongoing energy revolution, this share is expected to change in the near future. The energy production will have to be continuously restructured in order to integrate the intermittent production of renewable energies[2]. In contrast to centralized power generation systems, electricity produced by renewable energies, such as photovoltaic or wind power

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[2] Renewable energies are intermittent energy sources given that they are weather-dependent and thus not continuously available.

systems, is usually fed directly into the distribution grid. However, the current distribution system is not equipped with the technology to be introduced with intermittent energy sources. This has structural consequences for the entire electricity grid and bears risks for the grid's stability. In order to allow intermittent electricity feed-in from renewable energies, the technical infrastructure as well as the transmission capacity of transmission networks needs to be updated. Decentralized energy generation systems have to be established in order to meet the higher requirements of renewable energies (Akademien der Wissenschaften Schweiz (Ed.) 2012).

2.2.3 Challenge 3: Connection to the International Electricity Market

The Swiss electricity industry has been playing an active role in the European electricity trading for more than 50 years. This is *inter alia* due to Switzerland's geographically central position. For many decades, Switzerland exported electricity thanks to the high production reserves. However, given the continuously rising electricity consumption and the relatively slow increase of electricity production, the foreign electricity import share has been growing in the past years, especially during the winter months (Akademien der Wissenschaften Schweiz (Ed.) 2012).

It is therefore even more important to adapt the Swiss electricity grid not only to the domestic requirements but also to those of the neighboring countries. Bottlenecks in the Swiss electricity grid could affect the import and export of energy and need to be eliminated (Akademien der Wissenschaften Schweiz (Ed.) 2012). Due to the increase in electricity import from intermittent renewable energies, the network technology and the Swiss power market need to be tightly linked to Europe. How the European requirements to the Swiss electricity grid will develop remains nevertheless unclear and strongly dependent on changes in the energy policies of the neighboring countries, such as the nuclear phase-out in Germany (Bundesamt für Energie BFE 2015*b*).

2.3 Strategic Network 2025

As key element of the *Energy Strategy 2050*, the concept *Strategic Network 2025* (Bundesamt für Energie BFE 2015*b*) has been established in order to provide a new legal framework for the grid development and hence better conditions for urgent grid renewal and expansion. The Federal Council has adopted this concept in June 2013 based on which the Federal Department of the Environment, Transport, Energy and Communications (DETEC) prepared a draft legislation between November 2014 and March 2015. In April 2016, the Federal Council has approved DETEC's dispatch on the Federal Act on the renewal and expansion of the electricity grid, i.e. the Strategic Network 2025, and brought it to parliament for consideration.

The previous grid development procedure based on the SÜL (Bundesamt für Energie BFE 2001), was driven by the fact that there were no binding guidelines of the Federation regarding the renewal and expansion of the electricity grid. According to the concept *Strategic Network 2025*, the process previously was not transparent and did not take into account future requirements, e.g. the integration of decentralized energy production. Tasks and roles were not clearly assigned to the involved stakeholders. These weaknesses of the previous grid development procedure lead to investment and planning uncertainties.

The Strategic Network 2025 is supposed to be a first step towards smart grids and towards a demand-oriented as well as sustained acceleration of the grid development. Its main goal is to provide precise and clear specifications for the grid development and optimization. On the one hand, the approval procedure of grid construction projects needs to be improved and accelerated. On the other hand, it is envisaged to increase the acceptance of electricity network projects by involving concerned stakeholders and the public into the planning process in order to foster transparency. To hat end, a new procedure of grid development has been established:

1. As the previous procedure describes, the sectoral plan is first established. In the concept Strategic Network 2025, the SÜL is upgraded to the *Energy Network* sectoral plan (Sachplan Energienetze (SEN)). The SEN is divided into a preparatory and two further stages. At the end of each stage, a decision is taken, such that after each step the grid development process becomes more concrete. In procedural terms, this newly structured planning process aims at guaranteeing legal, planning and investment security.

   In the preparatory phase, the project applicant Swissgrid and the concerned cantons agree on common goals. The responsibilities and competences as well as the schedule are specified. Based on their agreement, Swissgrid and the concerned cantons submit a request for a sectoral plan to the Federal Office of Energy.

   In Stage 1, the Federal Office of Energy initiates the sectoral plan procedure and nominates a support group, which consists of representatives and experts of the concerned Swiss federal offices (ARE, SFOE, ESTI, ElCom), the cantonal authorities, organizations under private law, e.g. environmental protection organizations, and Swissgrid. The goal is then to establish a proposal for a planning territory[3] which is supported by all parties. It will then be used in Stage 2 as starting point.

   In Stage 2 different corridor variations within the planning territory are developed by the project applicant and evaluated based on the assessment scheme for transmission lines (Bundesamt für Energie BFE 2013) by the support group. On this occasion, the decision for underground or overhead transmission lines is made. After refinement, the variations are reduced to one single planning corridor which has to be approved by the Federal Council.

2. As in the prior procedure, once the planning corridor is defined, the concrete route of the transmission line is established in the detailed plan by the project applicant.

3. The detailed plan must then be approved by ESTI in the planning approval procedure. Regarding the approval procedure, no adaptations were made compared to the previous procedure. However, precise instructions aim at reducing the duration of the process: First, the possibility of complaints has been restricted by expanding the catalogue of inadmissible complaints. Second, deadlines have been introduced for all parties of the proceedings.

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[3] The determination of the planning territory leads the primary delimitation of the area of investigation. All involved stakeholders agree on a surface which will encompass potential corridors and thus also the the transmission lines.

The new procedure of grid development is designed to reduce a transmission line project by four to six years.

2.4 Smart Grids

As mentioned in the previous section, the Strategic Network 2025 aims at preparing Swiss electricity grid for the integration of a smart grid. In a smart electricity generation, storage and consumption are linked and controlled in a single network with decentralized power production (Akademien der Wissenschaften Schweiz (Ed.) 2012). Smart electricity networks are necessary in order to deal with the fluctuations in the energy production. In a smart grid, small decentralized and large centralized power plants can co-exist and supply electricity to different voltage levels without affecting each other (Akademien der Wissenschaften Schweiz (Ed.) 2012). Surveillance and control technologies guarantee a stable power grid by balancing out the disparity between the electricity production from renewable energies and the energy consumption (Bundesamt für Energie BFE 2015*b*). Smart grids apply the principle of *Smart Metering*: Intelligent measuring systems continuously capture data about the consumption and regulate the distribution of electricity. This enables a better control of the electricity consumption. Furthermore, excess electricity produced from renewable energy producers can be placed into an intermediate storage with the help of sensors and intelligent meters that switch on and off smart energy storage systems. This enhances efficient electricity production. (Swissgrid AG 2017*b*)

Smart grids are a component of the energy strategy 2050. In parallel to the grid strategy, the Federal Office of Energy is working on a Smart Grid Roadmap for Switzerland. It is a report which introduces the most important functionalities of future grids, anticipating technical developments and identifying challenges as well as needs for action.

Chapter 3

Related Work

Determining the optimal transmission line between two physical locations, is a typical application for *routing* analyses. Routing analyses aim at finding the optimal route between two places. It is a challenging problem as a single optimum needs to be found while considering multiple competing objectives. Geographic Information System (GIS) techniques are highly suited to tackle these kinds of problems. In Section 3.1, the most frequently used raster-based routing approach as well as its drawbacks are introduced. Alternatives to this method which apply vector-based methods and genetic algorithms are described in Section 3.2. Techniques providing the exact determination of the transmission tower sites are summarized in Section 3.3. In the last part of this chapter, the research gap addressed during this Msc thesis is presented in Section 3.4.

3.1 Raster-Based Least Cost Path Approach

Determining the optimal route of overhead transmission lines has been discussed in numerous previous research publications and several raster-based solutions based on modern GIS technologies have been proposed. The optimal path corresponds to the minimum accumulation of travel costs between two physical locations (Stefanakis & Kavouras 1995). The costs do not necessarily have to be of financial nature but can be based on geographical distance, time or other environmental, societal and technical aspects (Bagli et al. 2011). A common approach in the field of optimum path finding is to perform a raster-based least cost path (LCP) analysis, which consists of three main steps (Berry 2007*a*):

1. The definition of the *discrete cost surface*
2. The computation of the *accumulated cost surface*
3. The calculation of the *least cost path* (LCP)

The raster-based method is a very efficient technique to perform a routing analysis and thus, is a widely applied and popular methodology. It has been used to solve many kinds of problems: Some studies applied this approach for the alignment of utilities such as trails (Xiang 1996), others to roads and highways (Scaparra et al. 2014, Yu et al. 2003, Collischonn & Pilar 2000), to canals (Collischonn & Pilar 2000), to pipelines (Feldman et al. 1995), to walking routes in off-road terrain (Balstrøm 2002) or to electricity transmisison lines (Bagli et al. 2011, Eroglu & Aydin 2015, Houston & Johnson 2006, Bevanger et al. 2014, Berry 2007*a*, Schmidt 2009). In the following sections, we describe the implementation of the above mentioned steps of the LCP procedure.

3.1.1 Step 1: Discrete Cost Surface

Discrete cost surfaces are usually represented as raster maps where each raster cell encompasses a value that expresses the costs to cross it (Bagli et al. 2011). Various decision criteria of the built environment (Bagli et al. 2011, Monteiro et al. 2005) and natural environment (Berry 2007*a*, Houston & Johnson 2006) as well as some engineering requirements (Marshall & Baxter 2002, Schmidt 2009) and the risk of natural hazards (Bagli et al. 2011, Berry et al. 2004) have been integrated in such discrete cost surfaces. Berry (2007*a*) suggests a four-step procedure in order to combine these various criteria to a discrete cost surface:

1. The raw data such as the digital elevation model, settlements and environmentally sensitive areas are captured in *base maps*.

2. The criteria are deduced from the raw data and are each quantified in *derived maps*. Bagli et al. (2011), for instance, assessed from the digital elevation model the visibility of transmission lines or Berry (2007*a*) captured the proximity to settlements.

3. In order to express the degree of preference, information in derived maps are transformed to a common rating scale, e.g. from 1 (most preferred) to 9 (least preferred). Bagli et al. (2011) reduced the raster value to a Boolean range where 0 and 1 represent low and high impact, respectively. These kinds of maps are called *cost maps* or *avoidance maps*.

4. In the fourth and final step, a single discrete cost surface is generated by first, weighting the cost maps of each criterion and second, combining them in a map overlay. Methods such as weighted linear combination (e.g. Bagli et al. (2011), Bevanger et al. (2014), Monteiro et al. (2005)) or the analytic hierarchy process (e.g. Saaty (1987), Houston & Johnson (2006), Eroglu & Aydin (2015)) can possibly be applied in order to combine the different layers to a discrete cost surface (Malczewski & Rinner 2015).

Calibration and weighting of the different criteria is a very delicate process given the requirement for human judgment. A possible way to prevent the calibration bias is the application of the method called *delphi process* (Bevanger et al. 2014, Houston & Johnson 2006). This calibration technique aims at achieving consensus among a group of experts regarding a certain topic. It takes place in several rounds. In the first round, the experts are asked to express their opinion freely on different criteria, which are ranked by them in the second round. After having statistically evaluated the questionnaires of the first two rounds, the participants are asked to rerank the criteria. Outlier statements which strongly diverge from the majority-opinion are discussed separately in the expert group.

3.1.2 Step 2: Accumulated Cost Surface

The second step of the raster-based LCP procedure aims at computing the accumulated cost surface based on the previously generated discrete cost surface. From the starting point to each cell, the lowest accumulated costs[1] are computed and stored in the accumulated cost raster. There are two different approaches that have been applied to compute the accumulated cost surface: the iterative *splash* algorithm (Berry 2007*b*), also called *spread* (Tomlin 1986, Husdal 2000) or *wavefront* (Zhang & Armstrong 2008) algorithm, and the approach based on graph theory.

Starting at a source cell, the splash algorithm calculates for the cell neighbors the accumulated costs. In the beginning, the starting point corresponds to the source cell. The neighboring cell whose accumulated costs are the lowest becomes the new source cell from which again, the accumulated costs for the neighbors for which the accumulated costs have not yet been computed are determined. These steps are repeated until the accumulated costs are computed for each cell in the discrete cost surface (Lee & Stucky 1998, Berry 1993). Despite the simplicity and the high efficiency of this method, it cannot guarantee that for each cell the minimum accumulated cost is computed.

For the second, graph-based approach, the continuous space is organized into a rectangular raster which is usually given by the discrete cost surface (Stefanakis & Kavouras 1995). The cell centers are assigned to the vertices and each connection between neighboring vertices is assigned to an edge constituting, a graph which is often called connectivity graph (Yu et al. 2003, Antikainen 2013). For reasons of efficiency, the large majority of the research projects defined the cell neighborhood by means of a 3 × 3 matrix, which results in eight edges per cell. Once the structure of the graph is established, the edges need to be weighted in order to compute the accumulated cost surface. This is done based on the raster cell values of the discrete cost surface that the edges traverse, i.e. the weight corresponds to the costs caused by the crossing of an edge.

The calculation of the weight depends on the type of the discrete cost surfaces. According to Douglas (1994), Collischonn & Pilar (2000), Husdal (2000), Xu & Lathrop (1995), Yu et al. (2003), Antikainen (2013), one can distinguish between three types of discrete cost surfaces. The simplest one is the isotropic cost surface which has been applied e.g. by Berry (2007*b*) and Lee & Stucky (1998). The costs are uniform over the entire surface and are only dependent on the location. Isotropic costs of an edge which connects direct cell neighbors are computed as in the following equation from Yu et al. (2003):

$$W_{direct} = \frac{(C_S + C_N)}{2}\mu \tag{3.1}$$

where W_{direct} is the weight of the edge which connects a source cell S with its direct horizontal or vertical neighbor N. C_S and C_N correspond to the cost for traversing the respective raster cell. μ is the width of a cell, i.e. the resolution of the raster.

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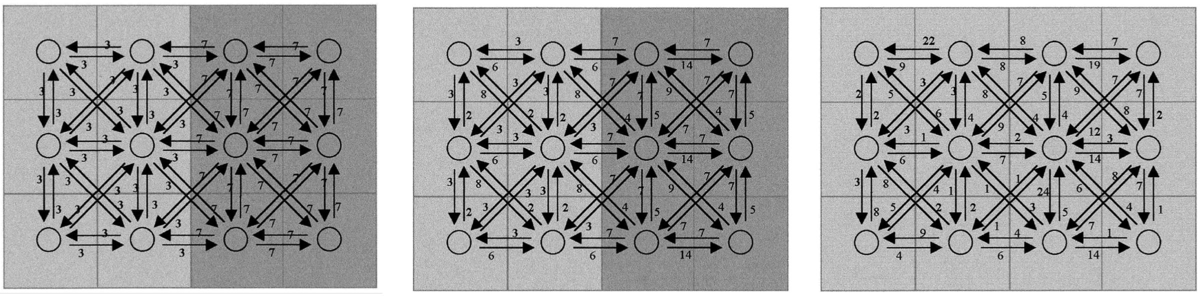
[1] The minimum accumulated costs correspond to the minimum sum of values that belong to the raster cells which connect the starting point and a given cell.



(a) Weighted edges based on isotropic cost surface (Collischonn & Pilar 2000).

(b) Weighted edges based on partially anisotropic cost surface (Collischonn & Pilar 2000).

(c) Weighted edges based on anisotropic cost surface (Collischonn & Pilar 2000).

Figure 3.1 – Different types of cost surfaces.

For diagonal neighbor cells, Equation 3.2 is applied:

$$W_{diagonal} = \frac{(C_S + C_N)}{2}\sqrt{2}\mu \tag{3.2}$$

An example is shown in Figure 3.1a where the weight of the edges are computed only with respect to the isotropic cost surface.

The second type is the *partially anisotropic* cost surface. This is the case when the costs are dependent on *one* direction. Xu & Lathrop (1995) for instance simulated the spread of fire based on the wind direction. In Figure 3.1b a partially anisotropic cost surface is illustrated, where edges pointing towards the east or towards the south east receive an additional weight.

In the third type, i.e. *fully anisotropic* cost surfaces, the cost of an edge is dependent on both, the location and the direction. There is not one prevailing direction as in the partially anisotropic type. An example of an anisotropic surface is shown in Figure 3.1c. Anisotropic cost surfaces have been firstly introduced by Zhan et al. (1993) and have been applied in cases where the topography is relevant when seeking the LCP. For instance Xu & Lathrop (1995), did use anisotropic cost surfaces in order to model transmission lines. Despite the fact that in reality movement in space is often dependent on the direction, the majority of the studies assumed isotropic cost surfaces, however.

Once the graph is weighted, the accumulated cost for each raster cell is computed. The accumulated cost of a raster cell corresponds to the minimum sum of the weighted edges from the starting point to that given raster cell. A shortest path algorithm can be applied for that purpose. The most common approach is the Dijkstra algorithm (Yu et al. 2003, Dijkstra 1959).

3.1.3 Step 3: Computation of the Least Cost Path

Based on the accumulated cost surface, the LCP can be easily determined from a given starting point to every single raster cell in the accumulated cost surface. The accumulated costs of the raster cells represent the minimum costs of the path. The LCP can be found by moving backwards from the destination to the origin and choosing a sequence of cells with decreasing values (Berry 2007*a*). If costs were mapped to the third dimension, the LCP would correspond to the *steepest downhill path* (Bagli et al. 2011, Houston & Johnson 2006). As Berry (1993) describes, it is as if you would *"place a raindrop somewhere on that surface and have it flow downhill as fast as possible to the ground. The result is the shortest [...] line between the two starting points."* (Berry 1993, pp. 32) A couple of researchers applied *backlink rasters* in order to backtrack the LCP (Xu & Lathrop 1995, Lee & Stucky 1998). It indicates the direction to take from a current grid cell in order to get back to the previous cell based on which the accumulated costs were calculated. Lee & Stucky (1998) use for this purpose an encoding from 0 to 7 to describe the different direction options. Given a starting point, one then only needs to follow the direction indications in the backlink surface to get the LCP.

3.1.4 Drawbacks

Despite its efficiency and popularity, the raster-based approach described in Section 3.1 is subject to drawbacks. This is mainly due to the discretization of the continuous space. A graph built based on a raster captures only an approximation of the infinite possibilities of routes in a given study area. The rectangular aspect of rasters is often associated with geometric distortions of the resulting route (Tomlin 1990). Goodchild (1977) defined in 1977 two types of geometric distortions: the elongation and the deviation distortion. Almost a decade later, Huber & Church (1985) introduced a third type, the proximity distortion. The first two types of distortion are due to the restricted direction possibilities, predefined by the cell neighborhood, and will be discussed in Section 3.1.4.1. The proximity distortion will be addressed separately in Section 3.1.4.2.

3.1.4.1 Elongation and Deviation Distortion

In order to estimate the elongation and deviation distortion, the computed LCP is compared to the *true* LCP, i.e. the direct connection between the start and the destination in the continuous space (Huber & Church 1985). The elongation ϵ corresponds to the ratio between the costs of LCP and the true LCP. The deviation distortion δ corresponds to the absolute difference in location between the LCP and the true LCP (Antikainen 2013). One would expect that the more the grid resolution decreases, the less the LCP would be distorted. However, according to Shirabe (2016) and Miller & Shaw (2001), both types of distortion are independent on the raster cell width. They are caused by the set of possible directions given by the predefined neighborhood and thus cannot be removed by finer resolution (Miller & Shaw 2001).

Various strategies have been developed to reduce the distortion by straightening the LCP. Two of them make adjustments in the graph set-up.

Neighborhood enlargement: A method more widely used is described by Huber & Church (1985), which establishes a more connected graph by enabling larger cell neighborhoods. When directional possibilities of a LCP are increased, a more accurate LCP representation is possible. The cell neighborhood can be defined in various ways: Stefanakis & Kavouras (1995) for instance, distinguish between three types of neighbor cells: first, there are the *adjacent* cells, those which share a common border; second, *indirect* neighbors, the diagonally located cells; and, third, *remote* neighbors, i.e. cells not touching each other. Regarding the remote neighbors, different levels of proximity to the source cell can be defined (see Figure 3.2).

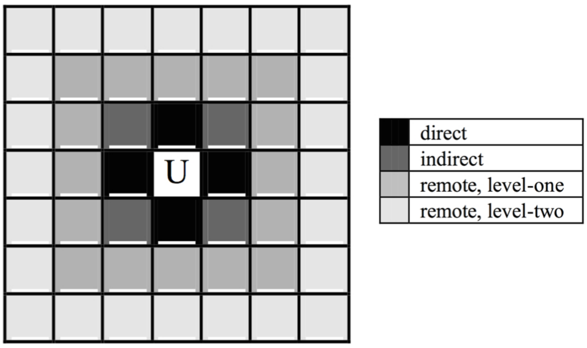


Figure 3.2 – Cell neighborhood types according to Stefanakis & Kavouras (1995).

Some researchers refer to an alternative classification of cell neighborhood. They differentiate between the Rook's-Neighborhood (4 cells), the Queen's-Neighborhood (8 cells) and the Knights-Neighborhood (16 cells). The last three neighborhood types are represented in Figure 3.3 (Yu et al. 2003, van Bemmelen et al. 1993, Zhang & Armstrong 2008).

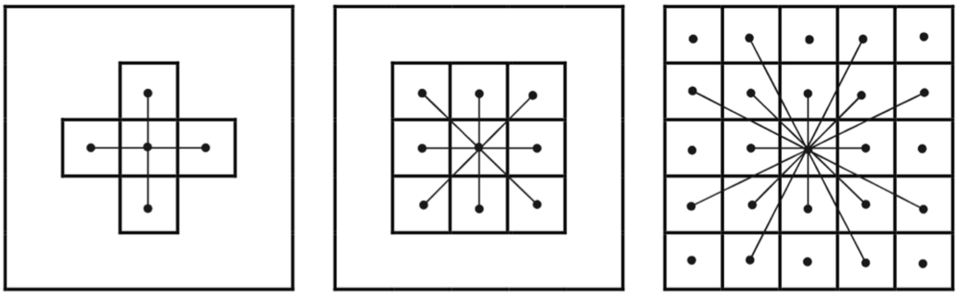


Figure 3.3 – Cell neighborhood types according to van Bemmelen et al. (1993). First, the Rook's-Neighborhood (4 cells), second, the Queen's-neighborhood (8 cells) and third, the Knights-Neighborhood (16 cells) is represented.

Rheinert (1999) reduces the neighborhood to an area between a minimum and maximum distance and he limits the spanning angle in order to meet the requirements of the electricity infrastructure appropriately (see Figure 3.4).

Extended Rasters: The other method increases the permutation of the LCP directions by placing the nodes at the sides of the raster cell instead of the raster cell center (see Figure 3.5). This is called the *extended raster* approach (Antikainen 2013, van Bemmelen et al. 1993). According to van Bemmelen et al. (1993) vertices do not have to correspond necessarily to the raster cell centers. *Snell's law of refraction of light* implies that a line within a uniform area,

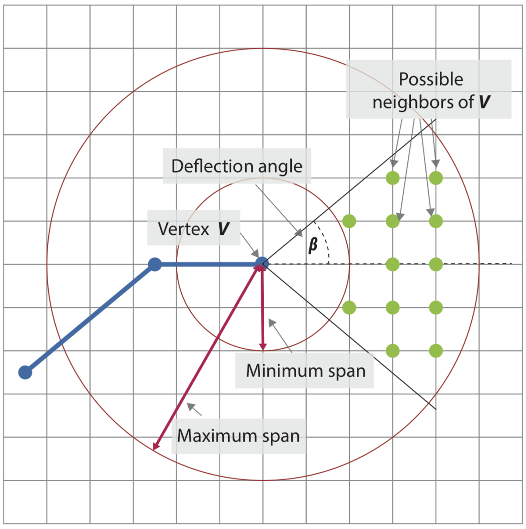


Figure 3.4 – Neighborhood according to Rheinert (1999).

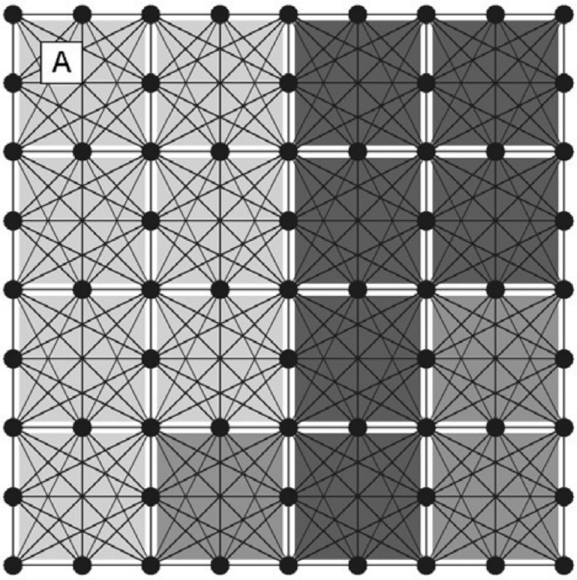


Figure 3.5 – Graph according to the *extended raster* approach (Antikainen 2013).

here a raster cell, is always a straight line. In addition to the increased direction possibilities, the computation of the edge weight is easier given that an edge is exclusively encompassed by one raster cell. According to Antikainen (2013), the use of an extended raster provides routes with lower costs than approaches in which the raster cell centers represent the vertices of the graph. Nevertheless, this approach is strongly dependent on the homogeneity of the discrete cost surface.

Berry (2007*a*), Grassi et al. (2014) and van Bemmelen et al. (1993) further address the issue of regions with uniform costs. In areas with minimal cost differences, the raster-based LCP frequently strikes an orthogonal path section followed by a diagonal one, instead of creating a straight connection which is equally expensive (see blue and green lines in Figure 3.6).

To that end Berry (2007*a*) isolated these *flat areas* in which he defines the interior proximity. The further away a pixel is from the surface center, the larger the assigned value is. The resulting distance raster is then multiplied by the cost surface in order to lower the cost values at the center of the originally uniform surface. As a consequence, the path crosses the area with low cost differences in its center (see red line in Figure 3.6). Berry (2007*a*) calls it the *centered* LCP.

Van Bemmelen et al. (1993) suggested a different approach and made the use of the advantages of quadtrees. Instead of saving each raster cell in a uniform area separately, they are grouped by common values. As a consequence, when crossing a region with low cost differences, less edges are needed and the zig-zagging is reduced. In addition, thanks to the decreasing number of nodes and edges in the graph, the algorithm needs less computational power and memory. One drawback remains to be considered: Within a group of cells not all of them have

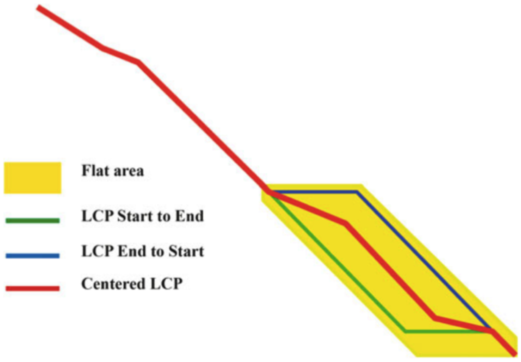


Figure 3.6 – LCP smoothing in areas with low cost differences (Berry 2007*a*).

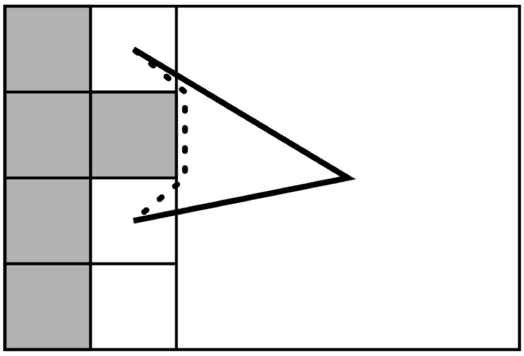


Figure 3.7 – Drawback of quadtrees for LCP analyses. A hook is built in the route by going through raster cell centers of cells grouped in the quardtree (van Bemmelen et al. 1993).

the same distance to the source cell. The algorithm goes from center to center and hence, tends to build hooks in the path, as illustrated in Figure 3.7.

In general, *post hoc* geometric rectification procedures of the LCP have been little implemented. As postulated by Berry (2007*a*), these smoothing techniques are inappropriate since they ignore the cost surface, resulting in the crossing of unsuitable areas as a consequence of straightening the path.

3.1.4.2 Proximity Distortion

The cause of proximity distortion is the ignorance of the values of neighboring cells while computing the cost of a raster cell. Depending on the data basis, large cost disparities between two neighboring cells might occur. In such a situation, it might happen that an inappropriate LCP is computed. As illustrated in Figure 3.8, a narrow series of raster cells surrounded by expensive, unsuitable raster cells is treated the same as if it was embedded in a low cost area (van Bemmelen et al. 1993). Huber & Church (1985) suggest two approaches to reduce this error.

In the first approach, the value of each cell is computed based on its own costs and of the ones of its neighbors. The neighbors may correspond to the nearest cells in terms of the number of cells but also in terms of their costs. The second approach smooths the discrete cost surface by increasing the lower cost values in a disproportional way in order to reduce the proximity distortion.

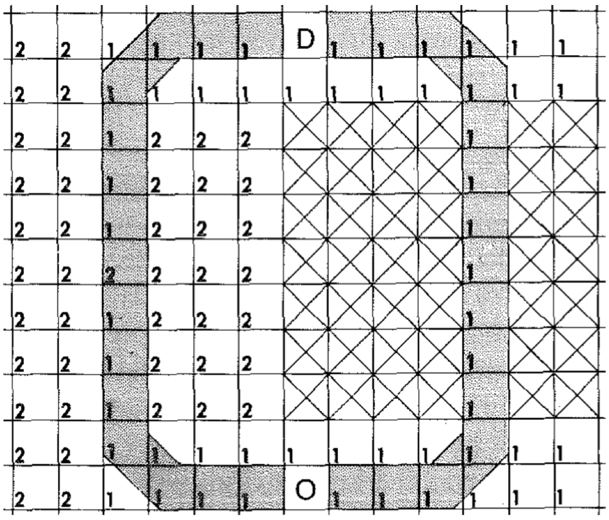


Figure 3.8 – Example of proximity distortion (Huber & Church 1985). Cells with a cross are not suitable for transmission lines and are therefore excluded from the LCP analysis.

3.2 Alternatives

3.2.1 Vector-Based Approaches

The LCP computed by the raster-based approach depends on the grid resolution and on the subsequent number of allowed direction permutations. In contrast, vector-based approaches provide *exact* solutions (van Bemmelen et al. 1993). A widely used vector-based technique to solve the LCP problem is the *weighted region problem* introduced by Mitchell & Papadimitriou (1991). In this method, the continuous space is subdivided into polygonal regions, also called *faces*. To that end, the authors suggest to apply the *unconstrained Delaunay triangulation* of the continuous phase. Each face has a positive weight α_f, which expresses the costs per traversed distance in a face f. An infinite weight is assigned to obstacles. This approach simulates a wavefront of light through the triangulation network. Starting at the source point, every time the wavefront traverses a face boundary, *Snell's Law of Refraction* is applied. As shown in Figure 3.9, the angles of entry θ and exit θ' of the edge obey to the following relation (Equation 3.3):

$$\alpha_f sin(\theta) = \alpha_{f'} sin(\theta') \tag{3.3}$$

where α_f and $\alpha_{f'}$ denote the weights of the faces f and f', which are crossed by the wavefront. The determination of the LCP being an optimization problem, Mitchell & Papadimitriou (1991) apply the *continuous Dijkstra* method. Due to the complexity of this approach, some researchers implemented an approximation of the weighted region problem by simplifying it to a LCP problem in a graph (Lanthier et al. 1997, Sun & Reif 2006). The approach of Dean (2011) is based on a TIN-based model. Nevertheless, the optimization of the path relies on the principle of linear programming. From Dean's study emerged that the TIN-based method achieves similarly

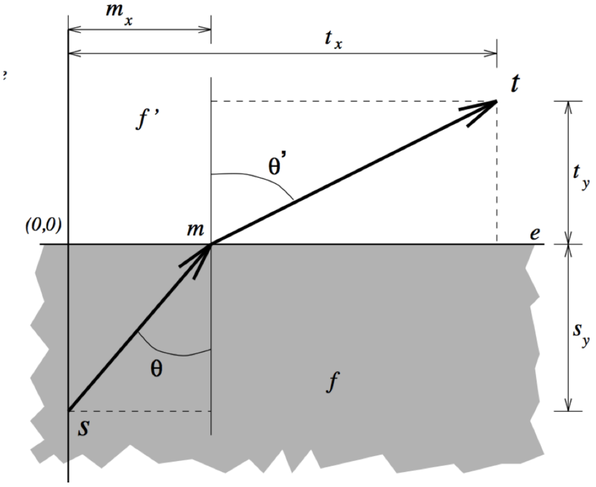


Figure 3.9 – Snell’s Law of Refraction (van Bemmelen et al. 1993): f and f' correspond to faces with weight α and α'. Θ and Θ' denote the angle of entry and exit, respectively.

good results as the state-of-the-art raster method. However, it has been tested only on very small datasets because it is computationally expensive.

Even though the above mentioned vector-based approaches seem promising, only few were reported in the literature. Despite the advantage of vector-based approaches providing exact routes, van Bemmelen et al. (1993), who compared the weighted region approach with different variations of the standard raster method, argued that they often require more computing power. Furthermore, according to Antikainen (2013), vector-based approaches are not well-suited to be applied on gradual, raster-based cost surfaces, which are often used as data basis for solving routing problems.

3.2.2 Genetic Algorithms

Examples of studies where the LCP problem has been solved by means of a genetic algorithm can be found in Rheinert (1999) and Zhang & Armstrong (2008). A genetic algorithm is a probabilistic approach, which works according to the paradigm of evolution. The fundamental component of this algorithm is the *evolutionary loop*, which consists of the fundamental principle of Darwinian evolution: *variation* and *selection*, connected to the change of the generation, called *reproduction*. It is a process in which structures or states are selected according to their fitness. Only the fittest structures survive, i.e. can reproduce themselves (Beyer 2001). These evolutionary stages have been implemented by Rheinert (1999) and Zhang & Armstrong (2008) in order to get the *fittest* solution for transmission lines. The main difference between the two is that the approach of Zhang & Armstrong (2008) is raster-based whereas Rheinert (1999) determines a path in the continuous space.

3.2.2.1 Population Initialization

At the beginning, an initial population which consists of individuals has to be generated. In the LCP problem for transmission lines, individuals correspond to randomly generated routes (Rheinert 1999). Zhang & Armstrong (2008) apply two alternative methods to generate individuals: a heuristic approach and an approach that feeds the genetic algorithm with solutions from the classical raster-based shortest-path algorithm. In contrast to Zhang & Armstrong (2008), the approach of Rheinert (1999) automatically rejects unfeasible routes by taking into account requirements of transmission lines such as avoidance areas, the span, as well as the deflection angle, while generating the individuals. When an individual ends up into a dead end, a back-tracking algorithm is applied. Also a maximum number of towers limits the length of the path.

3.2.2.2 Selection

Given an initial population, only those individuals are selected whose fitness are the highest. In other words, the fitness of an individual is the measure for how probable it is that an individual is selected from the initial population. Objective functions are formulated in order to express the fitness of individuals. Both, Rheinert (1999) and Zhang & Armstrong (2008) defined for each optimization criterion an objective function in order to find the route alternatives which achieve good results in terms of all objectives simultaneously. To that end, in both studies, the concept of Pareto-optimum is adopted (Rheinert 1999, Zhang & Armstrong 2008).

Once the fitness is assigned to each individual, one of the many methods to select individuals is applied (Bäck 1996). The *roulette wheel* and the *tournament* methods are two of the techniques implemented by Rheinert (1999) and Zhang & Armstrong (2008). In the roulette wheel selection, the higher the individual's fitness value is, the larger the proportion of the roulette wheel it occupies. Consequently, the probability that the ball stops in that section of the wheel increases. This procedure has to be repeated until the same number of individuals have been selected as there were in the initial population. As for the tournament selection method, the individuals are subdivided into sets, i.e. tournaments. From each set, the fittest individuals are selected who are used as parents for the next generation.

3.2.2.3 Variation and Reproduction

The fittest individuals are selected in order to pass on their genes to the next generation. Their genetic material is used to generate hopefully fitter individuals than their parents by means of crossover and mutation techniques (Bäck 1996).

Crossover methods aim at crossing two parent individuals by exchanging their genes. The resulting individuals replace their parents in the population. In the example shown in Figure 3.10, a possible crossover technique is to exchange the parts of the route where both parents intersect (Zhang & Armstrong 2008).

In contrast to crossover techniques, mutations change individuals randomly. A mutation can be carried out by varying single transmission towers but also by deleting a series of towers, which are subsequently recalculated (Rheinert 1999, Zhang & Armstrong 2008).

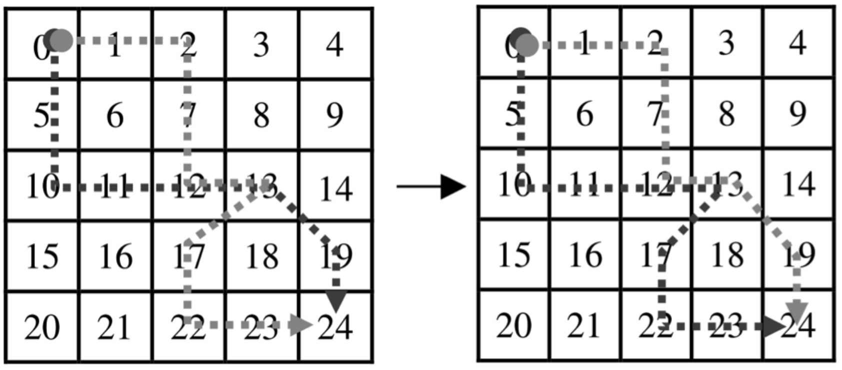


Figure 3.10 – Crossover technique: Both solutions exchange their partial-routes at the intersecting node 12 (Zhang & Armstrong 2008).

3.2.2.4 Advantages and Drawbacks of Genetic Algorithms

The evolutionary loop can be repeated any number of times, until satisfactory results are achieved. The outcomes of Rheinert (1999) and Zhang & Armstrong (2008) showed that excellent results can be achieved with a high degree of computational efficiency. For multi-criteria problems genetic approaches are particularly well-suited. The concept of population allows to optimize individuals according to various objective functions in a parallel manner (Rheinert 1999). But as the genetic algorithms are probabilistic and heuristic optimization algorithms, there is no guarantee that by the end of the procedure the optimal route is obtained (Zhang & Armstrong 2008). This kind of algorithm is therefore not recommended for problems which need to be solved in a deterministic manner. Furthermore, the output of genetic approaches strongly depends on parameters, such as the size of the population, the number of generations or the selection pressure.

3.3 Tower Siting Algorithms

Some studies pursued the goal of only determining the positions of transmission towers along a given transmission line (Zheng 1993, Viera & Toledo H. 2006, Olbrycht 1982, Mitra & Wolfenden 1968). The towers have to be sited in such a way that the absolute construction costs are minimized. Technical aspects such as the terrain situation, the span, as well as the ground clearance are paramount. As suspension and angle towers are considered important cost drivers, their number has been likewise integrated as parameters in their algorithms (Olbrycht 1982). The aim of these approaches is to model, in addition to the sites of transmission towers, also their height and their type (Viera & Toledo H. 2006).

The large majority of the tower siting algorithms are based on *Dynamic Programming*. Dynamic programming involves a systematic and deterministic procedure for determining the optimal combination of decisions, in this case, the optimal combination of possible tower positions and types in order to minimize the construction costs of transmission lines. In contrast to other approaches, there is no standard problem formulation or equation that can be applied for any dynamic programming issue. It must rather be seen as an approach of how to solve a problem and it must be adapted to each individual problem.

As a start, the optimal route of the transmission line is expected to be already computed. A set of possible tower sites along a given route profile are defined. For every tower position, the elevation is provided as well. The goal is to find the sequence of towers such that the construction costs are minimized. The approaches, which have been applied so far to solve this problem, used the same dynamic programming solution as for the *stagecoach problem* (Hillier & Lieberman 2010). According to Mitra & Wolfenden (1968), the problem can be defined as follows:

The goal of this algorithm is to determine a subset of tower sites

$$X_{selected} = \{x_i | i = 1, 2, ..., M \text{ and } x_{i-1} \prec x_i\} \tag{3.4}$$

from the total set of tower sites

$$X_{all} = \{X_j | j = 1, 2, ..., N \text{ and } X_{j-1} \prec X_j\} \tag{3.5}$$

where $X_{selected} \subseteq X_{all}$. Therefore, M corresponds to the number of selected tower sites for the transmission line and N denotes the total number of possible tower sites along the route. $X_{selected}$ has to be defined such that the cost function C is minimized as follows:

$$C_{total} = \min \sum_{i=1}^{M} C(x_i, h_i) \tag{3.6}$$

where the tower height h_i at the tower site x_i is selected from the predefined set of tower heights with cardinality Q:

$$H_{all} = \{H_k | k = 1, 2, ..., Q \text{ and } H_{k-1} < H_k\} \tag{3.7}$$

In addition, constraints regarding the admissibility of the tower site, the span, the deflection angle and the ground clearance must be satisfied in the model (Olbrycht 1982). Let us assume that $F(X_j, H_k)$ corresponds to the optimal construction costs from the starting node to the transmission tower site X_j with height H_k. While respecting the constraints, the optimal cost value $F(X_s, H_t)$ of a node (s,t) can be assigned based on the following rule:

$$F(X_s, H_t) = C(X_s, H_t) + \min F(X_j, H_k), j = 0, 1, ...s - 1; k = 1, 2, ...Q, \tag{3.8}$$

where $C(X_s, H_t)$ denotes the immediate cost of the tower site X_s and height H_t and $\min F(X_j, H_k)$ corresponds to the minimum costs from the unique starting point to X_j. This now represents the optimal costs from the starting point to tower site X_s with height H_t. By applying recursion over Equation 3.8, we can compute the optimal costs from the starting point to the destination point.

This kind of algorithm is very efficient and has not only been implemented in theory, but also used in relevant software (Viera & Toledo H. 2006). However, such algorithms can only be used when the route of a transmission line is known.

3.4 Research Gap

In summary, the raster-based method is the most known approach that has been applied in the last decades to solve routing problems. This is explained by the efficiency, simplicity and the use of continuous raster data as input of and for these approaches. Raster-based methods have therefore been preferred over the vector-based ones. Despite the promising results of genetic approaches, they cannot be applied to provide *the* optimal route of transmission lines, however.

The standard raster-based approach is widely accepted and a lot of research has been done to tackle the issues introduced by Goodchild (1977) and Huber & Church (1985). Nevertheless, they show limitations in meeting the technical requirements for transmission lines. As can be deduced from literature, technical aspects such as the deflection angle or the topography are neglected. So far, technical criteria have only been considered in the final stage of planning transmission lines, when the exact tower position is to be defined along a given route (see Section 3.3). However, these factors significantly characterize the route and would provide better results. The aim of this Master's thesis is to integrate technical features in the routing analysis such as the ground clearance, the transmission line span, and the angle of deflection. Furthermore, the goal is to analyze the impact of these technical criteria on the calculation of the optimal route for transmission lines. The findings of previous research work will be taken into consideration in order to address this research gap and to implement a novel transmission line routing algorithm.

Chapter 4

Methodology

This Msc thesis aims to develop a novel approach to solve the transmission line routing problem. The exact problem definition is provided in Section 4.1. Furthermore, this chapter introduces two approaches to compute the optimal route for transmission lines: the baseline method (Section 4.3.1) and the novel approach (Section 4.3.2). Both approaches require as input a discrete cost surface whose computation is described in Section 4.2. In Section 4.4, the theoretical background for the techniques used to evaluate the outcomes is provided.

4.1 Definition of the Transmission Lines Routing Problem

4.1.1 Basic Problem

The routing problem of transmission lines is an optimization problem, which consists of determining the optimal route of transmission lines between two given physical locations in a network. In this thesis, the network is represented by the graph $G = \{V, E\}$, where V and E denote the vertices and the edges of G. In the real world, V represents the towers and E the conductors of transmission lines. The starting and the destination point correspond to V_S and V_D. They have to be initially given. Let R denote a route between V_S and V_D, which consists of a sequence of transmission towers V_i, where $i = \{1, 2, ..., N\}$ and N is the total number of towers in the route. $R_{optimal}$ corresponds to the optimal route. It represents the route whose construction causes minimum costs compared to all possible routes in the network. In this context, the costs express the impact and conflicts transmission lines cause. *Optimization criteria* capture the costs and are structured into the following dimensions:

1. The *spatial planning* dimension
2. The *environment and landscape* dimension
3. The *technical implementation* dimension

Hence, the costs for transmission lines may vary from area to area depending on whether they encompass urban, environmental or landscape protection surfaces and on the conditions for technical implementation. These costs are mapped on the edges of the graph G. For each pair of vertices (V_i,V_j) there is a connecting edge with cost C_{ij}. Thus, the question is reduced to a standard least cost path problem based on a weighted graph.

In addition to the optimization criteria, *constraints* are taken into account. Constraints restrict the path possibilities of transmission lines. In the following sections, the constraints as well as the optimization criteria considered here are defined.

4.1.2 Constraints

Constraints are absolute and limiting factors that characterize how and where transmission lines are built. They aim at restraining the impact of transmission lines on the humans and on the environment. Furthermore, they integrate technical limitations into the computation of a route. The following constraints will be considered:

- *Avoidance area (Constraint 1):* Avoidance areas are surfaces, where transmission lines are not allowed. Settlements, for instance, are considered as strict avoidance areas. According to the Ordinance on Non-Ionising Radiation (NISV 1999), transmission lines have to be built as far as possible from buildings. Places frequented by the general public are neither allowed to be located near transmission lines.

  Avoidance areas have already been implemented in previous work (Houston & Johnson 2006, Bagli et al. 2011, Stefanakis & Kavouras 1995). In contrast to them, this work will elaborate this constraint by distinguishing between two kinds of avoidance areas:

  1. avoidance areas, in which transmission towers and conductors are not allowed to be built nor suspended.
  2. avoidance areas, in which it is prohibited to erect transmission towers but allowed to suspend a conductor.

  Both types of avoidance areas may be congruent but do not have to. For example, water bodies or moorlands are surfaces over which a conductor may be suspended but no transmission tower built (see Annex 4 in the Water Protection Ordinance (GSchV 1998)).

- *Span range (Constraint 2):* Transmission towers usually do not stand in regular intervals from one another. The distance between two transmission towers may vary by several hundred meters (Fischer & Kießling 2012). However, there is no legal base, which defines a minimum and a maximum distance between transmission towers. Therefore, in this work the possible distance range between transmission towers will rely on the expert's statements. Similar to Rheinert's (1999) approach, the span range is set between 200 and 600 meters, whereby 350 to 400 meters correspond to the average interval between two towers. This constraint aims at reducing the elongation and deviation distortion (Goodchild 1977, Huber & Church 1985).

- *Ground clearance (Constraint 3):* With respect to the lowest possible sag, the transmission lines have to comply with the ground clearance specified in Annex 3 of the Federal

Ordinance on Electric Lines (LeV 1994). As emerges from Table 4.1, the ground clearance depends on the roughness of the terrain and the span of the transmission lines. A distinction is made between the direct and the vertical distance.

Table 4.1 – Ground clearance according to the Ordinance of Electric Lines (LeV 1994): It is distinguished between the vertical and the direct distances to the ground which depend on the terrain roughness and the span of the transmission lines.

	Vertical distance	Direct distance
Transmission lines in rough terrain	6 m + s	5 m + s
Transmission lines in remaining areas	7 m + s	5 m + s
Wide-span transmission lines	7.5 m + s	5 m + s

$s = 0.01$ m pro kV nominal voltage

- *Maximum angle of deflection (Constraint 4):* The angle of deflection α is defined as in Figure 4.1. Since according to experts, deflection angles of more than 60° are highly unlikely, only transmission lines with a deflection angle of less than 60° are considered in this work. A similar constraint is integrated in the approach of Rheinert (1999).

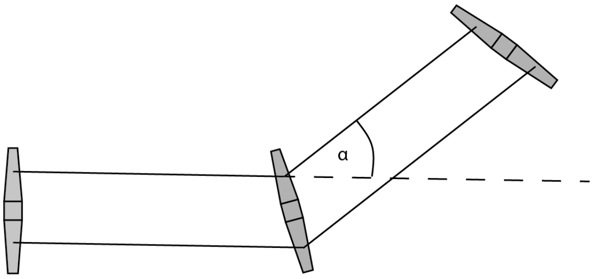


Figure 4.1 – Definition of the deflection angle α between three transmission towers.

4.1.3 Optimization Criteria

When transmission lines are planned, various competing criteria have to be taken into account. On the one hand, needs of the population have to be respected and the energy supply guaranteed. With the increasing environmental awareness on the other hand, many legal specifications promoting the sustainable and environmentally friendly development of the transmission grid have been introduced in the last decades and must be considered. Furthermore, the technical feasibility, which is closely coupled to the economic factor of transmission lines, needs to be integrated in transmission line projects. Despite the competing nature of these criteria, the objective of the transmission line routing problem is to optimize them in order to obtain as a final result the optimal route. In the following sections, the optimization criteria are introduced with respect to the dimension they belong to.

4.1.3.1 Optimization Criteria of the Spatial Planning Dimension

The spatial planning dimension describes how the human and the urban environment are affected by transmission lines. This dimension is particularly important for transmission line projects given the low public acceptance of transmission lines (Towers 1997, Jewell et al. 2009). It is expected that by optimizing these criteria, the popular opposition will decrease. The impact on this dimension can be described in terms of the proximity and the visibility of transmission lines.

Proximity: The distance between transmission lines and objects of spatial planning matter is defined by the NISV (1999) and mainly aims at protecting people against scientifically proven health hazards due to the exposure to electric and magnetic fields. High frequency radiation can cause fever by raising the body temperature, disturb the blood circulation and in an extreme case, lead to fatal heat strokes. Also non-thermic impacts on the human body have been observed. There is evidence for radiation impact on human brain waves and the sleeping behavior. The causes are however unclear (Bundesamt für Umwelt, Wald und Landschaft BUWAL 2005). To that end, *maximum immission values* of 5'000 V/m for the electric-field strength and 100 μT for the magnetic flux density have been stipulated given a frequency of 50 Hz of the conductors. These limiting values have to be respected in all situations in which there is a potential of human proximity, even if only briefly (NISV 1999).
Following the precautionary principle of the Law on Environmental Protection, *installation limit values* are determined in the NISV. These limits are defined individually for each facility and are significantly lower than the immisssion limit values. They must be complied with when people reside often in one place. To that end, the NISV specifies places with sensitive use (Orte mit empfindlicher Nutzung, OMEN). OMEN mainly encompass rooms in buildings in which people stay regularly and for a longer period of time. Examples for such places are living spaces, schoolrooms, hospitals, retirement homes and permanent work places.

Visibility: Affecting landscape aesthetics negatively, the high visibility of transmission lines often leads to citizens objecting and thus, impeding a transmission line project (Bevanger et al. 2014, Grassi et al. 2014, Marshall & Baxter 2002, Furby et al. 1988). In contrast to the immission limits, there is no legal base, which restricts the visible impact of transmission lines. Especially towers but also the conductors have an effect on the landscape character and on the view from houses, roads, tourist attractions and other important places. According to Marshall & Baxter (2002) and Furby et al. (1988), the visual impact depends on parameters such as the viewer's distance to the line, the tower type and the tower's backdrop. Furthermore, house owners often have concerns regarding the decreasing property value and perceive no direct benefit from these facilities (Marshall & Baxter 2002). Consequently, the number of cases increases in which transmission grid operators face conflict with customers whose electricity supply they seek to guarantee (Furby et al. 1988).

4.1.3.2 Optimization Criteria of the Environment and Landscape Dimension

The environment and landscape dimension includes promoting a sustainable and clean development of the natural world by protecting ecosystems, conserving natural habitats of wild fauna and flora and maintaining biodiversity and varied landscapes. According to the assessment scheme for transmission lines (Bundesamt für Energie BFE 2013), different environmental legislations have to be taken into account:

- *Forest protection:* The construction of transmission lines in forest areas necessitates an authorization of clear-cutting as stipulated in Act 4 of the Federal Law on Forests (Waldgesetz WaG (1991)). According to Act 5 in the WaG, an authorization is only issued when the applicant can provide important reasons for clearing, which overrule the ones for preserving the forests.

- *Biotope protection:* According to the assessment scheme (Bundesamt für Energie BFE 2013), especially mire biotopes, meadows, dry grasslands as well as aquatic and migratory bird reserves are important areas, which require particular consideration in the planning process of transmission lines. In mire biotopes, the construction of transmission towers is not allowed. However, suspending the conductor over such an area is permitted but has to be avoided because of landscape protection (Act 4, Hochmoorverordnung (1991)). Routes, which cross meadows and dry grasslands, cannot be ruled out *a priori*. However, the construction of transmission towers requires an overall balancing of interests and should be avoided whenever possible (Act 4, Auenverordnung (1992)). Aquatic and migratory bird reserves of national and international importance are assigned to a high conservation value and thus, generally have to be bypassed by transmission lines (Act 6, Verordnung Wasser- und Zugvogelreservate WZVV (1991)).

- *Groundwater protection:* In principle, the conductors of transmission lines are allowed to be suspended above groundwater protection areas according to the Water Protection Ordinance (GSchV 1998). Nevertheless, the placement of transmission towers depends on the type of groundwater protection zone. In the groundwater protection zone 1, transmission towers are strictly forbidden to be built. With a special authorization, they can be built in groundwater protection zones 2. Groundwater protection zones 3 are less strict than the previous two, but the construction of transmission towers is only allowed under particular conditions.

- *Landscape protection:* Switzerland is rich in landscape of extraordinary beauty and therefore, it must be guaranteed that transmission lines affect the landscape as little as possible. According to the assessment scheme of transmission lines (Bundesamt für Energie BFE 2013) the federal inventories, which comprise the most significant landscapes, are important tools to protect the landscape. The most important federal inventories in Switzerland are the Federal Inventory of Landscapes, Sites, and Natural Monuments of National Importance (Bundesinventar der Landschaften und Naturdenkmäler von nationaler Bedeutung BLN), the Federal Inventory of Valuable Sites of Local Character (Bundesinventars der schützenswerten Ortsbilder der Schweiz von nationaler Bedeutung ISOS) and the Inventory of the Historical Traffic Roads (Bundesinventar der historischen Verkehrswege der

Schweiz IVS). In accordance with the Federal Law on the Protection of Nature and the Landscape (Bundesgesetz über den Natur- und Heimatschutz NHG (1966)), these objects are to be preserved undiminished and thus, transmission lines are prohibited to traverse them (Act 6). However, in case it is not possible to bypass an inventory object, transmission lines are permitted under the condition that they are managed with the greatest possible care.

Special treatment is prescribed for mire landscapes, which are to be dealt with particular precaution. According to Act $23d$ of the NHG (1966), transmission lines are only allowed if they do not conflict with the preservation of typical properties of these types of landscapes.

- *Natural hazards*: Transmission lines have to be positioned to minimize concerns from natural hazards. If a bypass solution is not possible, the transmission towers have to be built and equipped to withstand the prevailing natural hazards.

4.1.3.3 Optimization Criteria of the Technical Implementation Dimension

Technical optimization criteria can be perceived from two points of view. On the one hand, transmission lines need to meet up-to-date functional requirements, e.g. the voltage, the number of circuits and the type of conductors or insulators, in order to guarantee electricity supply. On the other hand, there are technical parameters, which determine the course of a route. The focus of this thesis will lie on the latter one. According to (Fischer & Kießling 2012), factors such as the terrain situation, the subsoil and the share of suspension towers shape the technical implementation of transmission lines and belong to the main cost drivers of transmission lines. Consequently, the following technical criteria will be considered in this thesis:

- *Terrain:* In the first place, the ground clearance must be met, i.e. the sag of the conductor is to be determined such that it does not come too close to the ground (Fink & Beaty 1993). For that purpose, the digital elevation model and the exact modeling of the sag are necessary (Fischer & Kießling 2012). Furthermore, the slope of the terrain needs to be taken into consideration. In general, building transmission lines in a rougher terrain is technically more complicated and more expensive. Moreover, it is advisable to avoid exposed ridges in order to protect transmission lines against wind and lightnings (Fink & Beaty 1993). Thus, from a simple technical perspective, bypassing mountainous terrain is advisable (Fink & Beaty 1993). However, according to expert's statements, this criterion does not prevent the construction of transmission lines. With today's technology, it is possible to build transmission lines in every terrain situation.

- *Subsoil:* The selection and dimensioning of transmission tower foundations depends on the properties of the subsoil. Given that the foundation belongs to the most expensive elements of the transmission line, the subsoil thus directly influences the costs. Fischer & Kießling (2012) distinguishes in this context between unconsolidated rock, consolidated rock and backfill. The task of a foundation is to transfer steady-state and transient load into the soil and to stabilize the towers in order to protect them from natural hazards such as landslides or floods (Kandaris & Davidow 2015, Palic et al. 1992). However, the subsoil will not be the subject of investigation in this thesis.

- *Deflection angle:* Another technical property of transmission lines, which influences the final construction costs, is the angle of deflection. Depending on the angle of deflection, either suspension towers or angle towers are necessary (Fischer & Kießling 2012, Fink & Beaty 1993). Suspension towers belong to the less expensive type of transmission towers and aim at suspending the conductor in a straight line. It has usually a deflection angle between 0° and 3° (Fang et al. 1997). During standard operation, this type of transmission tower does not transfer tensile forces and thus needs less construction material than angle towers. In contrast, angle towers are erected where the transmission line changes direction. This type of tower supports deflection angles of up to 20° (Fischer & Kießling 2012). If this angle size is exceeded, unfavorable tower geometries are the results. In such situations dead-end towers are placed where a conductor mechanically terminates and a new one starts (Fang et al. 1997). Angle towers are significantly more expensive than suspension towers. Therefore, the highest possible share of suspension towers is sought (Fink & Beaty 1993). According to Fang et al. (1997), 80% to 90% of a transmission line usually encompasses suspension towers. Furthermore, as a consequence of minimizing the angle, the transmission line results in a shorter route and thus, reduces the costs of transmission lines.

- *Pooling with existing linear infrastructures:* A further guideline of the Federal assessment scheme for transmission lines (Bundesamt für Energie BFE 2013) is the pooling of transmission lines with existing linear infrastructures. The implementation of this technical property promotes the optimal use of already built-up areas and the preservation of the landscape. This technical criterion is closely coupled to the spatial planning dimension.

4.2 Input: the Discrete Cost Surface

As described in Section 3.1, raster-based approaches take as an input a discrete cost surface. The raster cell values express how much it costs to build a transmission line by crossing a raster cell. The cost surface has been implemented for the project *Application of 3D Geographic Information Systems for transparent and sustainable planning of electric power systems* at ETH Zurich by Joram Schito (Schito 2017).

A wide range of criteria concerning transmission lines have been integrated into the cost surface. As shown in Table 4.2, they can be divided according to the dimensions described in Section 4.1.3. The cost surface mainly reflects the costs of the spatial planning as well as of the environment and landscape dimension. Given that the roughness of the terrain for transmission lines is provided in the form of a raster, this factor has been integrated into the cost surface as well. Rough terrain can thus be expressed with higher costs and flat terrain with lower costs. Also, the subsoil and the existing linear infrastructures are integrated into the cost surface as technical criteria.

A three-step multi-criteria decision analysis (MCDA) method has been applied to combine all of these criteria to one discrete cost surface:

First, 16 experts have been asked in a questionnaire to assess the costs of the criteria in terms of three scenarios. The three scenarios comprise a strictly business-friendly, a strictly

Table 4.2 – Overview of the criteria considered for the MCDA method. They are organized according to the dimension they belong to.

Spatial Planning Dimension	Infrastructures, building zones, recreation areas, buildings, historical areas, ISOS-objects, IVS-objects, cultural assets agricultural zones
Environment and Landscape Dimension	Flood plains and spawning areas of national importance, mire biotopes, wetlands worthy of protection, dry grasslands, forests, groundwater protection zones, protected areas according to federal hunting law, bird reserves, nature reserves, parcs of national importance, biosphere reserves, UNESCO world heritages, Federal inventory of landscapes, sites, and natural monuments of national Importance, geotopes, mire landscapes, natural hazard zones
Technical Implementation Dimension	Digital elevation model, the subsoil, existing linear infrastructures (transmission lines, streets, railways etc.)

environmentally friendly, and an intermediate perspective. Since the third scenario includes both, economic and ecological interests, these answers to it were expected to be least biased. Therefore, the cost surface is computed based on the experts' criteria assessments for the intermediate scenario. The costs for each criterion is captured in separate cost surfaces according to a Likert scale, ranging from 1 (this criterion is suitable for building a transmission line) to 5 (this criterion is unsuitable to build a transmission line). Costs from 1 to 2 represent criteria favorable for building a transmission line, whereas criteria with costs of 3 are ranked as neutral. 4 to 5 correspond to criteria that are unsuitable for building a transmission line.

Second, the experts had to assess the weights of the criteria. The weight of a criterion represents the relative importance of its costs and thus strengthens the influence of a criterion on the cost surface. This weight ranges according to a Likert scale from 1 (neutral) to 3 (very important). As weights have an enhancing effect on the costs of the criteria, low costs have been distinguished from high costs. Thus, high weights applied on a low-cost criteria decrease the costs whereas high weights used on a high-cost criteria increases it.

Third, once having assessed and weighted all criteria, the total cost surface is calculated based on a modification of the Simple Additive Weighting method, i.e. the Logarithmically Adapted Simple Additive Weighting (Churchman & Ackoff 1954). The total cost surface was computed by summing the weighted costs of the criteria and then, by applying a logarithmic correction according to the following equation:

$$c_x = \left(\sum_{i=1}^{n} w_i \cdot c_{i_x} \right) \cdot \ln(r_x + 1) \qquad \forall c_x \geq 1 \tag{4.1}$$

where c_{i_x} denotes the costs a criterion i caused at location x and w_i corresponds to the weight assigned to criterion i. The sum of all weighted criteria is divided by the natural logarithm of $r_x + 1$ where r_x represents the number of overlapping raster cells of all n criteria located in x. The total cost in x is denoted as c_x. As a consequence, a cell with equal resistance but more overlapping cells than another, is assigned to a higher resistance since it is more difficult with respect to legal issues to build a transmission line on multiple protected areas than on single protected areas.

Furthermore, a novel concept of buffering has been integrated into the cost surfaces of each criteria. This buffering model assumes that the cost of a sensitive object does not have a clear boundary but rather diminishes with increasing distance (Figure 4.2). The costs can decrease according to logarithmic, linear or exponential functions.

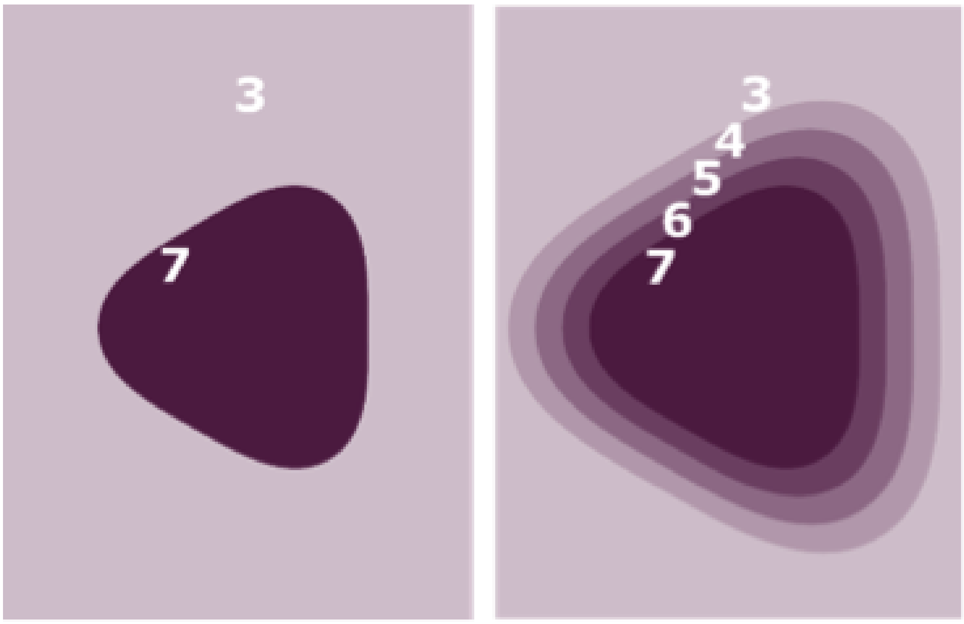


Figure 4.2 – A sensitive object (dark violet) represented with clear boundaries to the surroundings (left) and according to the buffer concept (right) (Schito & Wissen Hayek 2017).

The resulting cost surface was provided as a raster with a resolution of 100 meters. Other calculation methods for cost surfaces have been tested in the above mentioned research project at ETH Zurich. The author of the present work has chosen to use for her studies the Logarithmically Adapted Simple Additive Weighting technique combined with a linear buffer as the MCDA method because this combination has been highly accepted by experts who assigned to it the highest degree of realism compared to other MCDA methods.

4.3 Computation of the Route

In order to compute the route of transmission lines a routing analysis is performed. Two routing methods, the baseline method and the novel approach, are introduced in the following subsections.

4.3.1 Baseline Method

The baseline method corresponds to the raster-based, state-of-the-art approach, which has been described in Section 3.1. The accumulated cost surface is computed based on the discrete cost surface described in Section 4.2. To that end, a graph is built, where each raster cell center represents a node. Every node is connected by means of edges with the nodes within the Queen's neighborhood (van Bemmelen et al. 1993). A described by Yu et al. (2003), the edges are weighted based on the cost surface. In order to compute for each raster cell the accumulated costs, Dijkstra's LCP algorithm is applied. The LCP can then be determined by selecting the *steepest downhill path* in the accumulated cost surface from the destination to the starting point (Berry 2007*a*). Due to the resulting zigzag line, the route is geometrically smoothed by using ESRI's line simplification tool based on the *bend simplify* method and a simplification tolerance of 500 meters. After the line simplification, the vertices along the path, which represent the transmission towers, are kept if the distance between two vertices is smaller than 300 meters. Distances between two vertices over 600 meters were split in equal distances not smaller than 300 meters.

4.3.2 The Novel Approach

The novel approach consists of a graph-based algorithm which takes into account the constraints described in Section 4.1.2 and aims at optimizing the criteria described in Section 4.1.3 in order to compute the optimal route for transmission lines. It is structured into three steps:

1. Create the *Basic Graph*
2. Transform it into the *Weighted Line Graph*
3. Compute the *LCP*

These steps will be presented in detail in the following subsections. In order for other researchers to test the novel approach, the code as well as a test dataset is provided on github[1].

4.3.2.1 The Basic Graph G

The first step of the algorithm consists of constructing the basic graph. It corresponds to a directed graph $G = (V, E)$ where V and E are the vertices and edges, respectively. The basic graph is built on the assumption that the study area is discretized in raster cells with a given

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[1] The github repository can only be accessed on request. In order to get access to it, please send an e-mail to `nadine.piv@gmail.com` with your github username.

resolution. Each raster cell center represents a potential transmission tower and thus is modeled as a vertex in the graph. In order to meet Constraint 1, vertices that lie within avoidance areas are automatically excluded while the graph is set up.

Edges connect vertices and represent the conductors between two transmission towers. Which vertices are linked together by an edge, depends on their reachability. Any pair of vertices can reach each other if Constraints 1, 2 and 3 are met:

1. Avoidance areas, where conductors are not allowed to be suspended, are not allowed to be crossed by an edge. Vertices that intersect these areas are automatically eliminated.

2. The length of the edge has to comply with the span range, which is defined in Section 4.1.2. To that end, the origin vertex is consequently only connected to those vertices, which are within a distance between 200 meters and 600 meters.

3. The edges must comply with the ground clearance stipulated by law. Given that edges represent the conductors between two transmission towers, the sag is modeled for each edge. For that purpose, the formula introduced by Fischer & Kießling (2012) will be applied. The sag f_ξ at any position ξ is defined as follows:

$$f_\xi = 4 f_{max} \frac{\xi}{a}(1 - \frac{\xi}{a}) \tag{4.2}$$

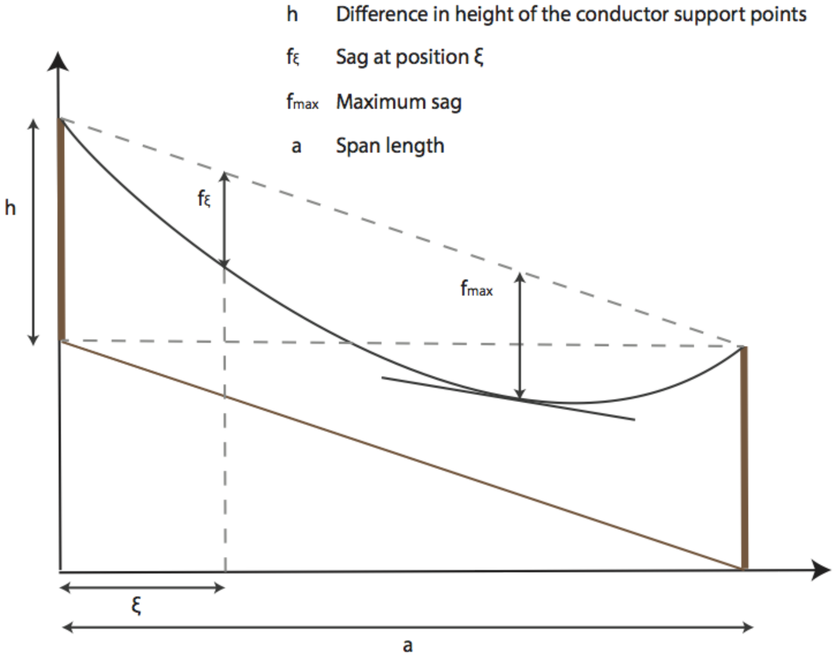

Figure 4.3 – Modeling the transmission line sag.

where f_{max} denotes the maximum sag and a the span between two transmission towers. In order to be able to compute f_ξ, f_{max} needs to be known. Equation 4.3 provides the formula to compute the maximum sag f_{max} :

$$f_{max} = \frac{m_c g \cdot a^2}{8H} \tag{4.3}$$

m_c corresponds to the rope mass $[kg/m]$ and H to the horizontal component of the rope tensile force $[N/mm^2]$. Since H strongly depends on the temperature, it must be calculated for extreme conditions. To that end, the following equation will be utilized:

$$H_2^2 \left[H_2 - H_1 + EA\frac{(m_{c1}g \cdot a)^2}{24H_1^2} + EA \cdot \epsilon_t (T_2 - T_1) \right] = \frac{EA(m_{c2}g \cdot a)^2}{24} \tag{4.4}$$

H_1 denotes the rope tensile force in normal conditions with temperature T_1 and rope mass m_{c1}. H_2 represents the rope tensile force in extreme conditions with temperature T_2 and m_{c2}. E and A are the elastic modulus and the rope diameter, respectively. The parameter values for transmission lines have been made available by Swissgrid AG.

Once having modeled the sag, it is compared to the digital elevation model. This is done by extracting in equal intervals[2] the elevation values from the digital elevation model and calculating the difference between the elevation and the sag. If the difference is smaller than the allowed ground clearance defined by law, the edge is excluded from the graph.

By integrating these constraints into the graph, the basic structure of the graph is created. However, there is one constraint, i.e. the angle of deflection, which has not yet been included in the graph. Since in a directed graph the sequence of three towers is not captured, it is not possible to include the deviation angle between two edges in the basic graph G. The next section will explain how this issue is tackled.

4.3.2.2 The Weighted Line Graph G'

In order to integrate the maximum deflection angle, the basic graph G (Figure 4.4a) is transformed into a line graph $G' = \{V', E'\}$ where V' denotes its set of vertices and E' its edges (Figure 4.4b). The transformation works according to two principles:

- *Basic graph edges E become line graph vertices V'.* For instance the edge AC in the original graph G becomes a vertex in the line graph G'.
- *Basic graph vertices V become line graph edges E'.* To illustrate that, we take vertex C of the basic graph G as example. In G there is the edge BC which leads to the vertex C and the edge CD which originates from the vertex C, i.e. both are connected by the vertex C. BC and CD of G are represented as vertex in G' and are connected by means of an edge because they have C in common and succeed each other.

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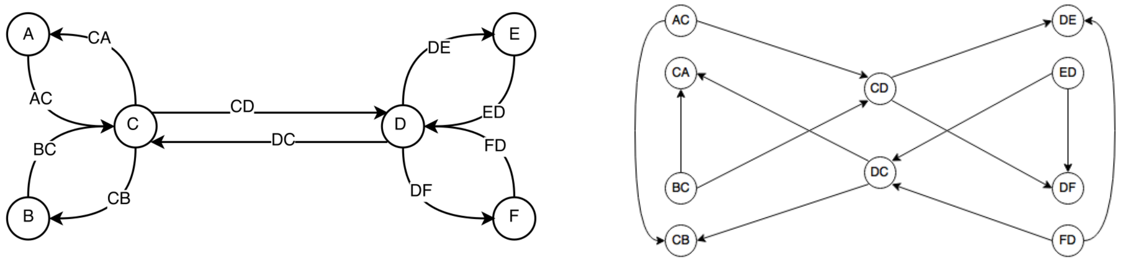
[2] As a function of the span, the intervals are 20 to 60 meters long.



(a) The original Graph G. **(b)** The line graph G'

Figure 4.4 – Transformation from the original graph G to the line graph G'.

In other words, if two vertices of G' are connected, they represent the connection of two edges in G. Thus, an edge in G' is well suited to represent the deflection angle between two edges in G. This allows us to integrate Constraint 4 by deleting all edges in G', which represent a connection between two edges in G whose angle is larger or equal 60°.

Once having included all constraints, the skeleton of the graph is built. However, before the LCP analysis can be performed, the weights of the edges E' need to be computed. The edge weights represent the optimization criteria and are composed of three optimization elements:

- *The cost surface* W_{CS}: W_{CS} corresponds to the weight of an edge in G', which is computed based on the cost surface. The cost surface mainly reflects the optimization criteria of the spatial planning as well as the environment and landscape dimensions but also includes some technical criteria such as the terrain roughness and the subsoil properties.

  Only the costs for the edge head in G' is computed because it is to be prevented that costs are computed twice. Let us explain that by means of an example. Assuming we have edge (BC, CD) in G', the head of the edge corresponds to CD. CD is also an edge in G. Thus, the costs of (BC, CD) corresponds to the added up costs of the two edges BC and CD in G. Two consecutive edges in G', let us say (BC, CD) and (CD, DF), have a vertex of G' in common, namely CD. The cost of the common vertex CD is not to be computed twice and therefore, only the cost of the edge head in G' is calculated.

  A zone of influence is defined since transmission lines are expected to impact their environment (Huber & Church 1985). The influence of transmission lines has been estimated to be 10 meters. Each cell value is assigned to the percentage of the influence zone it intersects. This percentage is then used to compute the weighted sum of all raster cell values that intersect the influence zone (Figure 4.5). This results in W_{CS}, the total cost of an edge head in G'. W_{CS} can obtain a value between 1 and 255.

- *The deflection angle* W_{DA}: As described in the problem definition in Section 4.1, the resulting route should encompass as few as possible angle towers due to economic reasons. This property is implemented by integrating the deflection angle into the weight of an edge in the line graph G'. Given that the maximum deflection angle corresponds to 60°, W_{CS} takes a value between 0 and 60.

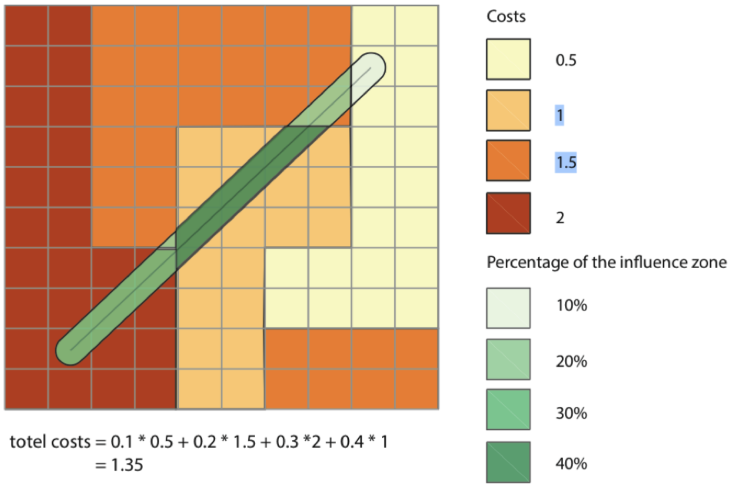


Figure 4.5 – Example for the weighting of an edge head in G' based on the cost surface. This results in the edge weight W_{CS}.

- *Intersections with existing linear infrastructures* W_{ILI}: In fact, the pooling of existing linear infrastructures is promoted in the cost surface by assigning low costs for raster cells where existing linear infrastructures (e.g. transmission lines, roads, railways etc.) are located. However, preliminary results have shown that the resulting LCP does not run in parallel to the existing linear infrastructures but intersects them repeatedly (Figure 4.6). In order to prevent this behavior of the route, the intersection of the route with existing linear infrastructures is integrated into the weight computation of the edge. This property further avoids difficult construction sites, which affect the traffic. As an edge is either intersecting a linear infrastructure or not, W_{ILI} is assigned to a Boolean value of 0 or 1.

By subdividing the edge weights into these three elements, the objective of this algorithm is to minimize along the route:

- The costs according to the cost surface
- The sum of deflection angles
- The number of intersections with linear infrastructures

Having calculated the three optimization elements W_{CS} , W_{DA} and W_{ILI} for each edge , they are normalized to a value between 0 and 1. The total weight of an edge can then be computed according to equation

$$w_{total} = c_{CS}w_{CS} + c_{DA}w_{DA} + c_{ILI}w_{ILI} \tag{4.5}$$

where c_{CS}, c_{DA} and c_{ILI} denote constants in the range of 0 to 1 and are used to weight the different optimization elements. The user can determine the constants. This allows him/her to

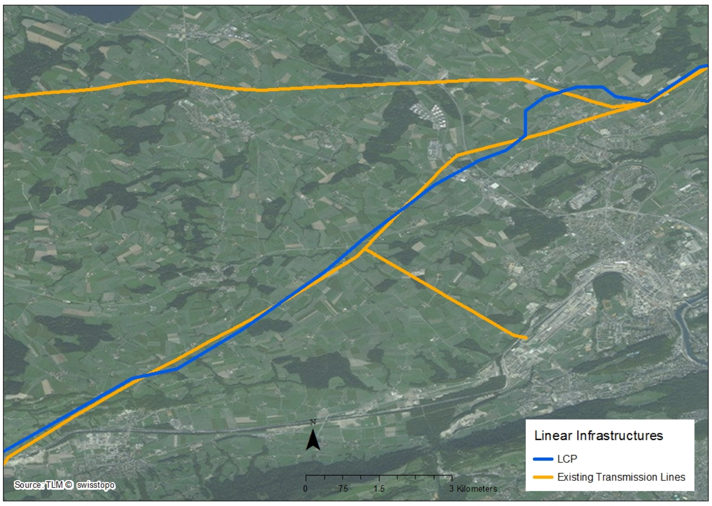


Figure 4.6 – Intersections between the LCP (blue) and an existing linear infrastructures (here: existing transmission lines (orange)).

decide to which degree the optimization criteria influence the computation of the route. The impact and the role of each optimization criteria has been investigated in Section 5.4.

4.3.2.3 Least Cost Path Analysis

After having created the basic graph, which is then transformed to a weighted line graph, the LCP can be computed. The LCP is computed based on the algorithm introduced by Dijkstra (1959) between a starting location S and a destination location D. To do that, some final adjustments have to be made in the graph. The vertices V_S and V_D in G, which are the closest vertices to the start and destination location S and D, need to be determined. All vertices in the line graph G', which include V_S or V_D, represent potential starting and destination vertices. In order to get unique starting and destination vertices in G', additional vertices V_S' and V_D' are added to the weighted line graph G'. They are accordingly connected to the vertices in G'.

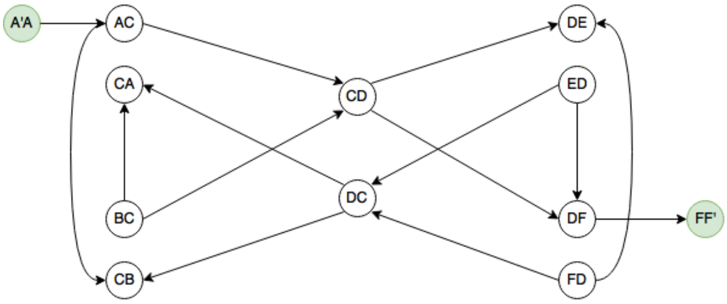


Figure 4.7 – The line graph G' with start and target vertices $A'A$ and FF'. Compare with Figure 4.4b

An example is illustrated in Figure 4.7. A and F corresponds to V_S and V_D, respectively. $A'A$ and FF' denote each V'_S and V'_D. The vertex $A'A$ is included in the line graph G' and is used as unique starting point to perform the LCP analysis. The weight of the edge that connects $A'A$ and AC is set to zero so that this edge has no influence on the final costs of a path. The same is done for the destination vertex F.

4.3.3 Novelties

The main differences between the novel approach and the baseline method can be summarized in four points:

1. Unlike in the baseline method, in the novel approach the route is not represented by a sequence of raster cells in a cost surface. The route corresponds to a path in a network. The vertices in the network represent the transmission towers and the edges correspond to the conductors between two towers.

2. The novel approach considers four additional constraints, which are not considered in the baseline method.

    - Two types of *avoidance areas* for transmission lines are defined in the novel approach: avoidance areas where it is neither allowed to build transmission towers nor to suspend conductors, and areas over which it is allowed to span conductors but in which it is prohibited to build transmission towers. Vertices and edges, which lie within these areas are accordingly excluded from the network.

      The baseline method assigns higher costs to avoidance areas. This kind of areas are thus not excluded from being traversed by a route.

    - The *span* of the conductor between two towers is defined by a minimum and a maximum distance. This constraint determines the connectivity of the graph: the larger the span range is, the more vertices are reachable from an origin vertex.

      In the baseline method, a vertex is only connected with the vertices it is surrounded by, i.e. those in the Queen's-Neighborhood (van Bemmelen et al. 1993).

    - *Ground clearance*: For a route computed by the novel approach, it is guaranteed that the ground clearance prescribed by law is met. This is not the case in the baseline method.

    - *Maximum angle of deflection*: Large angles of deflection are avoided whenever possible because they are more costly and technically more complicated to implement. This is why this constraint has been integrated into the novel approach by applying a line graph. In the baseline method, all angles are equally possible.

3. The baseline method aims at finding a sequence of raster cells in a cost surface such that the sum of their values is minimal. The novel approach optimizes not only the costs, but also minimizes both, the sum of deflection angles along the route and the number of intersections with existing linear infrastructures in order to favor pooling.

4. In the novel approach, the smoothing of the route is part of the optimization process by minimizing the angle of deflection while considering the cost surface and the intersections with existing linear infrastructures.

   However, for the baseline method a *post hoc* geometric route rectification, which is independent of the optimization procedure, is necessary.

Which impact the differences between both approaches have on the course of the route will be investigated and discussed in the following chapters.

4.4 Evaluation

This section provides the theoretical background to evaluate the outcomes of the novel approach base on a quantitative and a qualitative analysis. For the quantitative evaluation the baseline method and the novel approach are systematically compared based on numerical indicators, which are defined in Section 4.4.1. Interviews are conducted in order to qualitatively compare the novel approach with the baseline method. What kind of interviews will applied is described in Section 4.4.2. In order to investigate the effect and the importance of the optimization criteria, a sensitivity analysis is performed (Section 4.4.3).

4.4.1 Quantitative Evaluation: Indicators

The quantitative analysis compares the novel approach and the baseline methods based on route properties regarding the three dimensions *spatial planning*, *environment and landscape* as well as *technical implementation*. For that purpose, a range of indicators are defined for each dimension:

4.4.1.1 Spatial Planning Indicators

Transmission lines can be described by their impact on the spatial planning dimension. This route property is quantified by computing the length of the route that lies in areas with spatial planning functions. These surfaces encompass spatial planning zones and all kinds of infrastructures used by humans. They are represented in the Figures A.1 and A.2 in Appendix A where the blue and the green line correspond to the results of the novel and the baseline approach, respectively.

4.4.1.2 Environment and Landscape Indicators

Routes can be quantitatively characterized regarding their impact on the dimension environment and landscape dimension. This is done by computing the length of the route within surfaces of environmental and landscape matter. The indicator is further subdivided into its two components, environment and landscape, respectively, in order to investigate their individual effects. For that purpose, nature reserves and areas of protected landscape are taken into account separately. These surfaces are illustrated in the Figures A.3 and A.6 in Appendix A where the blue line and the green line correspond to the results of the novel and the baseline approach, respectively.

4.4.1.3 Technical Implementation Indicators

Concerning the dimension *technical implementation*, route properties can be expressed in various ways. We differentiate between indicators that are a measure for the dimensions of the route and its shape as well as those, which estimate the costs of a transmission line.

- *Dimensions of the route*: The dimensions of the route can be described by the route length, the number of towers and the difference in elevation. However, it must be noted that the latter indicator is strongly dependent on the terrain situation of the study area.
- *Shape of the route*: The shape of the route can be captured by measuring the straightness index and the mean terrain slope of the route. The straightness index corresponds to the ratio between the length of the route and the direct connection between the starting and destination point of the route. It can be used as indicator to express the degree to which a route is meandering: the higher the ratio, the less sinuous is the route.
- *Monetary costs estimation*: Based on the mean terrain slope and the length of the route, a first estimation of the monetary costs can be provided. This indicator is called *indicative costs*[3]. Furthermore, the number of suspension and angle towers is also an indication for the construction costs since suspension towers are considerably cheaper than angle towers.

4.4.2 Qualitative Evalution: The Interviews

In this work qualitative, semistructured experts interviews have been chosen as technique to qualitatively evaluate the outcomes of the novel approach. The interviews are organized such that the novel approach is compared with the baseline method.

4.4.2.1 Why Expert Interviews?

Qualitative, semi-structured expert interviews have been preferred over the quantitative approach of questionnaire surveys. Quantitative approaches aim at generalizing a complex problem to theories and at confirming hypotheses (Flick 2009). As investigated in the quantitative analysis before, generalizing indicators were computed to describe the entire route. However, they do not capture single situations along the route which are opposing them: Some sections of the modeled transmission line might particularly affect nature reserves or deteriorate the landscape, whereas other parts are especially difficult to implement from a technical point of view.

In order to obtain a geographically more differentiated view on the resulting routes, semi-structured expert interviews can be very insightful. Facts can be gathered that are difficult

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[3] The research group Geoinformation Engineering at ETH Zurich, who work on the project *Application of 3D Geographic Information Systems for transparent and sustainable planning of electric power systems*, has developed a function to compute this type of costs.

to accurately capture in numbers. It is for instance difficult to express numerically to which degree a transmission line has a negative impact on the aesthetics of a landscape. Furthermore, information are supplied which are not (yet) published or cannot be deduced from the literature. For instance, one may come to know about future projects of a municipality, which directly influence a transmission line project, or experts might directly provide suggestions for improvement. Experts dispose of local knowledge that can complete the entire picture and improve the quantitative evaluation of the outcomes.

Semi-structured Interviews: Qualitative interviews can be divided into two main categories: *structured* and *unstructured* Interviews (Martin 2007). In structured interviews, each interviewee is asked in the same order the same questions from a pre-established questionnaire to ensure that the answers are comparable (Edwards & Holland 2013). In contrast, unstructured interviews are not based on an interview guideline. The interviewees can freely talk about the topic from their own perspective and decide in which direction the discussion goes (Desai 2006).

According to Desai (2006) as well as Edwards & Holland (2013) there is a third type of qualitative interviews in empirical social research: *semi-structured* interviews. Questions are specified in an interview guide, but the interviewees can openly and freely formulate their responses. In contrast to structured interviews, it can be guaranteed that the main topics are addressed during the interviews without preventing the experts from developing their own ideas and thoughts (Desai 2006). In this study, qualitative, semi-structured interviews have been applied as questioning technique since there are certain topics that need to be covered but there should be no limits to the formulation of the answers.

Experts Interview: Meuser & Nagel (2009) describe experts interview as a type of semi-structured interviews, in which experts are questioned. An expert can be defined as a person who has knowledge that is specialized to a specific field of activity. Their expert know-how does not only consist of systematic expertise but also in many respects of practical knowledge (Bogner et al. 2002).

The type of the expert interview depends on its objective. Bogner et al. (Bogner et al. 2002) introduce in this context three types of expert interviews:

- The aim of expert interviews can be the *exploration* of a research field in order to generate hypotheses.
- In *systematizing expert interviews*, experts are assigned to the role of advisor. The expert's know-how is collected in order to complete and provide new insights to a given topic.
- *Theory-generating* expert interviews aim at conceptualizing expert knowledge to a generalized theory.

In this study, the role of the expert interviews is to complete the quantitative evaluation of the results. Their expertise allows the experts to judge whether a route is realizable in terms of factors they consider important for practical applications. Hence, the systematized expert interviewing technique is applied in this thesis.

4.4.2.2 Conducting the Expert Interviews

In the following paragraphs, the procedure is described how the expert interviews have been prepared, conducted and evaluated.

Interview guide: A key element of preparing expert interviews is to draw up an interview guide. The aim of an interview guide is to support and lead the narrative string of the interview (Flick 2009). This prevents the interviewer and interviewee from getting lost in topics of low relevance and ensures that each interview is structured similarly (Meuser & Nagel 2009). For this thesis, the expert interviews are structured into three blocks, whereby each block is dedicated to answer one key question.

In the first block, general information about the professional background and the specialization of the expert are collected. Block one aims to answer the following key question:

> *What is the **expert's role** in the energy sector?*

The second block addresses *RQ1*, which aims at comparing the novel approach with the baseline method. For that purpose, the experts are asked to compare the results of both methods in relation to the three dimensions *spatial planning*, *environment and landscape* as well as *technical implementation*. Questions to the three dimensions are enumerated in the interview guide in Appendix B. In order to facilitate the investigation of the different path solutions, the experts have been provided with a 3D visualization of both routes on Google Earth in addition to different maps representing information concerning the different dimensions (see Figures A.1 to A.6 in Appendix A). At the end of each dimension, the experts have been requested to answer the wrap-up questions regarding the dimension at issue in the questionnaire (Figure B.2 in Appendix B). Based on that, the key question for the second Block is formulated as follows:

> *What is the difference between the routes of the novel approach and the baseline method according to the three dimensions **spatial planning, environment and landscape** as well as the **technical implementation**?*

The objective of the third block is to investigate whether the experts could apply the novel approach in their day-to-day work and if it could contribute to the improvement and acceleration of the planning process of overhead transmission lines. In this sense the purpose of Block three is to answer *RQ3* and the following key question:

> *Could the novel approach be applied in **practice** and how does it contribute to the **planning process** of overhead transmission lines?*

Participants: The interviews were conducted with six experts in total (Table 4.3). The participants were mainly project and construction managers of transmission line projects, who are working for the Swiss electricity company BKW Energie AG and the transmission grid operator Swissgrid AG. One expert works for the consulting company AF-Consult Switzerland AG, which has been strongly involved in the implementation of the existing transmission lines in the study area between Mettlen and Innertkirchen. The qualitative evaluation of the transmission line routes is therefore limited to the point of view of the energy sector.

Table 4.3 – Overview of the experts with whom the interviews were conducted.

Expert	**Affiliation**	**Position**	**Years of experience in the domain**
1	BKW Energie AG	Head of Engineering	7
2	BKW Energie AG	Transmission line project manager	5
3	BKW Energie AG	Transmission line project manager	29
4	BKW Energie AG	Transmission line project manager	16
5	Swissgrid AG	Principal Engineer Grid Infrastructure	35
6	AF-Consult Switzerland AG	Head of the Group *Planung und Bau*	24

Transcription: In this Master's thesis a *selective* transcription has been chosen. The interviews were filtered by applying a *short cut strategy*, which suggests to transcribe *"only as much as needed"* (Strauss 1987, p. 266), i.e. only those parts of the interview which are relevant to the research questions (Flick 2009, Strauss 1987).

The interviews were consistently transcribed according to *simple* transcription rule system, which is based on the one introduced by Kuckartz (2014) and refined by Dresing & Pehl (2013). This type of transcription rule system is recommended when the focus of the interview evaluation is on the content of the expert's statements and not on non-verbal expressions.

4.4.3 Sensitivity Analysis

According to research question *RQ2*, this Msc thesis aims at investigating the impact of the additionally integrated technical factors. For that purpose, a sensitivity analysis of the optimization criteria is performed based on factorial designs.

4.4.3.1 Model Definition

Sensitivity analyses allow determining numerically how changes in the input variables impact the outcomes. Hence, a sensitivity analysis investigates which input variable contributes most to the output variability. In order to perform a sensitivity analysis, the input and output variables need to be defined and quantified in an initial step.

Since the weights of the optimization elements determine the resulting route, they correspond to the input variables in our model:

- *Weight of the cost surface*: This weight determines how strongly the costs caused by transmission lines enter into the computation of the route. It is presumed that the stronger the cost surface is weighted, the smaller the impact will be on the dimensions *spatial planning* and *environment and landscape.*

- *Weight of the deflection angles*: The degree to which a route is straightened is regulated by the weight of deflection angles. It is expected that the lesser this optimization criterion is weighted, the longer and more meandering the resulting route will be.

Table 4.4 – Output variables of the sensitivity analysis in terms of the three dimensions defined in Section 4.4.1.

Dimension	**Output Variables**
Spatial Planning	Impact on the spatial planning areas
Environment and Landscape	Impact on environment and landscape areas
Technical Implementation	Length
	Sinuosity
	Mean terrain slope
	Indicative Costs
	Share of Suspension Towers

- *Weight of the number of intersections with linear infrastructures*: The weight of the number of linear infrastructure intersections is also expected to have a considerable influence on the computed route. It is supposed to prevent linear infrastructure intersections as much as possible and to promote pooling between the resulting transmission line and existing linear infrastructures.

From the indicators defined in Section 5.2.1, seven are considered for the sensitivity analysis (Table 4.4). Regarding the spatial planning and the environment and landscape dimension, the indicators that express the corresponding impact are used as output variables. To describe the technical implementation dimension, only the length, the sinuosity, the mean terrain slope, the indicative costs and the share of suspension towers will be taken into consideration as output variables for the sensitivity analysis. The number of towers is ignored given that it is most likely highly correlated with the route length. As the difference in altitude strongly depends on the study area, it is not advisable to use it for a sensitivity analysis.

4.4.3.2 Factorial Designs

Factorial designs are a method used to investigate the effect of the input variables on the output (Martin 2007, Jain 1991, Anderson & Whitcomb 2015). In factorial designs, factors correspond to the input variables, which are also called independent variables. In this research, there are three factors that are investigated: the weight of the cost surface, Factor A; the weight on the sum of angles, Factor B; and the weight of the number of intersections with linear infrastructure, Factor C. The output variables correspond to the indicators described in Section 4.4.3.1. The impact of the factors on the output variables, in other terms the dependent variables, is usually unidirectional, i.e. either continuously increasing or decreasing (Martin 2007). It is for example expected that the larger the Factor B is, the shorter the route will be. The factor designs method assumes discretized factor values. The common approach is to reduce the factors to two levels: The low level ($-$), corresponding to the value 0, i.e. the factor does not occur or is ignored, and the high level ($+$), which is assigned to the value 1, i.e. the factor occurs or is taken into consideration (Table 4.5).

We then compute for both levels the investigated output variable. Being given the 3 factors

Table 4.5 – Factor levels.

Factor	**Low level** $(-)$	**High level** $(+)$
A	0	1
B	0	1
C	0	1

Table 4.6 – Dependent Variables for the 2^3 experiments.

Experiment	I_A	I_B	I_C	y
1	$+$	$+$	$+$	O_1
2	$+$	$+$	$-$	O_2
3	$+$	$-$	$+$	O_3
4	$+$	$-$	$-$	O_4
5	$-$	$+$	$+$	O_5
6	$-$	$+$	$-$	O_6
7	$-$	$-$	$+$	O_7
8	$-$	$-$	$-$	O_8

and 2 levels, we have $2^3 = 8$ experiments, leading to eight possible values O_1, O_2,...,O_8 for each output variable (Table 4.6)[4].

Based on these experiments the main effects and the importance of the factors can be computed.

4.4.3.3 Effects and the Importance of Factors

Main effects express the impact of a factor on an output variable, ignoring the effects of all other factors. It can be defined as difference of the output means when factor levels are low or high, respectively (Anderson & Whitcomb 2015).

The underlying model assumes that for each factor, say K, there is a quantity Q_K which is added to the mean output Q_0 (see Equation 4.6):

$$Q_0 = \frac{1}{8}(O_1 + O_2 + O_3 + O_4 + O_5 + O_6 + O_7 + O_8) \tag{4.6}$$

Q_K can be interpreted as the effect of the factor K on the output. The model goes even a step further and captures effects caused by *interactions* between factors. These interactions occur when both factors are at the same level, i.e. both high or both low. The quantity Q_{KL} will be added to Q_0 when the level of both factors K and L are equal and subtracted otherwise. Thus, Q_{KL} captures quantitatively the effect of the interaction between K and L.

Output O_1 to O_8 can be captured in an equation in which the quantities $Q_\bullet$ of each factor

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[4] The factors could have been discretized into more levels in order to obtain more detailed results. However, the number of experiments would increase exponentially in terms of the number of factors and polynomially regarding the number of levels.

and their interactions are added or subtracted from the mean output Q_0 depending on the level of each factor defined in Table 4.6. Thus, in an equation system, the model can be defined as follows:

$$O_1 = Q_0 + Q_A + Q_B + Q_C + Q_{AB} + Q_{AC} + Q_{BC} + Q_{ABC} \tag{4.7}$$

$$O_2 = Q_0 + Q_A + Q_B - Q_C + Q_{AB} - Q_{AC} - Q_{BC} - Q_{ABC} \tag{4.8}$$

$$O_3 = Q_0 + Q_A - Q_B + Q_C - Q_{AB} + Q_{AC} - Q_{BC} - Q_{ABC} \tag{4.9}$$

$$O_4 = Q_0 + Q_A - Q_B - Q_C - Q_{AB} - Q_{AC} + Q_{BC} + Q_{ABC} \tag{4.10}$$

$$O_5 = Q_0 - Q_A + Q_B + Q_C - Q_{AB} - Q_{AC} + Q_{BC} - Q_{ABC} \tag{4.11}$$

$$O_6 = Q_0 - Q_A + Q_B - Q_C - Q_{AB} + Q_{AC} - Q_{BC} + Q_{ABC} \tag{4.12}$$

$$O_7 = Q_0 - Q_A - Q_B + Q_C + Q_{AB} - Q_{AC} - Q_{BC} + Q_{ABC} \tag{4.13}$$

$$O_8 = Q_0 - Q_A - Q_B - Q_C + Q_{AB} + Q_{AC} + Q_{BC} - Q_{ABC} \tag{4.14}$$

The quantity Q_{ABC} is related to the interaction between the three factors. It can be interpreted as the interaction observed when an odd number of factors are on the same level. Considering Q_0, Q_A, Q_B, Q_C, Q_{AB}, Q_{AC}, Q_{BC} and Q_{ABC} as unknowns, the system can be solved as follows:

$$Q_0 = \frac{1}{8}(O_1 + O_2 + O_3 + O_4 + O_5 + O_6 + O_7 + O_8) \tag{4.15}$$

$$Q_A = \frac{1}{8}(O_1 + O_2 + O_3 + O_4 - O_5 - O_6 - O_7 - O_8) \tag{4.16}$$

$$Q_B = \frac{1}{8}(O_1 + O_2 - O_3 - O_4 + O_5 + O_6 - O_7 - O_8) \tag{4.17}$$

$$Q_C = \frac{1}{8}(O_1 - O_2 + O_3 - O_4 + O_5 - O_6 + O_7 - O_8) \tag{4.18}$$

$$Q_{AB} = \frac{1}{8}(O_1 + O_2 - O_3 - O_4 - O_5 - O_6 + O_7 + O_8) \tag{4.19}$$

$$Q_{AC} = \frac{1}{8}(O_1 + O_2 + O_3 + O_4 + O_5 + O_6 + O_7 + O_8) \tag{4.20}$$

$$Q_{BC} = \frac{1}{8}(O_1 - O_2 - O_3 + O_4 + O_5 - O_6 - O_7 + O_8) \tag{4.21}$$

$$Q_{ABC} = \frac{1}{8}(O_1 - O_2 - O_3 + O_4 - O_5 + O_6 + O_7 - O_8) \tag{4.22}$$

Equation 4.16 to 4.22 thus allow us to measure the absolute effect of each factor and interaction with respect to the mean output Q_0. As determined in Section 4.4.3.1, the effects of the factor and their interactions are computed for seven indicators defined as output variables. In order to be able to compare the impact of the different indicators, the ratio with the mean output Q_0 is calculated:

$$R_i = \frac{Q_i}{Q_0} \qquad (i = A, B, C, AB, AC, AB, ABC) \tag{4.23}$$

A negative value for R_i signifies that when a given factor is augmented, the output decreases. The opposite is true if the ratio is positive.

According to Jain (1991) the importance of a factor corresponds to *"the proportion of the total variation in the response that is explained by the factor"*(Jain 1991, p. 868). To that end, the total variation of the output O, also called the *Sum of Squares Total* (SST), is computed according to the following equation:

$$SST = \sum_{i=1}^{2^3} (O_i - Q_0)^2 \tag{4.24}$$

which is the same as:

$$SST = 2^3 Q_A^2 + 2^3 Q_B^2 + 2^3 Q_C^2 + 2^3 Q_{AB}^2 + 2^3 Q_{AC}^2 + 2^3 Q_{BC}^2 + 2^3 Q_{ACB}^2 \tag{4.25}$$

Equation 4.25 consists of seven parts. Each one corresponds to the portion of the total variation explained by the effect of the Factors A, B, C and their interactions AB, AB, AC as well as ABC. Thus, the equation could also be formulated this way:

$$SST = SSA + SSB + SSC + SSAB + SSAC + SSBC + SSABC \tag{4.26}$$

The percentage variation of a factor (see the example for Factor A in Equation 4.27) represents its importance. The higher the percentage of variation, the more important can the factor be considered.

$$\text{Percentage of variation explained by Factor} A = \frac{SSA}{SST} \tag{4.27}$$

Chapter 5

Results and Evaluation

This section is dedicated to presenting and evaluating the outcomes of the novel approach. In order to do that the route that resulted from the novel approach will be systematically compared to the one of the baseline method in a quantitative and qualitative analysis. In Section 5.1, the routes, which were computed based on the novel approach and the baseline methods, are presented. The outcomes of the quantitative and qualitative evaluations are described in Sections 5.2 and 5.3. Section 5.4 presents the results of the sensitivity analysis.

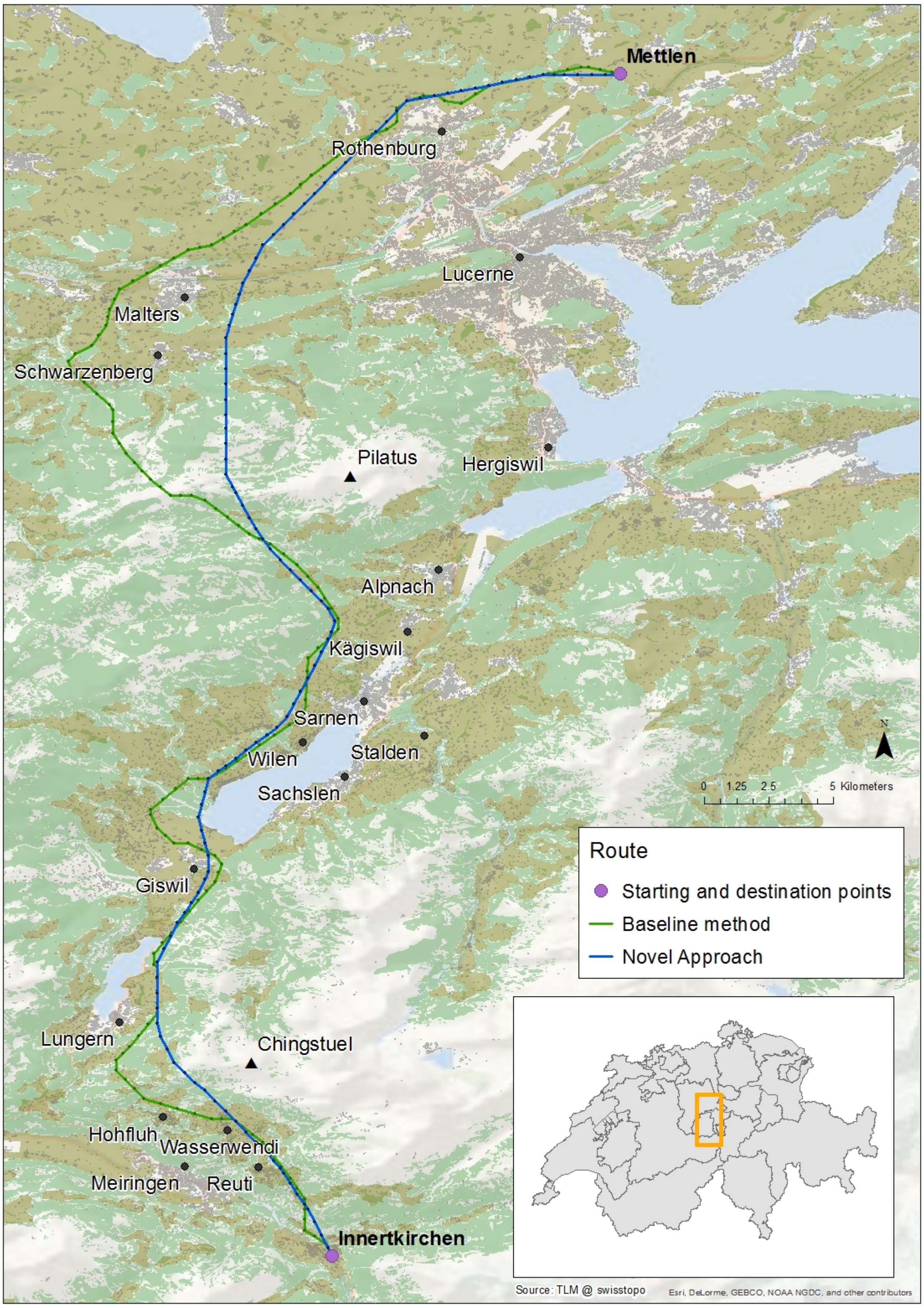
5.1 Results

5.1.1 Study Area

The novel approach has been tested by computing the route for the transmission line between Mettlen (Canton Lucerne) and Innertkirchen (Canton Bern). Both places are already connected by a 61 kilometers long 220 kV transmission line. However, 51 kilometers of the line are older than 60 years and do not meet present-day technology standards (Bundesamt für Energie BFE 2001). Furthermore, the existing transmission line traverses the UNESCO Biosphere Reserve Entlebuch in which various mires and other environmentally sensitive objects are located. The laws protecting these nature reserves, have been issued several years after the construction of the line. Therefore, the existing transmission line needs to be replaced by a 380 kV transmission line which takes into consideration not only the technical aspects, but also spatial planning as well as environment and landscape criteria.

5.1.2 Data

The novel approach as well as the baseline method require as input data a cost surface. The cost surface is a raster in which the value of each cell corresponds to the cost for building transmission lines. In other terms, the costs express the spatial resistance imposed on transmission lines.



Source: TLM @ swisstopo Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

Figure 5.1 – Resulting routes of the baseline method (green line) and the novel approach (blue line) between Innertkirchen (Canton Bern) and Mettlen (Canton Lucerne).

This cost surface has been computed based on the criteria enumerated in Table 4.2. The MCDA technique described in Section 4.2 has been applied to that end.

5.1.3 Parameter Setting

As described in Section 4.3.2, different parameters need to be initially determined. On the one hand, the constraints, on the other hand, the weighting of the optimization criteria need to be defined.

Parameters regarding the constraints have been defined as follows:

- Both types of *avoidance areas* initially encompass settlements. As a first step, water bodies and strictly protected reserves have been ignored given the risk that no path is found when excluding too many areas from the routing analysis.
- As suggested by experts, the *span range* is determined between 200 and 600 meters.
- Based on the LeV (1994), a *ground clearance* of 7 meters vertical distance is considered in the algorithm.
- A *maximum deflection angle* of 60° is defined.

The intensity to which optimization criteria influence the resulting route depends on how strong the optimization elements W_{CS}, W_{DA} and W_{ILI} are weighted by the constants c_{CS}, c_{DA} and c_{ILI}. In this thesis c_{CS} and c_{DA} are equal to 1.0, whereas c_{ILI} is assigned to 0.5. A smaller weight has been chosen given that the Boolean value of W_{CS} has a stronger impact on the output compared to the other two normalized optimization elements.

5.1.4 Routes of the Novel Approach and the Baseline Method

The resulting routes of the baseline method (green line) and the novel approach (blue line) are visualized in Figure 5.1. The blue line is 56.5 kilometers long and encompasses 119 transmission towers. As a counterpart, the green line has a length of 67.5 kilometers and comprises 152 towers. The novel approach and the baseline method generated routes that are similar between Innertkirchen and Wasserwendi, between Lungern and Giswil, from the left lakeside of the Lake Sarnen until their traverse of the foothills of Mount Pilatus and between Rothenburg and Mettlen. Along the resembling sections of both routes, the green line is often meandering whereas the blue line has a rather straight character.

However, there are three situations where the blue line takes a shortcut compared to the solution of the baseline method (Figure 5.1.4):

- The *short cut 1* between Wasserwendi and Lungern.
- The *short cut 2* near Giswil.
- The *short cut 3* which starts at the foothills of Mount Pilatus and finishes near Rothenburg.

Hereafter, both routes are evaluated based on a quantitative and a qualitative analysis. In the quantitative evaluation (Section 5.2), the results of the novel and the baseline method, respectively, are systematically compared based on indicators that quantify the route properties. In the qualitative part of the evaluation (Section 5.3), the results of the novel and the baseline method are evaluated by means of expert interviews. The opinions and statements of the interview participants will be used to qualitatively assess the results and to discuss whether the novel approach could contribute to today's planning process of transmission lines. Furthermore, a sensitivity analysis of the optimization criteria will be performed (Section 5.4). The goal in this context is to quantitatively capture the impact of the newly integrated technical elements on the resulting transmission route.

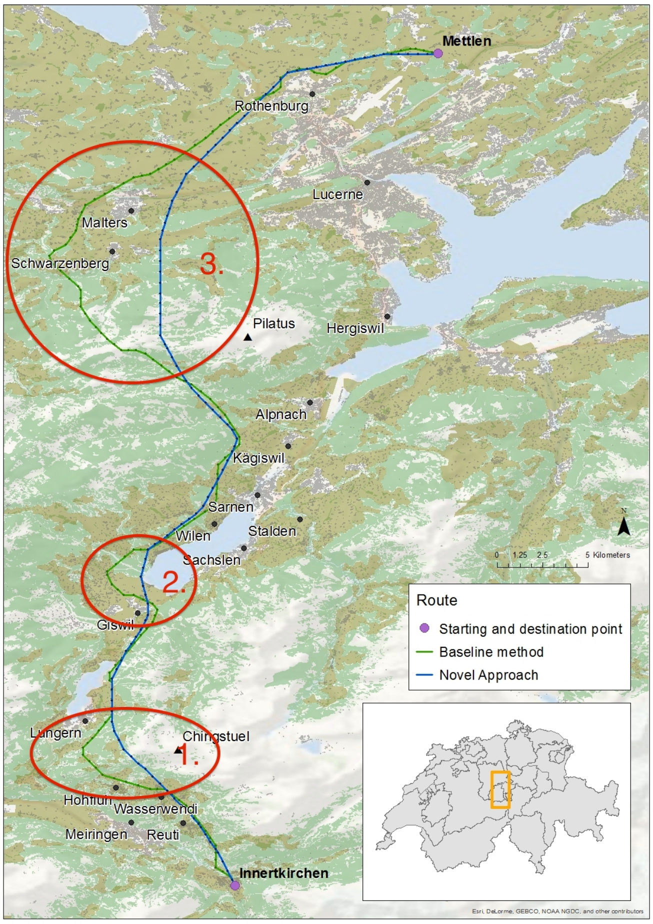


Figure 5.2 – The three shortcuts taken by the route of the novel approach compared to the results of the baseline method.

5.2 Quantitative Evaluation

In this section, the *RQ1* will be addressed by means of a quantitative evaluation of the novel approach. To that end, the routes between Mettlen and Innertkrichen that result from the novel approach and the baseline methods, respectively, are quantitatively compared based on the indicators defined in Section 4.4.1 (Table 5.1).

Table 5.1 – Overview of indicators and their values for the routes of the novel approach and the baseline method.

Dimension	**Indicator**	**Novel approach**	**Baseline method**
Spatial Planning	Impact on spatial planning areas	1'554 m	1'596 m
Environment and Landscape	Impact on environment and landscape areas	7'530 m	6'359 m
	Impact on landscape areas	5'849 m	5'205 m
	Impact on environment areas	1'940 m	1'247 m
Technical Implementation	Length	56'590 m	67'425 m
	Number of towers	119	152
	Difference in elevation	1'377 m	1'283 m
	Straightness index	0.82	0.69
	Mean terrain slope	13.66 °	13.77 °
	Indicative costs	141'500'000 CHF	236'000'000 CHF
	Number of suspension towers	84	82
	Number of angle towers	34	69

5.2.1 Spatial Planning Indicators

Only 2% to 3% of the routes computed by both approaches affect areas with spatial planning matter. As Table 5.1 shows, 1'554 meters of the blue line intersect spatial planning areas, which corresponds to a slightly smaller impact on the spatial planning dimension compared to the green line. However, by looking more closely at the intersections between the routes of both approaches and the spatial planning surfaces, it becomes apparent that there are three situations with high impact on the spatial planning dimension.

- As can be seen in Figure 5.3, the first high impact situation is around Innertkirchen and Meiringen where a couple of intersections can be found. Transmission lines concern especially population close to the power station of Innertkirchen. According to the number of intersections, the route computed by the baseline method seems to affect the population stronger than the novel approach. Subsequently, it can be observed that both routes traverse scattered settlements whereby the blue line crosses a couple of times single buildings. Near Wasserwendi, both transmission lines approach again residential zones. The green line even crosses them at a narrow part.

- The next high impact situation is located near Giswil (Figure 5.4). Southwest of the village, both routes traverse a stone pit. After that, the paths start to diverge. On the one hand, the blue line crosses twice an industrial and commercial zone as well as the tourism and recreation zone by the lake. On the other hand, the green line bypasses the spatial planning area and encounters occasionally single buildings in scattered settlements.
- The third high impact situation is located in the industry zone close to Rothenburg where both routes cross an industrial and commercial zone (Figure 5.5).

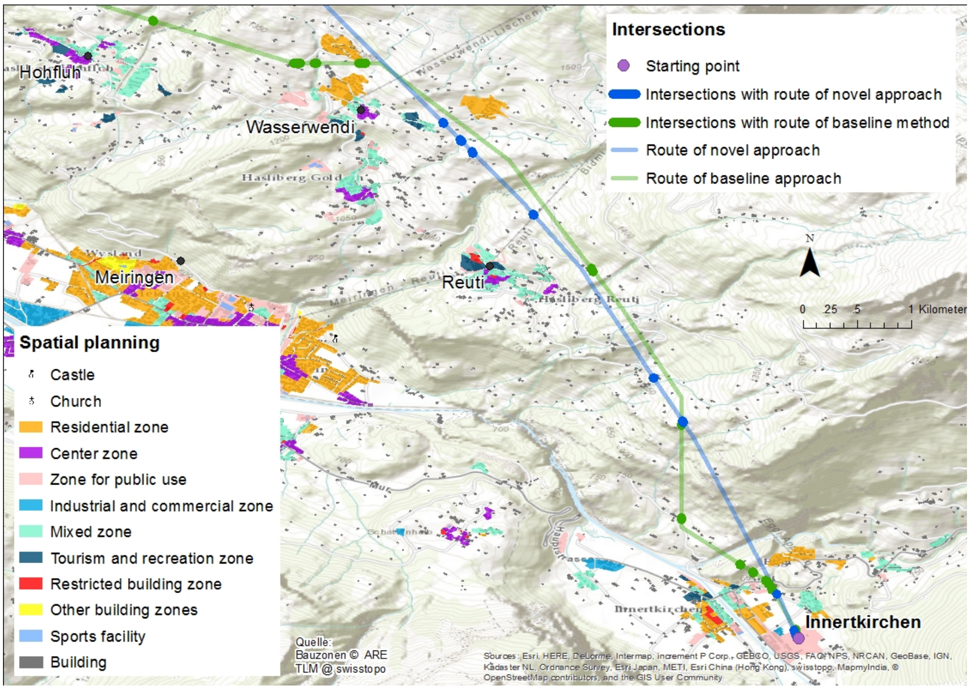


Figure 5.3 – Intersections between spatial planning areas and the routes of both approaches near Innertkirchen and Meiringen.

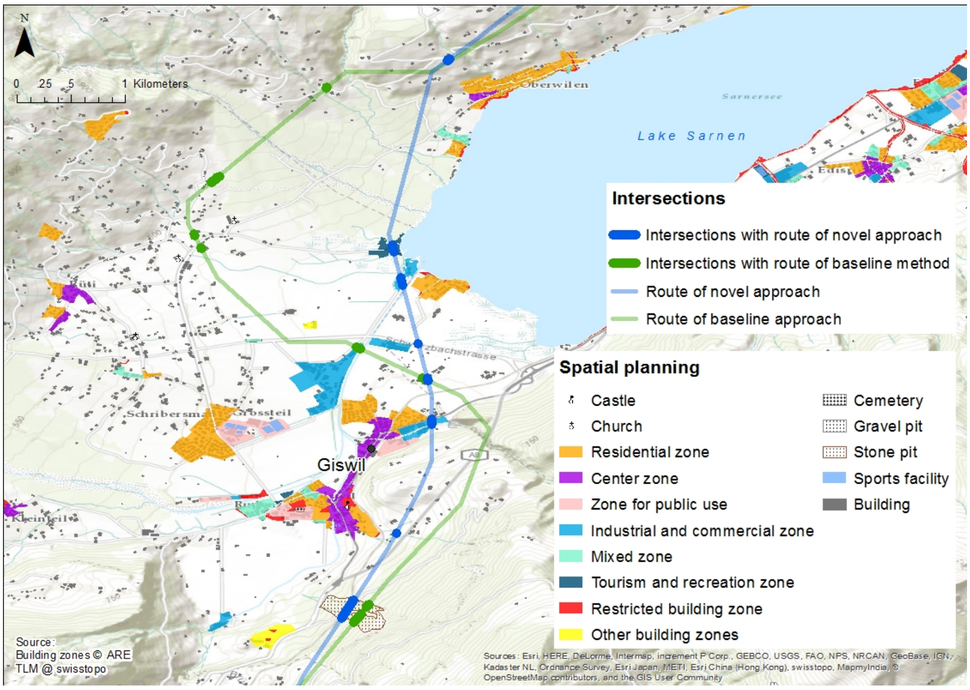


Figure 5.4 – Intersections between spatial planning areas and the routes of both approaches near Giswil and along the Lake Sarnen.

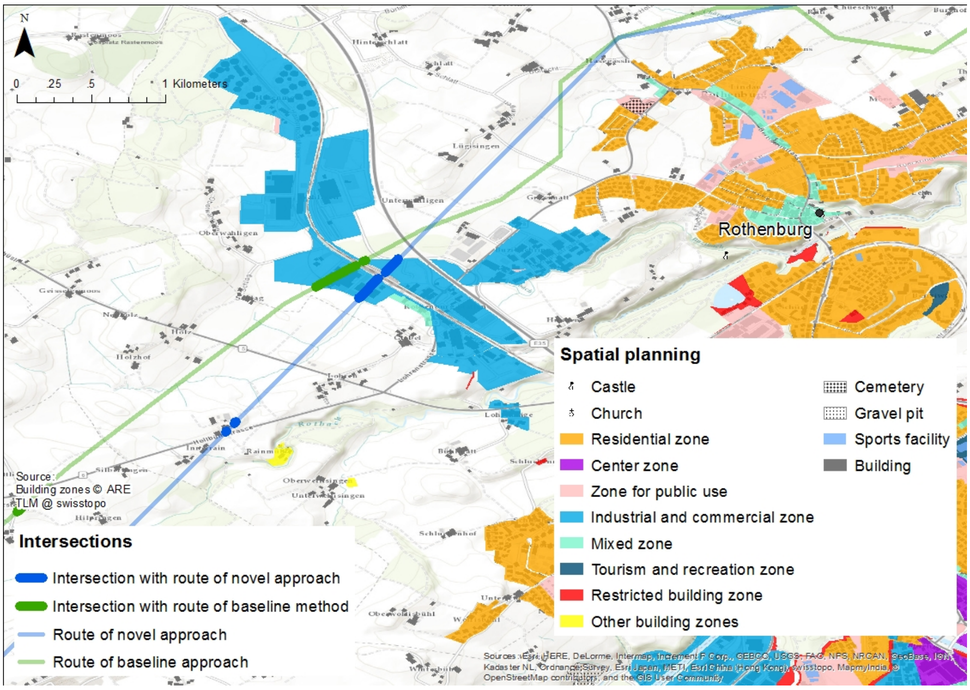


Figure 5.5 – Intersections between spatial planning areas and the routes of both approaches near Rothenburg.

5.2.2 Environment and Landscape Indicators

According to Table 5.1, the blue line affects to 1'171 meters more the dimension environment and landscape than the green line. Both routes have a significantly larger impact on areas with landscape protection function than on the environmentally sensitive areas (compare the indicators *impact on landscape* and *impact on environment* in Table 5.1).

By taking a closer look at the intersections along both routes, it appears that there are two situations with particularly large impact on the environment and landscape dimension:

- First, there are a lot of environmental protection areas near Giswil (Figure 5.6). Both routes, the blue line and the green line, traverse long distances within river areas with high biodiversity. Also the meadow at the river ravine that leads into the Lake Sarnen is severely affected, especially by the blue line. The green line first, bypasses these delicate areas and then crosses the meadow at its narrow parts.

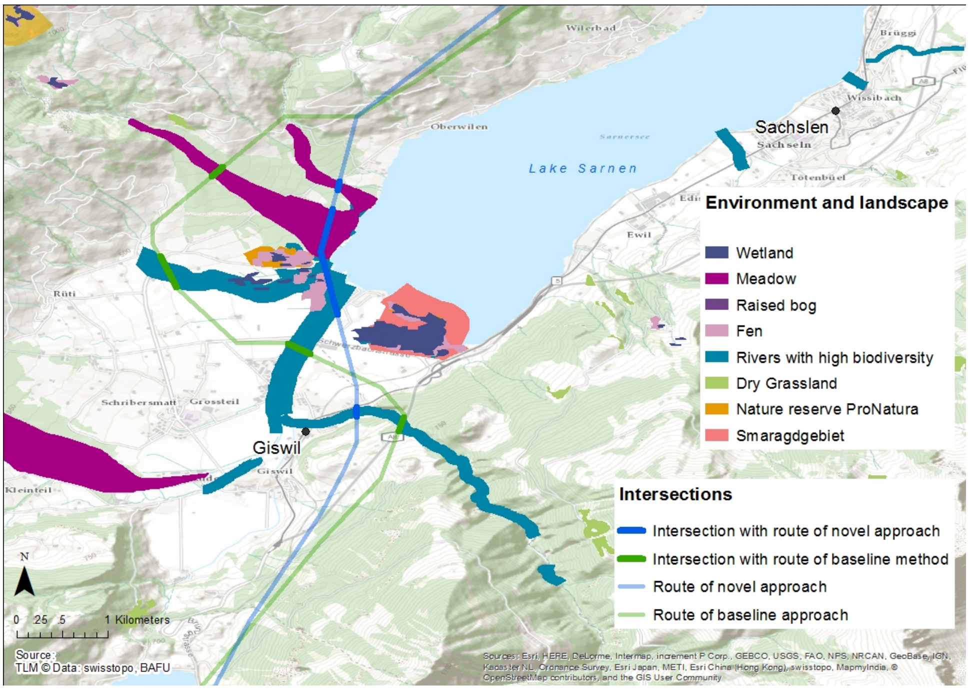


Figure 5.6 – Intersections between environment and landscape areas and the routes of both approaches near Giswil.

- Second, large distances of both routes traverse the Federal Inventory of Landscapes and Natural Monuments near Mount Pilatus (Figure 5.7). That explains also the high values for the impact on the landscape. In the same area, both routes cut through dense clusters of wetlands and fens.

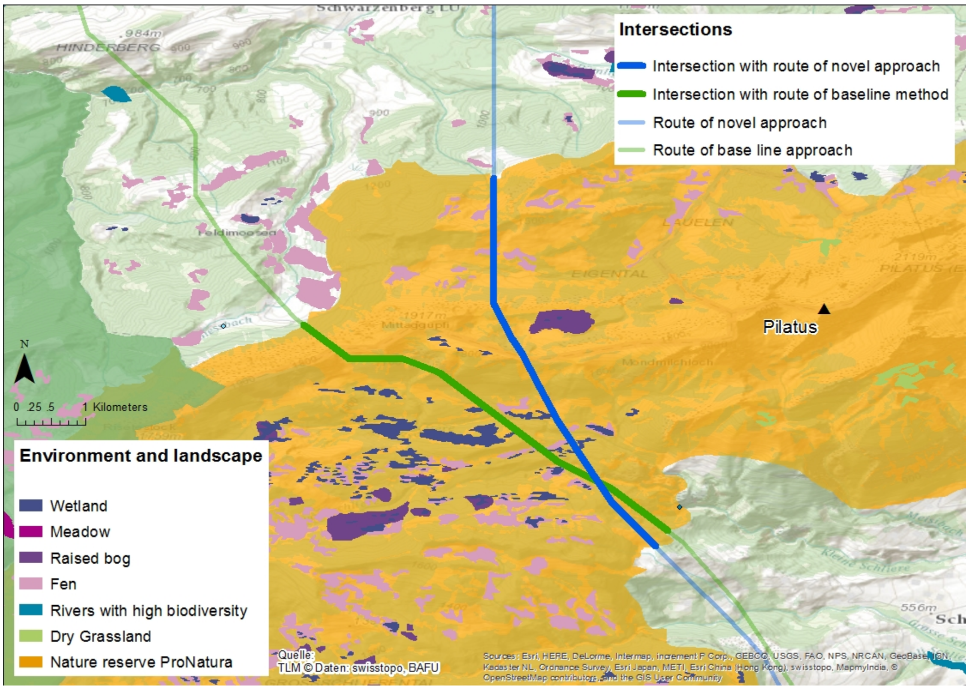


Figure 5.7 – Intersections between environment and landscape areas and the routes of both approaches at the foothills of Mount Pilatus.

5.2.3 Technical Implementation Indicators

As can be inferred from Table 5.1, the route of the novel approach is approximately ten kilometers shorter and encompasses nearly 22% fewer towers than the route of the baseline method. With an elevation difference of 1’283 meters, the route of the baseline method approximatively covers 100 meters less elevation than the one of the novel approach. Regarding the shape of the routes, the modeled transmission line of the novel approach appears to be closer to the direct connection between Innertkirchen and Mettlen. Hence, its straightness index is higher compared to the one of the baseline method. The mean terrain slope is nearly the same for both. As can be deduced from Figure 5.8, the statistics of both routes regarding the terrain slope resemble each other. The large standard deviation indicate that the terrain slope is strongly spread out around the mean for both routes. The minimum terrain slope for both solutions are quasi equal (blue line: 0.3°, green line: 0.2°), whereas the maximum slope of the green line is slightly steeper than the one of the blue line (blue line: 42.8186°, green line: 46.3364°). Given the large standard deviation, it is important to investigate the distribution of the terrain slope (Figure 5.9). Both distributions look similar. The slope angles are most frequently between 0° and 5°. The major difference between both distributions, is that the baseline method has many slope angles between 45° and 50°, whereas the novel approach has none in this range.

Since the indicative costs depend on the mean terrain slope and the length of a transmission line, the route of the novel approach costs approximately 20% less than the one of the baseline method. Also the type of transmission towers indicates that the route of the novel approach

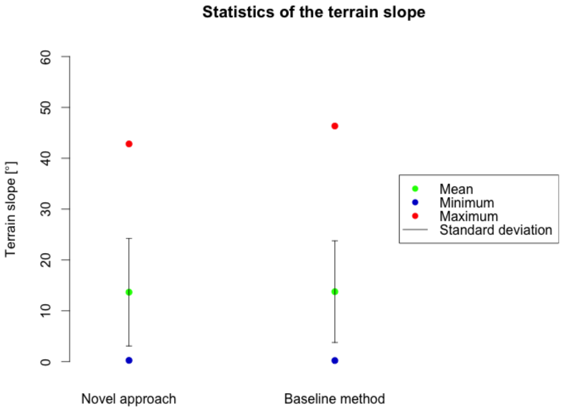


Figure 5.8 – Statistics of the blue line and the green line regarding the terrain slope.

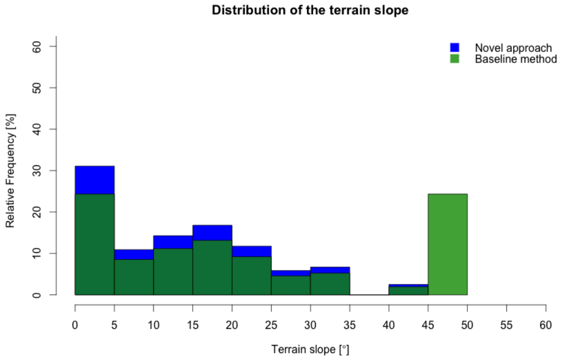


Figure 5.9 – Distributions of the terrain slope of the blue line and the green line.

would be a financially more favorable solution. 70% of the transmission towers have an angle equal to or less than 3° (Figure 5.11). The route of the baseline has a share of 53% suspension towers. The statistics concerning the deflection angles further confirm these observations (Figure 5.10). The mean as well as the maximum deflection angle of the blue line are significantly lower than the ones of the green line (blue line: 3.5° and 39.9°, green line: 12.4° and 62.3°). From a performance perspective, it would have been beneficial for the novel approach to reduce Constraint 4 from 60° to 40° as the maximum deflection angle along the blue route corresponds to 39.9°. The large standard deviation of the green line further indicates that the deflection angles are more spread out than the ones of the blue line.

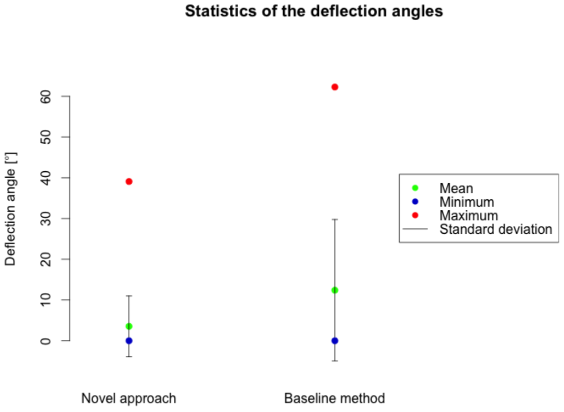


Figure 5.10 – Statistics of the blue line and the green line regarding the deflection angles.

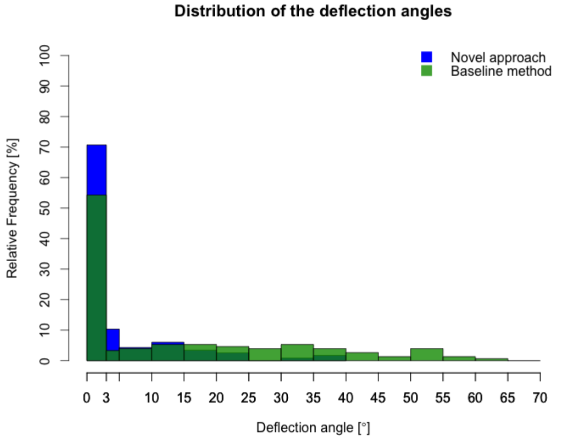
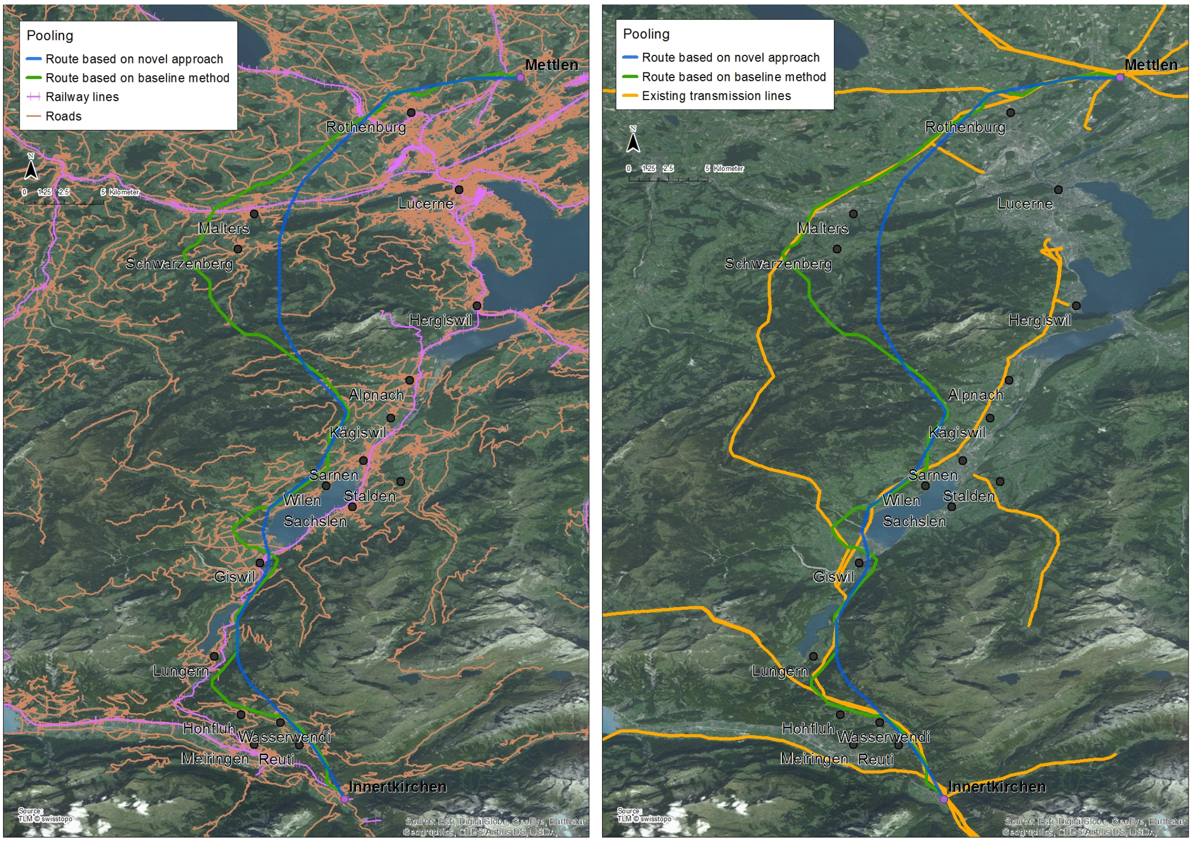


Figure 5.11 – Distributions of the deflection angles of the blue line and the green line.

A technical route property that has not been included as indicator is the degree to which the computed route is pooling with existing linear infrastructures. However, it still has been investigated based on map visualizations.



(a) Pooling situations of the routes based on the novel approach and the baseline method with roads and railway lines.

(b) Pooling situations of the routes based on the novel approach and the baseline method with existing transmission lines.

Figure 5.12 – Pooling situations of the routes based on the novel approach and the baseline method with existing linear infrastructures.

As shown in Figure 5.12a, only one pooling situation with roads and railway lines can be observed. On the east side of Giswil both routes, the green and the blue line, follow railway tracks over a distance of approximately four kilometers. More pooling situations can be identified with existing transmission lines (Figure 5.12b). Especially the green line follows the energy infrastructures from Malters to Mettlen and from Innertkirchen to Giswil. However, both routes repeatedly intersects the transmission lines and run only for short trajectories in parallel, the green line more than the blue line.

5.3 Qualitative Evaluation

In order to qualitatively evaluate the resulting route of the novel approach, qualitative, semi-structured expert interviews have been conducted (Section 4.4.2). The experts were asked to systematically compare the solution of the novel approach to the one of the baseline method in terms of the three dimensions *spatial planning*, *environment and landscape* as well as *technical implementation*. Each of the following three subsections will be dedicated to one of these dimensions. The objective is to complete the insights from the quantitative analysis with expert knowledge.

In Section 5.3.4, *RQ3* will be addressed by presenting the opinions and statements of the experts concerning the third block of the interview guide. As represented in Figure 5.1, the blue and the green transmission lines correspond to the results of the novel approach and the baseline method, respectively.

5.3.1 Experts' Statements regarding the Spatial Planning Dimension

The experts were asked how they estimated the impact of the routes of both approaches on habitations and other infrastructures and whether there were situations along both transmission lines that are not conform with the legal basis of spatial planning.

While talking about the influence of transmission lines on settlements, all experts addressed this topic from two perspectives.

The legal perspective: Many experts founded their statements on the Ordinance on Protection against Non-Ionizing Radiation (NISV 1999). In the municipality Hasliberg for instance, all experts pointed out the proximity of both transmission lines to the villages Reuti and Wasserwendi. In this part of the study area, both lines are very similar until Wasserwendi where both routes split up (Figure 5.13).

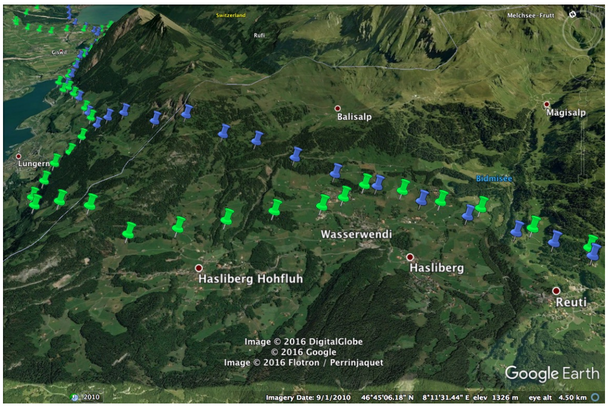


Figure 5.13 – The blue and green line in the municipality Hasliberg.

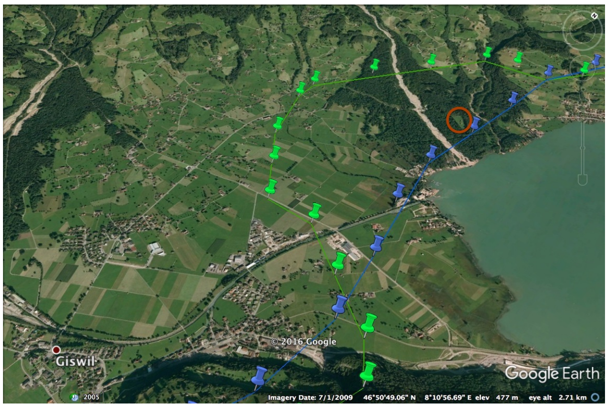


Figure 5.14 – The blue and green line near Giswil. The meadow in the red circle is of great importance for the municipality of Giswil.

Due to the shortcut, the experts in general preferred the blue line, which according to them affects the habitations to a lesser degree. Despite the higher construction costs caused by crossing the rougher terrain, they expect less political opposition from affected citizens for the blue solution. Also the fact that the green route splits the village of Wasserwendi into two parts has been criticized by the Experts 4 and 6.

In this context, the majority of the experts urged to consider a generally larger separation distance between the transmission lines and the settlements in order to take into account the future growth of settlements. In the concrete case of Hasliberg, Expert 4 recommended to build the route slightly higher on the hillside. Expert 3 observed a similar situation in Malters, a village with high settlement pressure. The green line traverses the settlement expansion areas of Malters, i.e. the green line will probably come into conflict with building projects planned in the future. In this situation, the blue line has been more approved by the experts given that it is further away from Malters. According to Expert 6, the settlement expansion of Innertkirchen has even lead to the request of the municipality to expand the building zones in the northeast of the village where today, transmission lines are located. The transmission grid operator Swissgrid AG has declared their willingness to respect their regards. They announced that these zones will be bypassed for future projects and agreed to relocate existing transmission lines if necessary.

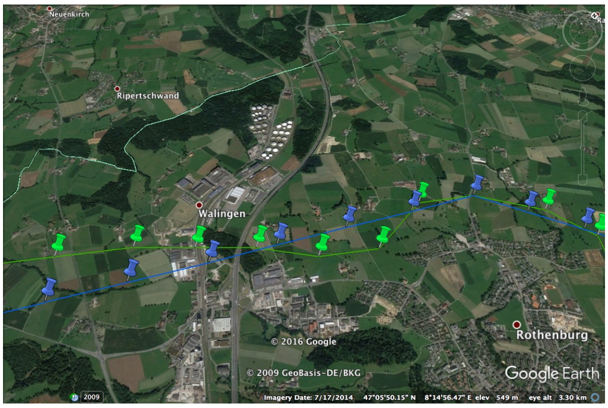


Figure 5.15 – The blue and the green line near Rothenburg.

Figure 5.16 – The blue and the green line as well as the experts' suggestion near Giswil.

A further critical situation that attracted the experts' attention was the valley at Giswil being crossed by both routes. There, the blue line goes very close along the Lake Sarnen and traverses a campground (Figure 5.14). The majority of the experts assessed the way through this zone of recreation and tourism as not realizable. Although the green line bypasses this site, it cuts through the scattered settlements, which some experts consider difficult to implement. As explained by Expert 6, it must be first clarified whether there is a transmission line corridor, which is compliant to the NISV (1999). Second, it needs just one unsatisfied citizen to impede the construction of the route. The more people live in the affected area, the more probable it is that the transmission line project meets opposition from the population. That is why four experts could imagine a compromise solution between the blue and the green line. It would go further away from the lakeside but not too deep into the scattered settlements of Giswil.

However, for that solution the statement of Expert 6 regarding the clearing in the wood (see red circle in Figure 5.14) must be considered. This pasture is of particular importance to the inhabitants of Giswil, since for several years a festival is organized at this place. A transmission line is not imaginable there according to Expert 6.

Also, near Rothenburg, there is an industry zone which is traversed by both transmission lines (Figure 5.15). According to Expert 5, it is necessary to verify in an initial step whether the concerned buildings belong to the places with sensitive use (Orte empfindlicher Nutzung OMEN) as defined in the NISV (1999). Stricter regulations have to be respected in this case. However, Experts 1, 2 and 6 do not regard this site as critical since people do not live there and have no emotional relationship to these buildings.

The psychological and political perspective: The experts attached a great importance to the political and psychological point of view on transmission lines. Transmission lines are often perceived as a disturbing factor. Mountain ranges and lakes, for instance, are seen as value assets of quality of life. The experts recalled a number of situations in which people have stood up against construction projects of transmission lines due to landscape degradation. Especially in Giswil a major part of the experts criticized the green and the blue lines, which build a barrier between Giswil and the Lake Sarnen. Both lines interrupt the view from the village to the lake. That is why Experts 2, 5 and 6 suggested the line to traverse the valley before Giswil and to circumvent the scattered settlements as much as possible, similar to the red line in Figure 5.16.

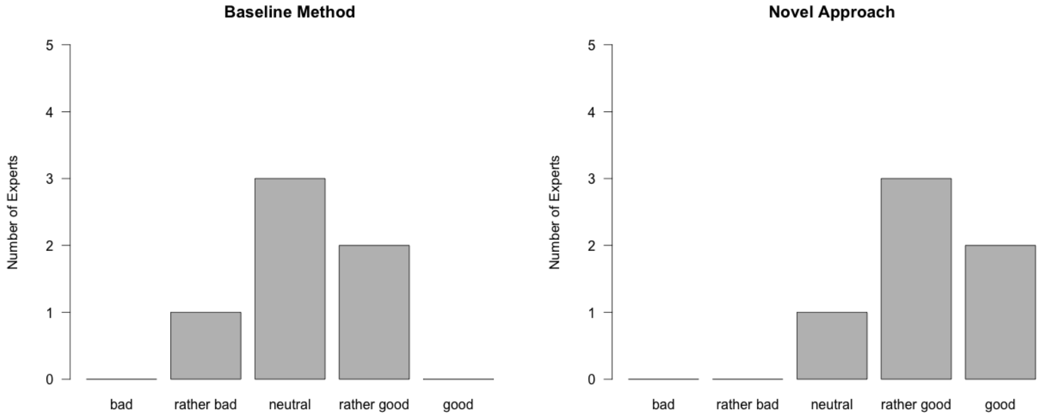


Figure 5.17 – Evaluation of the experts' responses to the question: How well did the route of the novel approach (right) and the route of the baseline method (left) meet requirements of the spatial planning dimension?

Another situation where the construction of transmission lines can cause political issues is the straight section between Giswil and Sarnen along the Lake Sarnen. Expert 3 criticized that the landscape, which is visible from the eastern lakeside, will be disfigured by both transmission lines. The fact that citizens who live on that side of the lake have paid for this view is a possible source for objections. Also the tourism would be concerned. The golden pass express, a popular tourist attraction, from which passengers can enjoy a magnificent view, runs along the eastern lakeside of the Lake Sarnen. That is the reason why Expert 3 suggested the transmission line to run through the eastern lakeside where there already are linear infrastructures such as the train. It would also be on the shadow side of the valley, which further hides the transmission lines.

Furthermore, transmission line projects may also encounter resistance from the population by interfering with local recreation areas. Expert 6 observed such a situation along the blue line where a popular hiking region in the Eigenthal is crossed.

The evaluation of the questionnaire revealed that the blue line has better been rated than the green line (Figure 5.17). The experts argued that the blue line avoids more systematically settled areas. Furthermore, constructing a shorter route by taking shortcuts affects less the spatial planning dimension. However, they emphasized that some adaptations, especially near Giswil, are necessary to optimize the route.

5.3.2 Experts' Statements regarding the Environment and Landscape Dimension

In this section, the experts were asked to evaluate both, the route of the novel approach (blue line) and the one of the baseline method (green line), according to three topics: conservation areas (Figure A.3), natural hazards (Figures A.4 and A.5) and landscape protection (Figure A.6).

Conservation areas: A big impact on conservation areas caused by the routes has been noticed by all the experts near the village Giswil at the Lake Sarnen. In this situation, the blue line crosses river areas with high biodiversity, meadows and fens (Figure 5.6). The green line circumvents these environmentally sensitive areas by building a sinuous line around it. The experts therefore rather favored the green solution. However, three of them suggested a compromise solution between both routes, i.e. one that affects less scattered settlements and which bypasses environmental protection zones.

The mires and wetlands in the Entlebuch region which both routes traverse have been regarded as uncomplicated by the experts since both routes predominantly avoid the concerned small surfaces. Experts 5 and 6 favored the blue line since it leaves this area with high mire and wetland density earlier and therefore affects the environment to a lesser degree. Occasionally, a couple of groundwater protection zones are traversed. However, by positioning the transmission towers accordingly, they can be bypassed. All experts agreed on the fact, that ground water protection zones can only be traversed when the transmission towers are not built within these critical areas.

Natural hazards: Giswil was also perceived by the experts as problematic regarding natural hazards. The plain in which Giswil is located is particularly concerned by floods (Figure A.4 in Appendix A). According to Expert 6, buildings in Giswil were regularly flooded in the last couple of years. He talked about a considerable interval of four to five years. That is the reason why the municipality intends to build flood discharge tunnels in the near future in order to mitigate the risk. Despite the acute situation due to natural hazards, the majority of the experts do not see an issue but rather a challenge in the construction of transmission towers. More robust towers are needed in order to overcome natural hazards. Even if more robust towers require additional costs, this issue can easily be solved today. In spite of the fact that the green line intersects less flood-concerned area, the experts mostly preferred the blue solution. Even though more expensive foundations would be necessary for the towers, the blue route is considered to be less expensive due to the lower amount of towers and its shorter distance.

Some regions are concerned by landslides. For instance, near the alluvial cone in Giswil, Expert 6 anticipated landslides. In the past, farmyards had to be evacuated in this region due to danger of landslip. Another hot spot for landslide hazards has been observed by the experts near Reuti, Wasserwendi and Hohfluh (Figure A.5 in Appendix A). In this regard, the blue line scored better given that it leaves the landslide risk zones at Wasserwendi. However, the green line runs along these risky areas until Hohfluh. Nevertheless, Experts 3 and 4 did estimate the landslide risk as marginal since there already are settlements on this hillside.

Furthermore, south of Lungern, the green line runs horizontally along a very steep slope. According to Expert 6, the railway lines, which also follow along this slope but at a lower level than the green line, once slipped as a consequence of a landslide in the past. However, also concerning this point all experts agreed that taking additional construction measures for transmission towers can reduce this risk.

Landscape protection: Regarding the landscape protection, the experts identified the long intersections with the areas of the Federal Inventory of Landscapes, Sites, and Natural Monuments of National Importance (BLN). All experts agreed on the fact that this inventory can be crossed by the routes if necessary and is not considered as an exclusion criterion. However, Expert 5 stated more precisely that considerable legal obstacles will have to be expected for mire landscapes given that they are under particular protection.

In addition, the experts addressed the situation at the section of both routes, which cross the foothills of Mount Pilatus. In general, traversing mountain ranges is critical from a landscape protection point of view. Transmission lines are visible from practically everywhere around the ridge and thus deteriorate the mountain scenery. A forest or a hillside in the background reduces the visibility of transmission lines.

Expert 1 and 2 suggested to cross the foothills a few kilometers further away where the slope is less steep whereas Experts 3, 4 and 5 thought that exposed positions of transmission lines have sometimes to be accepted and dealt with.

Generally speaking, all experts agreed on the fact that the shorter the route is, the lesser the landscape is affected. That is why Experts 2 and 5 favored the vertical valley transition of the blue line near Malters.

According to the questionnaire completed by the experts, four experts rated the baseline solution as *neutral*, and two as *rather good* (Figure 5.18). As for the assessment of the novel approach, the experts expressed disparate opinions. On the one hand, the route was rated *rather bad* to *neutral* because of the delicate situation near Giswil. On the other hand, some experts rated it as *rather good* to *good* since the blue transmission line is in general shorter and consequently affects the environment and landscape in briefer sections.

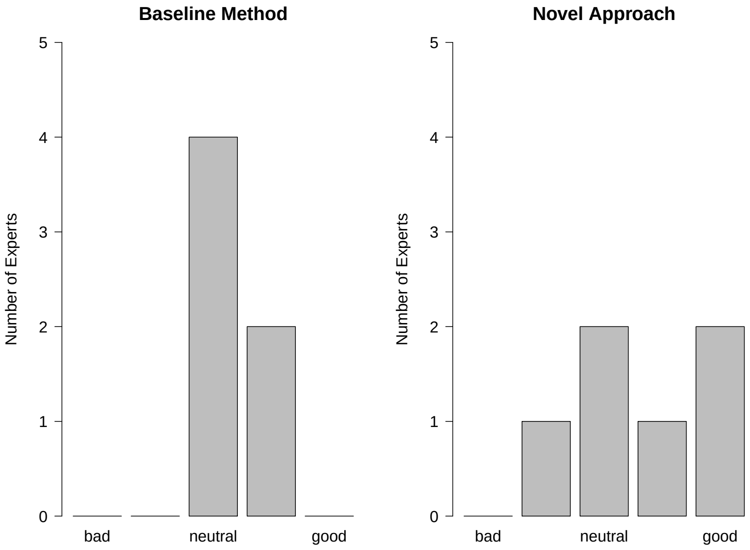


Figure 5.18 – Evaluation of the experts' responses to the question: How well did the route of the novel approach (right) and the route of the baseline method (left) meet requirements of the environment and landscape dimension?

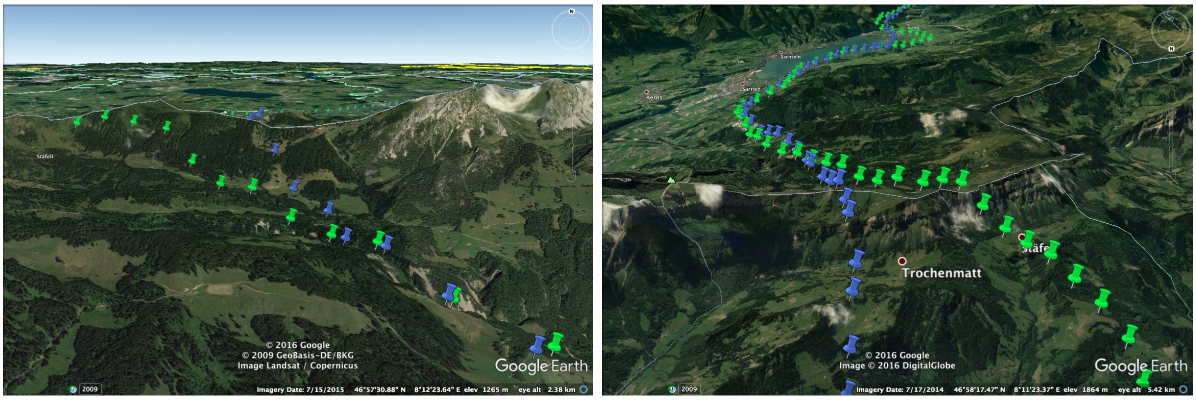
5.3.3 Experts' Statements regarding the Technical Implementation Dimension

Considering the dimension *technical implementation*, the experts were asked questions about three topics. First, the experts were requested to compare the routes based on their shape. Especially the shortcuts taken by the blue line are addressed. Second, the potential of pooling between the computed routes and the existing linear infrastructures (streets, railway lines, transmission lines) and third, the terrain situation of both routes are discussed.

The shape of the route: In general, the experts preferred the blue route over the green one because of its linearity. The more linear a route is, the lower the construction costs will be. This is an aspect which has become more relevant in the last couple of years according to Expert 3. The experts argued that the linearity directly influences the share of suspension towers along a route, a major cost driver of transmission lines. Suspension towers are cheaper compared to angle towers, but require a deflection angle of maximum 3°. In addition to the financial benefits of suspension towers, they are technically easier to implement. They have to endure fewer forces and necessitate less material and less maintenance.

Comparing the blue and the green line, the large majority of the experts agreed to Shortcut 1 between Wasserwendi and Lungern and Shortcut 3 between the foothills of Mount Pilatus and Lucerne (Figure 5.1.4). According to them, the detours taken by the green line in both situations are not justified from the spatial planning, environmental and landscape protection point of view. Near Giswil, Shortcut 2 was not appreciated by five experts given that - as mentioned in Section 5.3.2 - the blue line traverses conservation areas, which have to be circumvented. However, the sinuous shape of the green line has been strongly criticized as the construction of such a line is considered to be a considerable challenge. The blue line does not show such pronounced twists.

Pooling with existing linear infrastructures: With regards to the pooling between the computed routes and existing linear infrastructures, all experts agreed that this aspect is a nice-to-have specification of the Confederation, which has little implementation potential in this study area. This is mainly due to the fact that transmission lines have little in common with rural roads, which dominate the study area. The radii of the streets are smaller and they often cross settlements. Railway lines and highways could come into consideration but as Expert 4 points out, mainly for longer trajectories such as the connection between Zurich and Bern. As already mentioned in Section 5.3.2, Expert 3 would see a possible pooling between the transmission line and the linear infrastructures on the eastern lakeside of the Lake Sarnen. Many experts wished that existing transmission lines need to be considered as much as possible. However, Expert 5 argues that it is important to deliberate in which cases it is advisable to build transmission lines along already existing ones. If the new route can be easily integrated in the landscape, it is worth ignoring existing transmission lines.



(a) The blue line and the green line where they cross the mountain ridge at the foothills of Mount Pilatus seen from the South to the North.

(b) The blue line and the green line where they cross the mountain ridge at the foothills of Mount Pilatus seen from the North to the South.

Figure 5.19 – The route of the novel approach (blue line) and the one of the baseline method (green line) at the foothills of Mount Pilatus.

The terrain situation: The terrain strongly influences the construction of transmission lines. According to all experts transmission towers in rough terrain, need larger foundations and more material, which has to be transported via helicopters if the spot is not connected to roads. Furthermore, Expert 5 states that the construction conditions are more difficult above 1'300 meters a.s.l. Nevertheless, as all the experts at least once said, *"today nothing is impossible [in the construction of transmission lines]."* (Expert 5, 24.02.2017) As many experts explained, the final position of the tower will be decided based on local investigation. In steep hills, there is often a small flatter spot where the construction of a transmission tower is more favorable, explains Expert 2.

According to Experts 2, 5 and 6 the steepness is not the problem in the first place but rather the direction in which a steep slope is crossed. For transmission lines, which follow the slope horizontally, the foundations need to be anchored deeper in the ground which often needs rock drilling. Also, the horizontal distance between the transmission tower and the slope needs to be taken into account. The proximity of the tower to the slope directly influences its height. The foundation and the height of a tower are important cost factors.

There are two situations with rough terrain which have been closely investigated by the experts: the elevation between Wasserwendi and Lungern as well as the foothills of Mount Pilatus. In the first situation, four of six experts preferred the blue solution because the elevation is traversed more directly and especially, vertically to the slope. However, Experts 4 and 6 preferred the green route because it rather follows the topography.

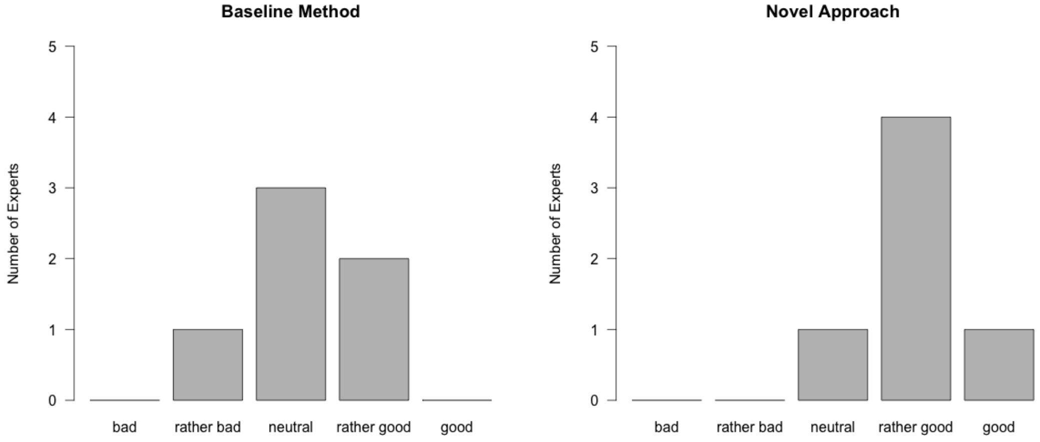


Figure 5.20 – Evaluation of the experts' responses to the question: How well did the route of the novel approach (right) and the route of the baseline method (left) meet requirements of the technical implementation dimension?

The terrain becomes particularly rough in the second situation. Five of six experts favored the blue route because it traverses the mountain ridge more directly and vertically (Figures 5.19a and 5.19b). Experts 1 and 4 in particular liked the fact that the blue route traverses a small col and does not cross the foothills at its steepest point, as does the green line. The horizontal transition of the green line along the mountain flank (Figure 5.19a) has been criticized by Experts 4 and 5. According to Expert 3, the green solution is more suitable because it better considers the topography.

In terms of the dimension *technical implementation*, the evaluation of the questionnaire revealed that the blue line has been better rated than the green line (Figure 5.20). The interviewees argue that the blue line better considers financial aspects than the green route by being more linear and by being better placed in the terrain.

5.3.4 Application in Practice

In the third block of the interview, the experts were asked whether they see application potential of the novel approach in practice. Five of six did respond positively to this question.

The experts appreciate the linearity of the route computed by the novel approach and therefore, consider the inclusion of the deflection angle in the optimization process as an advantage. On the one hand, the share of suspension towers is maximized. As the Experts 1 and 2 argued during their interviews, this property of the route is an important cost-reducing factor. Thus, the route that results from the novel approach reduces construction costs. On the other hand, according to the Experts 3 and 4, long straight sections of the route provide more freedom to position the transmission towers. Along a meandering course of the route, the options of placing towers are reduced.

Another advantage the experts saw is that the novel approach computes paths that are technically realizable in terms of the terrain. Routes of transmission lines are modeled in the early planning stage in which the corridor is determined. According to the Experts 2, 4 and 5, the earlier insight is achieved into the technical implementation of a transmission line, the better. So far, after having modeled a possible route, they had to verify its feasibility in the field. Providing a tool that already indicates which path is possible in terms of the terrain might improve this time-consuming process of developing the definitive route.

Furthermore, the experts appreciated the flexibility of the novel approach. There are a series of parameters that can be set such as the avoidance areas, the height of the transmission towers and the maximum deflection angle. Thanks to this functionality, different scenarios of transmission lines can be tested and compared with each other. According to Expert 5, this allows to identify problematic spots in the study area and to present a variety of possible routes to the contracting authorities, which rely on different bases of decision-making. Expert 2 further argued that if the decision-making authorities approved this approach, it would be possible to use the generated routes as basis for argumentation in court. The acceptance of this tool would significantly simplify the approval procedure for transmission line projects.

5.4 Sensitivity Analysis of the Optimization Criteria

This section presents the outcomes that resulted from the sensitivity analysis of the optimization criteria based on factorial designs. The goal is to investigate the effects and the importance of the factors and their interactions regarding the route computation. The theoretical background for these examinations is provided in the Sections 4.4.3.2 and 4.4.3.3. As defined in Section 4.4.3.1, the factors correspond to the three optimization elements:

- Factor A: the cost surface
- Factor B: the deflection angles
- Factor C: the number of intersections with existing linear infrastructures

The output variables correspond to the indicators. The sensitivity analysis will be structured according to the three dimensions *spatial planning*, *environment and landscape* as well as *technical implementation*. For each dimension, the respective output variables are analyzed separately. In addition to the individual factors, only those interactions with an importance of more than 10% will be examined.

5.4.1 Sensitivity according to the Spatial Planning Dimension

Expectations for the output variable *impact on spatial planning areas*: It is expected that the stronger Factor A is weighted, the smaller will the impact on spatial planning areas be since Factor A weights the cost surface and thus, promotes the avoidance of settlements and other infrastructures. However Factors B and C, which optimize technical aspects of the route and which do not take into account surfaces with spatial planning functions, have the opposite effect on transmission lines.

Observations: The 2^3 experiment outputs of the output variable *impact on spatial planning areas* are represented in Table 5.2. The mean output Q_0 is 3'613 meters, which corresponds to approximately 6% of the route that has on average an impact on the dimension spatial planning. By looking at the outputs O_6 and O_8, it becomes apparent that the routes where Factor A and Factor C are simultaneously not weighted, i.e. both factors are at the low level, have the highest impact on spatial planning areas. However, when only Factor A is taken into account, the output is the lowest with an impact of 1'477 meters.

Table 5.2 – Output table of the output variable *impact on spatial planning areas.*

	Factor A	**Factor B**	**Factor C**	**Impact on spatial planning**
O_1	$+$	$+$	$+$	3'500 m
O_2	$+$	$+$	$-$	2'023 m
O_3	$+$	$-$	$+$	1'758 m
O_4	$+$	$-$	$-$	1'477 m
O_5	$-$	$+$	$+$	2'832 m
O_6	$-$	$+$	$-$	8'290 m
O_7	$-$	$-$	$+$	3'760 m
O_8	$-$	$-$	$-$	5'266 m

Also the outcomes of Table 5.3 show similar patterns. Factors A and C have each a decreasing effect on the output variable. The output values when Factor A is at the high level (O_1 to O_4)

are on average 39% lower than the mean output Q_0. The outputs with Factor C at the high level (all $O_\bullet$ with odd indices) show similar behavior but with an effect of -18%. Having an importance of 45% and 9%, Factor A has a more significant role in the computation of the output variable than Factor C. In contrast, Factor B has a positive effect on the output variable, i.e. the impact on spatial planning areas increases when B is included. Setting B at the high level, the outputs have on average a 15% higher impact on the spatial planning dimension than the mean output Q_0. Additionally, Factor B has a rather marginal importance of 7%.

Table 5.3 – Effect and importance of the factors and their interactions according to the output variable *impact on spatial planning areas.*

	Absolute Effect	**Relative Effect**		**Importance**
Q_0	3'613 m	100%	SST	100%
Q_A	-1'424 m	-39%	SSA	45%
Q_B	548 m	15%	SSB	7%
Q_C	-651 m	-18%	SSC	9%
Q_{AB}	24 m	1%	$SSAB$	0%
Q_{AC}	1'090 m	30%	$SSAC$	27%
Q_{BC}	-345 m	-10%	$SSBC$	3%
Q_{ABC}	643 m	18%	$SSABC$	9%

The outcomes of the factorial design partially confirm the expectations. As assumed, Factor A has a significant decreasing effect on the output variable, whereas the impact on spatial planning areas increases when Factor B is taken into account. Although an opposite response was expected from Factor C, it can be explained: When Factor C is weighted, the algorithm tries to avoid linear infrastructures in order to prevent intersections. Since in areas where linear infrastructures such as streets and railway lines are dense, the algorithm is more likely to encounter settlements, the impact on spatial planning areas decreases when Factor C is at the high level.

However, it might appear at first glance contradictory that the interaction AC with an importance of 27% has the opposite effect (+30%) compared to the individual Factors A (-39%) and C (-18%). This observation can be explained based on Figure 5.21. Factors A and C interact when both have the same value, i.e. when both are either at the low level (see blue points) or at the high level (see red points). The effect of AC corresponds to the difference in percentage between the mean of all outputs when both factors interact (O_1, O_3, O_6, O_8) and the mean output Q_0. It becomes visible that when Factor A and C are both at the low level (O_6, O_8), the output values are significantly higher than the mean output Q_0. In particular when B is high, the output value ($O_6 =$ 8'290.34 meters) is even more than twice as big as Q_0. When Factors A and C are at the high level (O_1, O_3), the output values are close to or smaller than the mean output Q_0, i.e. the impact on spatial planning areas decreases on average. When Factor B is low ($O_3 =$ 1'758.49 meters), we even get the route with the second lowest impact on the dimension spatial planning. So, although the total effect of the interaction AC is positive, former statements regarding the single effect of the Factors A and C are confirmed.

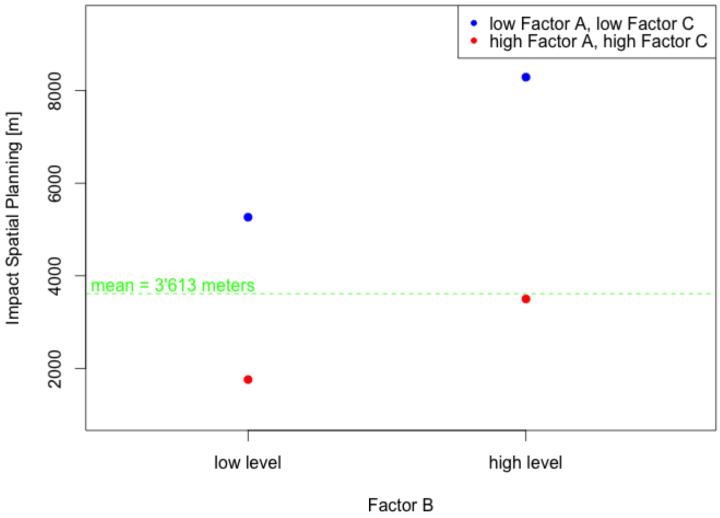


Figure 5.21 – *Impact on spatial planning areas*: The output values when there is an interaction between the Factors A and C. The dashed line represents the mean output Q_0.

5.4.2 Sensitivity according to the Environment and Landscape Dimension

Expectations for the output variable *impact on environment and landscape areas*: It is expected that Factor A has a negative effect on the output variable. By weighting the cost surface, environmentally sensitive and landscape protection areas should be avoided. However, the technical Factors B and C do not take into account these areas and hence, have the opposite effect on the output variable, i.e. the impact on environment and landscape areas is expected to increase when the Factors B and C are at the high level.

Table 5.4 – Output table of the output variable *impact on environment and landscape.*

	Factor A	**Factor B**	**Factor C**	**Impact on Environment and Landscape**
O_1	$+$	$+$	$+$	7'203 m
O_2	$+$	$+$	$-$	6'652 m
O_3	$+$	$-$	$+$	7'543 m
O_4	$+$	$-$	$-$	6'100 m
O_5	$-$	$+$	$+$	25'242 m
O_6	$-$	$+$	$-$	18'932 m
O_7	$-$	$-$	$+$	25'042 m
O_8	$-$	$-$	$-$	15'970 m

Observations: The outputs of the 2^3 experiments regarding the output variable *impact on environment and landscape areas* are shown in Table 5.4. The mean output corresponds to 14'086 meters, which signifies that on average approximately 22% of the route have an impact on the dimension environment and landscape. The routes with the lowest and the highest output values can be observed when only Factor A is at the high level (O_4) and when only Factor A is at the low level (O_5), respectively.

Also the outcomes in Table 5.5 point to similar patterns. Factor A has a strong negative effect of -51% on the output, i.e. the mean output Q_0 is more than twice as big as the mean of all output values where Factor A is at the high level (O_1 to O_4). It also explains 87% of the output variation and is consequently the most important factor for this output variable. Factor B and C augment each the impact when they are weighted (Factor B: 3%, Factor C: 15%). However, they both play a minor role, considering the percentage of importance (Factor B: 0%, Factor C: 8%). According to the model, all interactions have an importance below 10% and are therefore not further investigated.

This confirms our expectations that the stronger the cost surface is weighted, the more are environment and landscape sensitive areas taken into account and avoided by the route. Whereas Factors B and C, which are technical factors, ignore these areas and therefore affect more the environment and landscape when they occur. The insignificant role of Factors B and C is however rather surprising.

Table 5.5 – Effect and importance of the factors and their interactions according to the output variable *impact on environment and landscape areas.*

	Absolute Effect	**Relative Effect**		**Importance**
Q_0	14'086 m	100%	SST	100%
Q_A	-7'211 m	-51%	SSA	87%
Q_B	422 m	3%	SSB	0%
Q_C	2'172 m	15%	SSC	8%
Q_{AB}	-369 m	-3%	$SSAB$	0%
Q_{AC}	-1'673 m	-12%	$SSAC$	5%
Q_{BC}	-457 m	-3%	$SSBC$	0%
Q_{ABC}	234 m	2%	$SSABC$	0%

5.4.3 Sensitivity according to the Technical Implementation Dimension

The following indicators describe the dimension *technical implementation*:

- length
- straightness index
- mean terrain slope
- indicative costs
- share of suspension towers

In the following paragraphs, these indicators are used as output variables for factorial designs and the corresponding results presented for each indicator individually

Table 5.6 – Output table of the output variable *length*.

	Factor$A$	**Factor B**	**Factor C**	**Length [m]**
O_1	+	+	+	55'479
O_2	+	+	−	56'553
O_3	+	−	+	76'531
O_4	+	−	−	61'222
O_5	−	+	+	73'510
O_6	−	+	−	50'983
O_7	−	−	+	78'371
O_8	−	−	−	50'708

Table 5.7 – Effect and importance of the factors and their interactions according to the output indicator *length*.

	Absolute Effect [m]	**Relative Effect**		**Importance**
Q_0	62'920	100%	SST	100%
Q_A	-473	-1%	SSA	0%
Q_B	-3'788	-6%	SSB	12%
Q_C	8'053	13%	SSC	56%
Q_{AB}	-2'642	-4%	$SSAB$	6%
Q_{AC}	-4'494	-7%	$SSAC$	17%
Q_{BC}	-2'690	-4%	$SSBC$	6%
Q_{ABC}	-1'406	-2%	$SSABC$	2%

Expectations for the output variable *length*: Regarding Factor A, it is anticipated that the route will take detours in order to avoid sensitive areas and consequently, the transmission line will be longer. Given that Factor B is supposed to have a smoothing effect on the route, it is expected that the total length of the route decreases when Factor B is at the high level. Factor C is supposed to have a lengthening effect by avoiding intersections with linear structures.

Observations: The outputs of the output variable *length*, which resulted from the factorial design, are represented in Table 5.6. The resulting routes of the factorial design are on average 62'920 meters long. The longest route is the one where only Factor C is at the high level. The minimum length can be observed when all factors are at the low level. In this case, the graph is not weighted and the algorithm takes the first best path.

According to Table 5.7, Factor C appears to have the largest effect and plays with 56% importance the most significant role for the computation of the output variable. Its effect is positive, i.e. the mean of all output values where Factor C is at the high level ($O_\bullet$ with odd indices) is 13% higher than the mean output Q_0. This signifies that the stronger Factor C is emphasized, the longer the route is. Factor B has the opposite effect (-6%), which is however less influential considering the percentages of the importance (12%). The effect and the importance of Factor A is small and thus negligible (Effect: -1%, Importance: 0%).

However, 17% of the output variation is explained by the interaction AC. This interaction has a negative effect of -7% on the output variable. The output values where Factors A and C interact (O_1,O_3,O_6,O_8) are visualized in Figure 5.22. When Factors A and C interact, all outputs are below the mean, except for the case where Factors A and C are high and Factor B is low (O_3). Thus, promoting the interaction of AC reduces the route length, given that the mean of all outputs is below the mean output Q_0. The outlier can be explained by the relatively stronger effect of Factor B on the output.

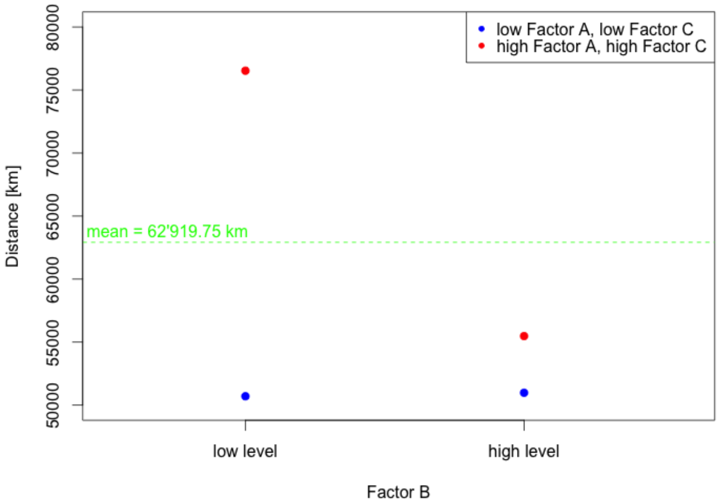


Figure 5.22 – *Length*: The output values when there is an interaction between the Factors A and C. The dashed line represents the mean output Q_0.

The fact that Factor C has a prolonging effect on the transmission line confirms the expectations. Although Factor B has the assumed negative effect on the output variable, it has been overestimated. The insignificant role of Factor A is also rather surprising.

Expectations for the output variable *straightness index*: In order to avoid sensitive areas, the resulting route is expected to meander more when Factor A is weighted, i.e. the straightness index tends to be lower than the mean. By contrast, emphasizing Factor B is expected to increase the straightness index, i.e. the route is anticipated to come closer to the direct connection between the starting point and the destination point. Regarding Factor C, it is assumed that the route will become more sinuous, i.e. the straightness index will decrease. An explanation for the negative effect on the output variable is that by emphasizing Factor C linear infrastructures are avoided and detours are taken.

Observations: Regarding the output variable *straightness index*, the outputs which resulted from the factorial design, are shown in Table 5.8. The most sinuous route occurs when Factor C is the only factor at the high level (O_7). When all factors are at the low level, the maximum straightness index can be observed (O_8). This can be explained by the fact that the algorithm looks for the most direct path when the graph is not weighted. However, it could have been expected that the straightness index is 1 when all factors are at the low level. This is not the

Table 5.8 – Output table of the output variable *straightness index*.

	Factor$A$	**Factor B**	**Factor C**	**Straightness index**
O_1	+	+	+	0.84
O_2	+	+	−	0.82
O_3	+	−	+	0.61
O_4	+	−	−	0.76
O_5	−	+	+	0.63
O_6	−	+	−	0.91
O_7	−	−	+	0.59
O_8	−	−	−	0.92

case given that the study area has been tailored in such a way that the direct connection is not possible. According to experts' statements, a transmission line which would have cut through the south west of Lucerne has been excluded years ago. That is why that part of the study area has been clipped and a direct connection between the starting end destination point made impossible. The mean straightness index Q_0 corresponds to 0.761.

Table 5.9 – Effect and importance of the factors and their interactions according to the output indicator *straightness index*.

	Absolute Effect	**Relative Effect**		**Importance**
Q_0	0.761	100%	SST	100%
Q_A	-0.003	0%	SSA	0%
Q_B	0.041	5%	SSB	11%
Q_C	-0.093	-12%	SSC	55%
Q_{AB}	0.032	4%	$SSAB$	7%
Q_{AC}	0.058	8%	$SSAC$	22%
Q_{BC}	0.027	3%	$SSBC$	4%
Q_{ABC}	0.015	2%	$SSABC$	2%

As shown in Table 5.9, Factor C has the biggest effect with -12% and explains the largest share of the output variation (55%). This signifies that the output values where Factor C is at the high level ($O_\bullet$ with odd indices) are on average 12% smaller, i.e. less straight, than the mean output Q_0. Factor B has a straightening effect of 5% and is of little importance (11%) compared to the importance of Factor C. Factor A has no effect and no importance with regard to the straightness index of the route.

However, the interaction AC has a positive effect on the output and explains 22% of the output variation. Although this may appear rather unexpected given that Factor C has the opposite effect (-12%), it can be explained based on Figure 5.23. The majority of the outputs where Factors A and C interact (O_1, O_3, O_6, O_8) are above the mean, except for the case when both, Factors A and C, are high and Factor B is low (O_3). Given that the mean value of all outputs where Factors A and C interact is larger than the mean output Q_0, the total effect of the interaction AC is positive. The most probable cause for the outlier O_3 is that without Factor B, there is a tendency to obtain values above the mean (compare with Q_B: +5%).

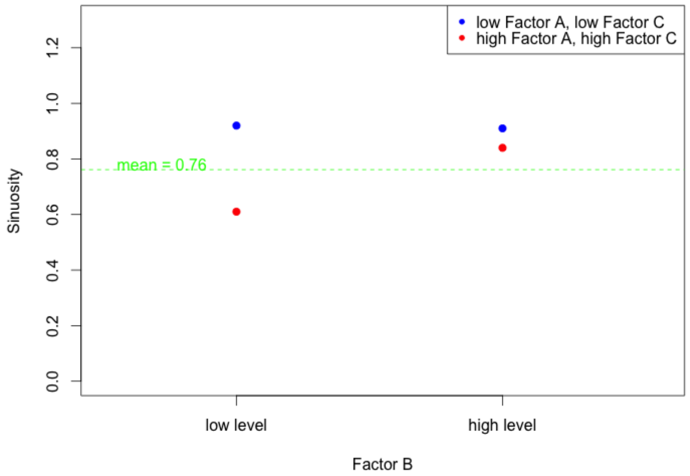


Figure 5.23 – *Straightness index*: The output values when there is an interaction between the Factors A and C. The dashed line represents the mean output Q_0. The dashed line represents the mean output Q_0.

Table 5.10 – Output table of the output variable *mean terrain slope*.

	Factor A	**Factor B**	**Factor C**	**mean terrain slope**
O_1	$+$	$+$	$+$	14.30
O_2	$+$	$+$	$-$	13.02
O_3	$+$	$-$	$+$	13.37
O_4	$+$	$-$	$-$	12.96
O_5	$-$	$+$	$+$	12.82
O_6	$-$	$+$	$-$	14.53
O_7	$-$	$-$	$+$	12.41
O_8	$-$	$-$	$-$	16.12

The expectations have only partially been met. The low impact and importance of Factor A is rather surprising. Even though the effect of both Factors B and C are as expected, their difference regarding their role was estimated differently. It was anticipated that Factor B would explain a larger share of the output variation.

Expectation for the output variable *mean terrain slope*: As the cost surface considers the suitability of the terrain, it is expected that Factor A has a reducing effect on the mean terrain slope. However, the effect is assumed to be softened due to the fact that the cost surface mainly considers criteria of the spatial planning and the environment and landscape dimension. The impact of Factors B and C on the output variable is presumed to be neutral and of insignificant importance for the computation of the output.

Table 5.11 – Effect and importance of the factors and their interactions according to the output variable *mean terrain slope.*

	Absolute Effect [CHF]	**Relative Effect**		**Importance**
Q_0	13.69	100%	SST	100%
Q_A	-0.28	-2%	SSA	6%
Q_B	-0.03	0%	SSB	0%
Q_C	-0.47	-3%	SSC	17%
Q_{AB}	0.27	2%	$SSAB$	6%
Q_{AC}	0.89	6%	$SSAC$	60%
Q_{BC}	0.36	3%	$SSBC$	10%
Q_{ABC}	-0.14	-1%	$SSABC$	1%

Observations: The results of the output variable *mean terrain slope*, which resulted from the factorial design, are shown in Table 5.10. The mean terrain slope of all experiments corresponds to 13.69°. The route with the lowest mean terrain slope can be observed when only Factor C is at the high level. The largest mean terrain slope is assigned to the route where all factors are at the low level.

According to Table 5.11, Factors A and C have a slightly negative effect on the output variable, i.e. the mean terrain slope marginally decreases when Factors A and C are weighted. In addition, Factors A and C explain each 6% and 17%, respectively, of the output variation. Factor B appears to be neutral and has an importance of 0%. With a percentage of 60%, the interaction AC appears to be of great importance for the computation of the output variable. It has a positive effect of +6% on the output variable, i.e. the mean terrain slope increases when the interaction between Factors A and C is promoted.

The expectations have been only partially met. It is rather surprising that Factor A has such a small negative effect on the mean terrain slope. As anticipated, the impact of Factor B is neutral and plays an insignificant role. A smaller effect and importance has been predicted for Factor C. These patterns are unexpected and there is no immediate explanation.

Expectation for the output variable *indicative costs*: A neutral effect on the indicative costs is expected for Factor A. On the one hand, the suitability of the terrain, which the cost surface considers, is expected to decrease the indicative costs. On the other hand, criteria concerning the spatial planning, the environment and the landscape are anticipated to have the opposite effect on the indicative costs. Factor B will probably have a negative effect on the output variable given that it shortens the route and consequently reduces the indicative costs. In contrast, Factor C is estimated to increase the indicative costs due to its lengthening effect on the route.

Table 5.12 – Output table of the output variable *indicative costs*.

	Factor A	**Factor B**	**Factor C**	**Indicative Costs [CHF]**
O_1	$+$	$+$	$+$	194’200’000
O_2	$+$	$+$	$-$	198’000’000
O_3	$+$	$-$	$+$	267’900’000
O_4	$+$	$-$	$-$	214’300’000
O_5	$-$	$+$	$+$	183’800’000
O_6	$-$	$+$	$-$	178’500’000
O_7	$-$	$-$	$+$	274’300’000
O_8	$-$	$-$	$-$	126’800’000

Table 5.13 – Effect and importance of the factors and their interactions according to the output variable *indicative costs*.

	Absolute Effect [CHF]	**Relative Effect**		**Importance**
Q_0	204’725’000	100%	SST	100%
Q_A	13’875’000	7%	SSA	9%
Q_B	-16’100’000	-8%	SSB	13%
Q_C	25’325’000	12%	SSC	32%
Q_{AB}	-6’400’000	-3%	$SSAB$	2%
Q_{AC}	-12’875’000	-6%	$SSAC$	8%
Q_{BC}	-24’950’000	-12%	$SSBC$	31%
Q_{ABC}	10’600’000	5%	$SSABC$	6%

Observations: The outputs of the output variable *indicative costs*, which resulted from the factorial design, are presented in Table 5.12. According to this output variable, the route that costs the least is the one where all factors have been switched off (O_8). This is probably due to the fact that it corresponds to the shortest route (see factorial design outcomes of the output variable *length* in Table 5.6). The most expensive route is the one where only Factor C is at the high level (O_7).

According to the sensitivity model, Factor C is at the same time the most important factor and the factor with the largest impact of +12% (Table 5.13). This signifies that the higher Factor C is, the more expensive is the route. This is probably because Factor C has an increasing effect on the length of a transmission line and the indicative costs are computed based on the route length. Also, Factor A has a positive effect on the output (+7%), which is however smaller and less important compared to Factor C. The indicative costs decrease when Factor B is high. According to the model, the output values where Factor B is at the high level (O_1, O_2, O_5, O_6) are on average 8% below the mean output Q_0. 13% of the output variation is explained by Factor B.

Also the interaction between B and C has a negative effect on the indicative costs. In Figure 5.24, it can be observed that when both factors are at the same level, the majority of their outputs are below the mean output Q_0. However, the indicative costs are higher than Q_0 when

Factor A is at the low and the other to factors at the high level (O_5). The reason for the outlier O_5 is probably that when Factor A is at the low level the cost surface and thus the terrain are ignored which are both criteria considered in the computation of the indicative costs. The expectations for Factor A have partially been met. Against our assumptions, Factor A has a positive effect on the output variable, i.e. the indicative costs tend to increase when Factor A is weighted. However, it explains only 9% of the output variation and thus plays a relatively insignificant role. As expected, Factor B has a cost-reducing function and Factor C works the opposite way. It is however rather surprising that the interaction BC has a decreasing impact on the indicative costs and that it plays an important role in the computation of the output variable. This indicates that in combination, the technical Factors B and C have a cost-reducing effect on the route.

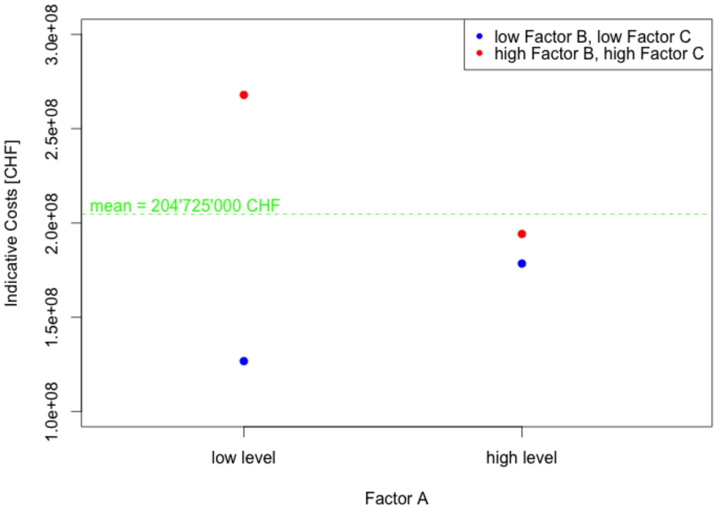


Figure 5.24 – *Indicative costs*: The output values when there is an interaction between the Factors B and C. The dashed line represents the mean output Q_0.

Expectations for the output variable *share of suspension towers*: It is expected that Factor A has a negative effect on the share of suspension towers, given that the more meandering the route is, the more angle towers are necessary. Regarding Factor B, a strong opposite effect is anticipated. The effect and role of Factor C is estimated to be rather neutral.

Observations: The results of the factorial design for the output variable *share of suspension towers* are shown in Table 5.14. Based on the output table, it can be said that the maximum suspension tower share occurs when only Factor B is set to the high level (O_6). The ratio is the lowest in the opposite case, i.e. when Factor B is switched off and the other two factors are at the high level (O_3).

Similar patterns can be observed in Table 5.15. It emerges that Factor B has the largest effect on the share of suspension towers, with nearly 50%. This signifies that the outputs where Factor B is at the high level (O_1, O_2, O_5, O_6) are on average 50% larger than the mean output

Table 5.14 – Output table of the output variable *share of suspension towers*.

	Factor A	**Factor B**	**Factor C**	**Share of Suspension Towers**
O_1	$+$	$+$	$+$	0.69
O_2	$+$	$+$	$-$	0.756
O_3	$+$	$-$	$+$	0.153
O_4	$+$	$-$	$-$	0.2
O_5	$-$	$+$	$+$	0.667
O_6	$-$	$+$	$-$	0.840
O_7	$-$	$-$	$+$	0.323
O_8	$-$	$-$	$-$	0.421

Table 5.15 – Effect and importance of the factors and their interactions according to the output variable *share of suspension towers*.

	Absolute Effect	**Relative Effect**		**Importance**
Q_0	0.556	100%	SST	100%
Q_A	-0.059	-11%	SSA	5%
Q_B	0.260	46%	SSB	87%
Q_C	-0.051	-9%	SSC	4%
Q_{AB}	0.027	8%	$SSAB$	3%
Q_{AC}	0.012	4%	$SSAC$	1%
Q_{BC}	-0.012	-2%	$SSBC$	0%
Q_{ABC}	0.011	1%	$SSABC$	0%

Q_0. Furthermore, it can be ranked as the most important factor, with a 90% share of the output variation. The remaining few percentages of the variation are mainly explained by Factors A and C. Both have a negative impact on the output (Factor A: -11%, Factor C: -9%). Thus, when Factor A and C are emphasized, the share of suspension towers decreases. According to the sensitivity model, the interactions between the factors can be neglected.

The expectations regarding the effect and importance of Factor B in terms of the share of suspension towers are hereby confirmed. It shows that it has the functionality of straightening the route. However, the opposite effects of the Factors A and C have been anticipated to be more elevated.

Chapter 6

Discussion

The main goal of this Master's thesis was to implement a novel, graph-based approach to the transmission line routing problem. The innovations of the proposed approach are presented in Section 6.1. In order to assess the novel approach, three research questions have been formulated. They will be addressed separately in Section 6.2, Section 6.3 and Section 6.4, respectively.

6.1 Innovations of the Proposed Approach

The main goal of this research has largely been reached by introducing a novel approach to compute the optimal route for transmission lines. The proposed algorithm is novel in terms of the fact that it not only optimizes spatial planning, environment and landscape criteria but also technical properties of the routes. In order to solve the transmission line routing problem, constraints as well as optimization criteria constitute the foundation of the proposed algorithm.

6.1.1 Constraints

Previous research studies focused on the optimization process by determining the LCP over the accumulated cost surface (Bagli et al. 2011, Bevanger et al. 2014, Collischonn & Pilar 2000, Douglas 1994, Houston & Johnson 2006, Berry 2007*a*). However, only few approaches defined in a preliminary step constraints which aim to guarantee that the generated route meets certain transmission line properties. The following constraints have been considered in the novel approach:

- *Avoidance areas:* A widely used method to avoid areas which are unsuitable for transmission lines is to assign to these surfaces very high costs (Houston & Johnson 2006, Eroglu & Aydin 2015) or even infinite costs (van Bemmelen et al. 1993). In the novel approach the principle of avoidance areas introduced by Stefanakis & Kavouras (1995) is applied: Vertices of the graph which lie within areas where transmission towers are not allowed to be built are excluded from the routing analysis. In contrast to previous work, the novel approach introduces a more nuanced definition of avoidance areas. It differentiates between two types:

1. Areas in which both, transmission towers and conductors, are not allowed to be built nor suspended.
2. Areas in which the construction of transmission towers is prohibited but conductors are allowed to be suspended.

This constraint allows to distinguish, for instance, between settlements, where the towers as well as the conductors of the transmission lines are not allowed to be built, and environmentally sensitive areas, such as groundwater protection zones or mires, where towers are strictly prohibited but not excluded to be overarched by a conductor. Thus, a route that is computed in a graph that considers this constraint does not have to make a detour around obstacles over which it is allowed to suspend a conductor.

- *The span range:* Limitations regarding the span have been little investigated. By generating the optimal route based on an accumulated cost surface, the majority of the publications do not model the span. The span usually is determined *post hoc* when the towers are sited along a precalculated route (Mitra & Wolfenden 1968, Olbrycht 1982, Viera & Toledo H. 2006, Zheng 1993). According to our knowledge, only Rheinert (1999) explicitly defines limitations to the span in a network of transmission towers.

  In the novel approach, the route corresponds to a path in a network in which vertices represent the transmission towers and the edges model the conductors between two consecutive towers. The span is not limited to a single, constant distance. According to experts' statements, a range between 200 meters and 600 meters is defined. Determining a range allows to vary the span depending on the terrain. Rough terrain can be overcome with several small spans, whereas valleys can be traversed with a minimum number of towers by selecting the longest possible distance. However, it has not been examined if this property has been optimally implemented.

- *The ground clearance:* The large majority of previous studies ignored the ground clearance and thus computed routes whose technical feasibility regarding the terrain is not ensured. Only Rheinert (1999) did consider this constraint in his genetic algorithm. As edges represent the conductor between two towers, the novel approach removes those from the graph whose sag is too close to the ground.

- *The maximum angle of deflection:* Large angles of deflection are extremely rare along transmission lines. Their number can be reduced by assigning a maximum angle of deflection as constraint. Even though various handbooks of transmission lines determine the angle of deflection as an important aspect of routes (Fischer & Kießling 2012, Fink & Beaty 1993), the majority of existing algorithms ignored this property of transmission lines. To our knowledge, Rheinert (1999) is the only researcher who takes into account a maximum angle of deflection but does not explain how it is integrated in his approach.

  The representation of transmission towers as vertices in a network has proven to be well-suited to capture the angle of deflection between three consecutive towers. To that end, the advantages of line graphs have been used (Section 4.3.2.2). Edges in the line graph that do not meet the maximum deflection angle constraint are excluded from the routing analysis.

To sum up, the constraints restrict the route possibilities. In this algorithm, this is achieved by removing vertices and edges in the graph that are not valid in terms of the above defined constraints. To our knowledge, this constellation of constraints has so far not been applied on a graph-based approach, and particularly not in a raster-based approach.

6.1.2 Optimization Criteria

So far, optimization criteria have been conflated to a single discrete cost surface, where each raster cell expresses the costs of being traversed by a transmission line. The costs represent the spatial resistance imposed on transmission lines in terms of criteria of the built environment and natural environment as well as criteria regarding the risk of natural hazards (Bagli et al. 2011, Houston & Johnson 2006, Bevanger et al. 2014). The majority of the existing approaches computed a sequence of raster cells in a cost surface such that the sum of the raster cell values is minimal (Bagli et al. 2011, Bevanger et al. 2014, Collischonn & Pilar 2000, Houston & Johnson 2006, Berry 2007*a*).

In contrast to previous methods, the novel approach does not only consider the cost surface in the optimization process. Also the sum of deflection angles along the route as well as the number of intersections with existing linear infrastructures are minimized. The optimization of the deflection angle aims at straightening the route and maximizing the share of the suspension towers. As suspension towers are less expensive than angle towers, this technical criterion is expected to have a direct bearing on the construction costs of transmission lines. Minimizing the number of intersections is expected to promote pooling between the computed route and existing transmission lines while running parallel to each other.

In order to evaluate the approach and assess the role of the newly integrated technical criteria, three research questions have been formulated in Chapter 1. Each of the following sections will address one of these questions in turn.

6.2 Comparing the Baseline Method and the Novel Approach

This section aims to respond to *RQ1*:

> ***RQ1:*** *How do the baseline method and the novel approach differ in terms of the three dimensions (1) Spatial Planning, (2) Environment and Landscape as well as (3) Technical Implementation?*

In order to answer this research question, the routes of both approaches are compared systematically by contrasting the insights of the quantitative and the qualitative evaluations with each other. In the quantitative analysis, the routes were evaluated based on a set of indicators, each describing one of the three dimensions. The routes were further assessed from a qualitative point of view by means of expert interviews. Combining both perspectives aimed at completing the generalizing findings from the quantitative analysis with experts knowledge.

While discussing both approaches in terms of the three dimensions, it will be in particular referred to the Shortcuts 1 to 3 singled out in Section 5.1. Sections of the routes that resemble each other a lot are expected to have similar effects on the three dimensions and are therefore not further discussed.

Each of the following sections will compare both routes in terms of one of the three key dimensions. As introduced in Section 5.1, the discussion will refer to the green and the blue line, respectively, when speaking about the routes of the baseline method and the novel approach.

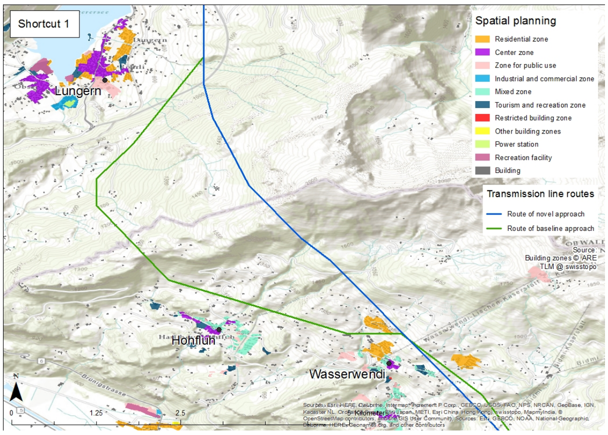
6.2.1 Comparison based on the Spatial Planning Dimension

The outcomes of the quantitative analysis, were confirmed by the ones of the qualitative analysis. The novel approach generally performed better than the baseline method in terms of the spatial planning dimension. On the one hand, the indicator values showed that the blue line affected slightly less settlements and other infrastructures. On the other hand, the experts appreciated that the blue line avoided more systematically spatial planning areas. According to the experts, at Shortcut 1 (Figure 6.1a), additional construction costs due to rougher terrain are willingly assumed if public opposition can be avoided. Also at Shortcut 3 (Figure 6.1c), the blue line, which avoided Malters, was rated better compared to the green line, which traversed settlement expansion areas of this village. However, for Shortcut 2 (Figure 6.1b) both solutions were criticized by the experts who suggested consequently alternative solutions.

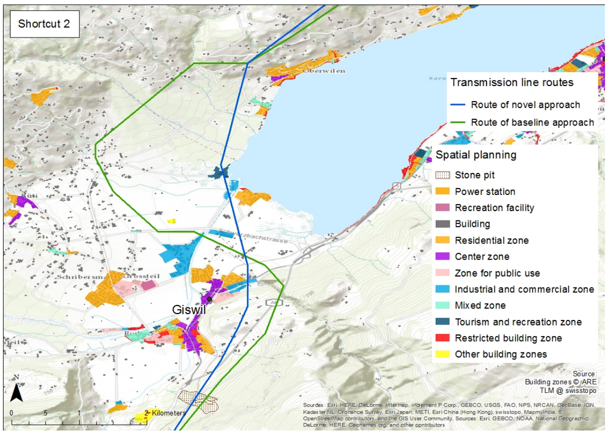
Furthermore, the quantitative analysis showed that both routes frequently crossed industrial and commercial zones, as for instance at Shortcut 3 near Rothenburg. However, according to the majority opinion of the experts, this passage is implementable given that first, the existing line also crosses these industrial and commercial zones, and second, according to some experts, people associate less emotions to buildings in which they work and in which they do not live for a longer period of time.

6.2.2 Comparison based on the Environment and Landscape Dimension

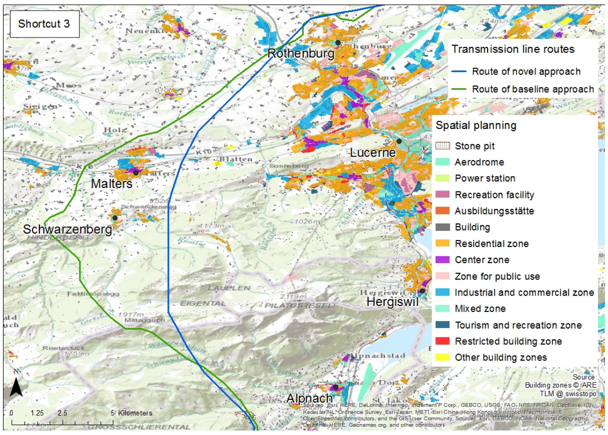
The quantitative evaluation revealed that the route of the baseline method affected less environment and landscape areas than the one of the novel approach. However, the experts' statements



(a) Shortcut 1: The routes of the novel approach and the baseline method split up at Wasserwendi and meet again in Lungern.



(b) Shortcut 2: The routes of the novel approach and the baseline method take different courses near Giswil.



(c) Shortcut 3: The routes of the novel approach and the baseline method split up before they traverse the foothills of Mount Pilatus and meet up after Malters near Rothenburg.

Figure 6.1 – Shortcuts: The routes of the novel approach and the baseline method mainly differ in three situations.

of the qualitative analysis did not support all respects of this observation. There were situations where the experts preferred the green line over the blue one, and others where the route of the novel approach was ranked better than the one of the baseline method.

At Shortcut 2 near Giswil for instance, the outcomes of the quantitative analysis showed that the blue line crossed several environmentally sensitive areas, which the green line traversed only at their narrow parts (Figure 5.6). This negative impact of the blue line was accordingly criticized by the experts. In contrast, despite of the fact that the blue line cut through more areas concerned by water-related natural hazards, the experts favored the route of the novel approach. They argued that first, both routes would be concerned by floods anyway due to the flat valley, and second, that by being shorter the blue line would be the less expensive solution as less towers need to be equipped against floods compared to the green line. Nevertheless, all the experts agreed on the fact that natural hazards are not an excluding factor for transmission lines and can be dealt with by taking additional construction measures. Also in Shortcut 3, the experts preferred the blue line over the green one as it earlier left the delicate mire and fen areas in the Entlebuch region.

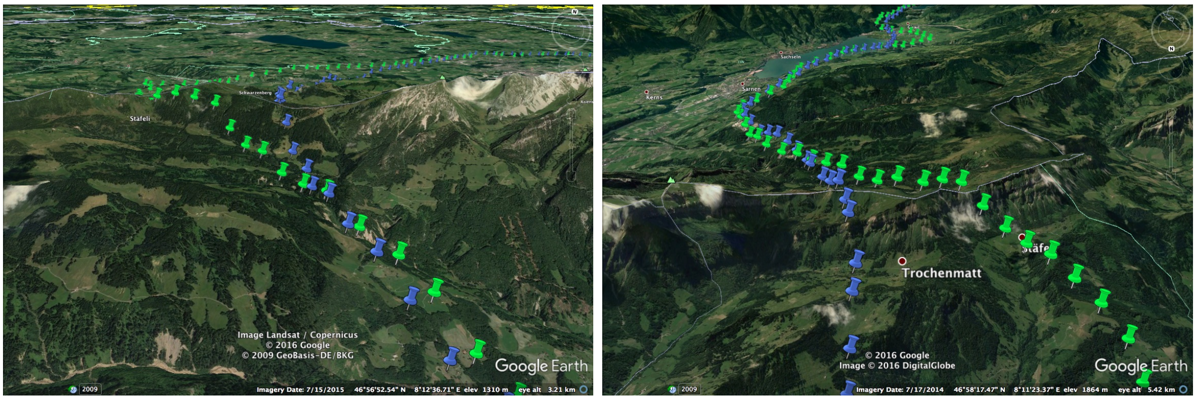
Furthermore, it became apparent from the outcomes of the quantitative evaluation, that long sections of both routes traversed landscape protection areas. However, according to the experts, inventories of landscape objects are not considered as excluding factor for transmission lines. In this context, all the experts addressed the situation where both routes cut through the very rough terrain at the foothills of Mount Pilatus. Placing transmission lines on the mountain ridge was perceived as critical, as the energy infrastructures would be visible from more places than if they were placed on a slope covered by forest. Some experts appreciated the earlier and more direct crossing of the blue line (Figure 6.2a) at the less steeper part of the mountain ridge (Figure 6.2b). Also, the perpendicular traverse of the blue line through the valley was preferred over the meandering patterns of the green line. Some experts argued that the longer the transmission line is, the more the landscape is affected.

6.2.3 Comparison based on the Technical Implementation Dimension

In the quantitative as well as in the qualitative evaluation, the novel approach did generally provide better results regarding the technical implementation dimension. The indicators of the quantitative analysis revealed that the blue line was shorter, straighter and less costly. The observations made by the experts confirmed these outcomes. They perceived two major benefits of the blue line:

- Thanks to its linearity, the blue line would be easier to implement from a technical point of view as less angle towers are necessary. The large amount of suspension towers need to endure fewer forces, require less material and have to be maintained less. The sigmoid course of the green route at Shortcut 2 near Giswil, for example, was judged by the experts as particularly difficult to implement.

- Being shorter and having a larger share of suspension towers, the blue line has been estimated by the experts to be less expensive.



(a) Crossing of the mountain ridge at the foothills of Mount Pilatus seen from the **South to the North**.

(b) Crossing of the mountain ridge at the foothills of Mount Pilatus seen from the **North to the South**.

Figure 6.2 – The blue and the green line at the foothills of Mount Pilatus from different perspectives.

Furthermore, the experts confirmed the results of the quantitative analysis, which stated that the green line tended to traverse more rough terrain than the blue line. The majority of the experts argued that the steepness is not the major challenge in a first place but rather how the slope is traversed by transmission lines. Crossing steep areas vertically to the slope, as the blue line does in Shortcut 1 and 3, is technically easier to implement. Routes, which follow the slope horizontally, are more exposed to natural hazards such as landslides, have to endure more forces and need more sophisticated foundations which require rock drilling. The green line which horizontally followed the slope at Shortcut 1 and 3 was rather criticized in this regard.

As for the pooling with linear infrastructures, the quantitative evaluation revealed that the route of the baseline method followed more existing linear infrastructures, especially transmission lines. However, the experts had no favorite route with respect to pooling. In general, they considered the pooling potential in this area being rather low. Pooling would be worth considering if there were longer sections of highways or railway lines, which do not enter settled areas. However, given the mountainous region, the study area is characterized by a large amount of winding mountain roads, which have little in common with transmission lines.

6.2.4 Concluding Remarks

As initially expected, the novel approach did on the one hand provide results that were clearly better regarding the technical implementation dimension, which is closely coupled with the financial aspects of transmission lines. On the other hand, it generated a route that affected the environment and landscape dimension to a higher degree. Somewhat surprisingly the novel approach performed better than the baseline with regard to the spatial planning dimension.

The expert interviews offered a geographically more differentiated view on the routes that resulted from the novel approach and the baseline method. According to the experts, the detours taken by the green line in Shortcuts 1 and 3 were neither from a spatial planning nor from a environmental and landscape protection point of view justified. However, in Shortcut 2 the experts criticized both solutions and suggested alternative routes.

Generally speaking, it should be noted that the findings from the comparison of both routes only apply for this study area and cannot be generalized to all kinds of situations. Contrasting the outcomes of the quantitative and the qualitative evaluation has shown that a differentiated assessment of the route is necessary. In some situation the novel approach performed better, even though the indicators implied the opposite. Problematic spots along the routes can be identified and used to improve the parameter configuration of the algorithm. For instance, in order to prevent the crossing of recreation and tourism zones as well as environmentally sensitive surfaces by the blue route these areas could be additionally defined as avoidance areas.

6.3 The Impact of the Technical Criteria

From a methodological point of view, both, the novel approach and the baseline method mainly differ from one another with respect to the technical criteria, which are included in the novel approach and not in the baseline method. Thus, the following research question is discussed in this section:

> ***RQ2:*** *How and to which extent do the integrated technical criteria impact the course of the route?*

In order to quantify the degree to which the technical criteria influence the route computation, a sensitivity analysis has been performed. The next sections are dedicated to analyzing the three optimization elements with regard to the impact and importance on the route computation of the technical criteria they include. As in Section 5.4, the optimization elements are called Factor A (the cost surface), B (the deflection angles) and C (the intersections with existing linear infrastructures).

6.3.1 The Impact and Importance of the Cost Surface

The impact of Factor A on each indicator as well as its importance are set out in Table 6.1. The cost surface had a negative effect on the mean terrain slope, i.e. the mean terrain slope tended to decrease when emphasizing the cost surface. This confirmed that the terrain suitability criterion of the cost surface had an impact on the route computation. However, this impact was small, as the percentage of the effect and the importance of Factor A in Table 6.1 show. This is probably due to the fact that technical criteria in the cost surface were sidelined by the criteria of the spatial planning and the environment and landscape dimensions, on which Factor A had a negative impact of -39% and -51%, respectively.

Accordingly, the cost surface did not have the expected decreasing effect on the indicative costs that depend on the mean terrain slope and the length of a route.

Furthermore, the cost surface had a minor influence on the shape of the route: There was almost no apparent impact of Factor A on the length and straightness index, with an effect of -1% and 0% and an importance of 0% each. In contrast, a stronger impact of the cost surface on

Table 6.1 – Impact and importance of Factor A regarding the different indicators. This table encompasses the results presented in section 5.4 that concern Factor A.

Indicator	**Impact**	**Importance**
Impact on spatial planning areas	-39%	45%
Impact on environment and landscape areas	-51%	87%
Length	-1%	0%
Straightness index	0%	0%
Mean terrain slope	-2%	6%
Indicative costs	7%	9%
Share of suspension towers	-11%	5%

the share of suspension towers could be observed. With a negative effect of -11%, the number of angle towers increased compared to the number of suspension towers when emphasizing the cost surface. This effect of Factor *A* indicates that the cost surface had an opposite effect on Factor *B* which aimed to minimize the deflection angles of the route. In other terms, as a consequence of emphasizing the cost surface, the route obtained a more sinuous character by avoiding environmental and landscape protection areas.

6.3.2 The Impact and Importance of the Angle of Deflection

The impact as well as the importance of Factor *B* regarding each indicator are listed in Table 6.2. Factor *B* had especially an impact on the share of suspension towers, for which it explains 87% of the variation. When Factor *B* was weighted, the share of suspension towers increased on average by 46%. Consequently, it could be assumed that Factor *B* had a construction cost reducing function since suspension towers are significantly less expensive than angle towers. Also the impact on the indicative costs confirmed that Factor *B* promotes cost-effective solutions (Impact: -8%, Importance: 13%).

Moreover, it becomes apparent that Factor *B* had a shortening (length: -6%) and straightening effect (straightness index: +5%) on the route. This is due to the fact that the deflection angle along the resulting route was minimized. Thus, the route was closer to the direct and therefore shortest connection between the starting and the destination point.

As expected, Factor *B* had no effect on the mean terrain slope and had accordingly a negligible importance of 0%.

Moreover, the increasing impact on the spatial planning (Effect: +15%, Importance: 7%) and the environment and landscape areas (Effect: +3%, Importance: 0%) further confirms that the deflection angle was the opposing factor against the cost surface.

Table 6.2 – Impact and importance of Factor *B* regarding the different indicators. This table encompasses the results presented in section 5.4 that concern Factor *B*.

Indicator	**Impact**	**Importance**
Impact on spatial planning areas	15%	7%
Impact on environment and landscape areas	3%	0%
Length	-6%	12%
Straightness index	5%	11%
Mean terrain slope	0%	0%
Indicative costs	-8%	13%
Share of suspension towers	46%	87%

6.3.3 The Impact and Importance of Intersections with Existing Linear Infrastructures

For the route of the novel approach only few pooling situations could be observed. The experts confirmed that the pooling potential in this study area is generally low. The predominant rural roads are winding and have thus little in common with transmission lines. Therefore, these linear infrastructures are unsuitable for pooling (see Section 5.3.3).

Regarding the impact and the importance of Factor C with respect to the indicators (Table 6.3), the expectations were not met in two respects: On the one hand Factor C had a considerably strong effect on the indicators. For the majority of the indicators, it explained a major percentage of their variation (see percentages in column *importance* in Table 6.3). In addition, the impact on each indicator was higher than 10%, except for the mean terrain slope and the share of suspension towers (see percentages in column *impact* in Table 6.3). This strong impact of Factor C may be explained by the fact that intersections were assigned to a Boolean value and thus had either a very strong influence on the edge weighting in the graph or none at all. A further consequence of this Boolean weighting scheme is that, for instance, small rural roads were treated equally to highways. A possible technique to tackle this issue would be to weight intersections in inverse proportion to the importance of the linear infrastructure in terms of pooling.

On the other hand, the impact of Factor C on the indicators was opposite to the desired effect. Longer, more meandering and more expensive routes were generated when Factor C was emphasized. This is probably due to the fact that the study area is characterized by a dense network of rural, winding roads. In order to minimize the number of intersections, the route took detours by avoiding this dense road system, without considering the environment and landscape dimension. The impact on spatial planning areas decreased, however. A possible explanation for that observation would be that linear infrastructures were particularly dense in built-up areas and thus bypassed by the route.

Generally speaking, by using only Factor C, the routing algorithm is reduced to a procedure, which aims to find the path with the smallest overall number of intersections. As the generated path is highly dependent on the existing linear infrastructures, the resulting impact and importance of factor C are thus inconclusive and difficult to fathom.

Table 6.3 – Impact and importance of Factor C regarding the different route indicators. This table encompasses the results presented in section 5.4 that concern Factor C.

Indicator	**Impact**	**Importance**
Impact on spatial planning areas	-18%	9%
Impact on environment and landscape areas	15%	8%
Length	13%	56%
Straightness index	-12%	55%
Mean terrain slope	-3%	17%
Indicative costs	12%	32%
Share of suspension towers	-9%	4%

6.3.4 Concluding Remarks

To sum up, it can be concluded that some technical optimization criteria had a clear and strong impact on the route properties whereas others stood out only marginally in the sensitivity analysis. Some criteria met the expectations, others influenced the route not as expected. The insights regarding the impact of each technical criterion are summarized below:

- *Terrain:* The technical criterion *terrain* was included in this algorithm in two ways:
  - The **ground clearance** constraint guaranteed that the resulting route was feasible in terms of the terrain.
  - The **slope of the terrain** was integrated in the cost surface. Thereby the algorithm determined a route that passed as little as possible through rough terrain. However, as the sensitivity analysis showed, the cost surface had only a small impact on the slope reduction along the route. This was probably due to the degree to which this criterion was taken into account for the computation of the cost surface. The strong impact of the cost surface on the spatial planning and the environment and landscape dimensions indicated that the criteria of those dimensions were overriding the terrain slope. In order to verify this statement, it would be necessary to compute the route based on a cost surface in which the terrain slope is emphasized more.
- *Angle of deflection:* As for the terrain, this technical criterion was considered both as constraint and as optimization criterion, respectively:
  - The **maximum deflection angle** prevented that large and thus technically complicated and expensive deflection angles were generated for a route.
  - The **sum of deflection angles** were optimized along the route in order to promote a large share of suspension towers for a route. The sensitivity analysis revealed that this criterion shortened as well as straightened the route and increased the share of suspension towers to a strong degree. Also the indicative costs of the route decreased when emphasizing the optimization of the deflection angles.
- *Pooling with existing linear infrastructures:* In order to promote pooling, existing linear infrastructures were integrated in the cost surface and the intersections between them and the computed route were minimized. However, only few pooling situations between the blue line and existing linear infrastructures could be observed. Furthermore, the optimization of intersections with linear infrastructures in the mountainous study area led to longer, more sinuous and more expensive roads. As a result of the strong effect of Factor C that influenced the indicators in a opposite way as desired, following measures could be taken:
  - The intersections could be weighted in inverse proportion to the importance of the linear infrastructure (e.g. highways are more important than rural roads).
  - The set of linear infrastructures could be reduced to highways, the most important railway lines and existing transmission lines.
  - Factor C could be ignored for the routing analysis.

6.4 Applicability of the Novel Approach in Practice

This section is dedicated to provide an answer to *RQ3:*

> ***RQ3:*** *To which extent is the novel approach applicable in practice and how does it contribute to the planning procedure of transmission lines?*

Experts have been asked during the interviews whether they consider the novel approach to be applicable in practice and how it would contribute to the approval procedure of transmission line projects. Five of the six experts answered positively to this question. The perceived benefits can be summarized in three points:

- *The linearity of the computed route is an asset of the novel approach.* Integrating the angle of deflection into the routing algorithm has been greatly valued by the experts. By maximizing the share of suspension towers, the construction costs are reduced as suspension towers are significantly cheaper than angle towers. Furthermore, long straight sections along the computed route have been appreciated by the experts, given that they provide more freedom to position the transmission towers. A meandering path predefines more where a tower is to be placed.

- *The computed route is technically realizable in terms of the terrain.* The consideration of the terrain at an early stage of the planning procedure of a transmission line has been recommended by the experts. So far, once having modeled a possible route, it had to be verified in the field if the transmission line is technically feasible. A tool providing this information would improve this time-consuming process of developing the definitive route and is thus seen as a major advance.

- *The novel approach offers many configuration options.* The other aspect that the experts did appreciate is the flexibility of the approach. A series of parameters can be set in the novel approach, e.g. the avoidance areas, the height of the transmission towers and the maximum deflection angle. This allows to test different scenarios of routes, which can be presented to the contracting authorities. Furthermore, if the novel approach would be accepted by decision-taking authorities, it would be possible to use the resulting routes as basis for argumentation in court. The acceptance of this tool would significantly simplify the approval procedure for transmission line projects.

In summary, the experts appreciated the newly integrated technical aspects of the algorithm and could imagine to apply this approach as a tool in the transmission line projects. The technical criteria promote solutions that are not only technically feasible but also financially viable. This also contributes to the improvement and acceleration of the planning procedure of the transmission lines. However, before this approach can be proposed for practical applications, the limitations outlined in the concluding chapter (Chapter 7.3) need to be taken into account.

Chapter 7

Conclusion

The most widely applied method to solve the transmission line routing problem involves the determination of the raster cell sequence in a cost surface that costs the less, i.e. the least cost path. The novel approach, which has been proposed in this Master's thesis, aims to improve this state-of-the-art approach by considering technical transmission line properties in addition to spatial planning, environmental and landscape protection criteria. In Section 7.1 the contributions of the novel approach are summarized. The findings of this Master's thesis are presented in Section 7.2. Sections 7.3 and 7.4 will address the the limitations of the novel approach and provide suggestions for future work, respectively.

7.1 Contributions

A novel, graph-based approach to compute the optimal route for transmission lines has been proposed and implemented in this Master's thesis. Following aspects of the proposed approach are contributions to today's state of the art:

- In the novel approach, the optimal route corresponds to a path in a graph where the vertices represent transmission towers and the edges model the conductors between two towers. Considering towers as vertices in a graph allows to consider the criteria governing the construction of transmission lines in a highly differentiated way. Apart from enabling to model technical criteria realistically, this also offers the possibility to differentiate between the placement of towers and the spanning of conductors, which in some avoidance areas, such as groundwater protection zones, may be possible (see below).

- The developed routing algorithm considers not only criteria of the dimensions *spatial planning* and *environment and landscape* but also from the *technical implementation* dimension.

- Technical criteria are integrated in the form of constraints and optimization criteria.

  - Constraints limit the route possibilities. Based on avoidance areas, a predefined span range as well as a maximum deflection angle, the graph is filtered. Moreover, the inclusion of the ground clearance further guarantees that the resulting route is feasible in terms of the terrain.
  - In order to compute the optimal route, optimization criteria of the three dimensions are taken into account. In addition to the cost surface, which mainly considers criteria of the spatial planning and the environment and landscape dimension, the novel approach optimizes the sum of deflection angles along the route as well as the intersections with linear infrastructures.

- The technical criteria are closely coupled to the economic aspect of transmission lines. Thus, optimizing these criteria inherently reduces the construction costs of the modeled transmission lines.

7.2 Findings

In order to evaluate the novel approach it has been put in contrast with the baseline method (*RQ1*). To that end, both approaches, the novel approach and the baseline method, have been tested in a mountainous study area. The resulting routes of both approaches were then compared based on a quantitative and a qualitative evaluation. For the quantitative analysis, indicators were defined which describe route properties in terms of the three key dimensions. The qualitative evaluation, for which expert interviews have been conducted, completes the insights gained from the quantitative evaluation. The main findings of the quantitative and the qualitative evaluations are summarized with regard to the respective dimension:

The Spatial Planning Dimension

- The quantitative evaluation showed that the route of the novel approach provided better results, as it affected slightly less settlements and infrastructures of the spatial planning dimensions.

- Also, the expert interviews revealed that the route of the novel approach was more suitable in terms of the spatial planning dimension than the outcome of the baseline method. The novel approach avoided more systematically habitations and respected the future expansion areas of settlements to a greater extent than the baseline method. Nevertheless, the experts pointed out a few adaptations to reduce the impact on this dimension even more.

The Environment and Landscape Dimension

- According to the quantitative evaluation, the route of the novel approach had a larger impact on the environmentally sensitive and landscape protection areas compared to the one of the baseline method.

- The experts' opinions were somewhat undecided. In some situations, the route of the novel approach was favored and in other situations, the route of the baseline method was preferred by the experts.

The Technical Implementation Dimension

- The route of the novel approach was shorter, had fewer towers and was less sinuous than the one of the baseline method. As a consequence, the share of suspension towers was significantly higher and the indicative costs significantly lower compared to the results of the baseline method. According to the distribution of the terrain slope, the route of the baseline method traverses more rough terrain compared to the novel approach. Furthermore, the line generated by the baseline method did pool more with existing linear infrastructures than the one of the novel approach.

- The experts preferred the route of the novel approach over the one of the baseline method due to its linearity, shortness and also its expected lower construction costs. The majority of the experts perceived the route of the novel approach to be better embedded in the terrain. In general, the possibilities of pooling with linear infrastructures was estimated as low for this study area.

As can be deduced from the quantitative and qualitative evaluations, the route computed by the novel approach and the route of the baseline method significantly differ from each other. Given that the main difference between both approaches is that the novel approach considers technical properties of transmission lines, which the baseline method ignores, this Master's thesis has in particular investigated the impact caused by criteria of the technical implementation dimension on the route computation (*RQ2*). The influence of an optimization criterion is defined by the weight that is assigned to the three optimization elements. To that end, a sensitivity analysis has been performed. The main findings for each optimization element are summarized bellow:

- When the weight of the cost surface is increased, mainly the impact of the computed route on areas with spatial planning, environmental and landscape protection functions decreased. However, the technical criteria included in the cost surface, e.g. the terrain roughness, were sidelined by the criteria of the spatial planning and the environment and landscape dimension. Only a marginal effect on the mean terrain slope of the route could be observed when the cost surface was weighted.

- When emphasizing the angle of deflection, generally shorter, less sinuous and less costly routes resulted. The deflection angles particularly influenced the share of suspension towers by increasing it. Thus, optimizing the sum of deflection angles promotes routes, which are cost-effective and technically easier to implement.

- Promoting the minimization of intersections with existing linear infrastructures appeared to have the opposite effect as expected. Only few pooling situations between the computed route and existing transmission lines could be observed. Moreover, the routes were longer, more sinuous and more expensive when the number of intersections was minimized. This behavior of the algorithm is probably due to the fact that the study area was mainly characterized by a dense network of winding rural routes which have little in common with the general straightness of transmission lines. The algorithm thus took detours by avoiding the network of existing linear infrastructures as much as possible. As indicated by the experts, the potential for pooling with existing linear infrastructures is low in this study area. It can generally be said, that it is not meaningful to use this optimization criterion alone and that it only makes sense to apply it in conjunction with others.

The social motivation of this Master's thesis is to contribute to the improvement of the transmission line planning procedure. That is why it has been investigated, whether the novel approach has the potential of being applied in practice and whether the newly integrated technical criteria are worth being taken into account when routes are modeled (*RQ3*). The large majority of the interviewed experts could imagine to apply the novel approach in their daily work. The fact that technically feasible routes in terms of the terrain are computed and that the share of suspension towers is maximized has been appreciated a lot by them. Furthermore, the various configuration possibilities allow to calculate various route scenarios which can be compared with each other for assessment purposes. The acceptance of such a tool by the decision-making authorities would significantly improve and accelerate the planning procedure.

By introducing the novel approach, this Master's thesis could demonstrate the benefits of integrating technical aspects of transmission lines in routing analyses.

7.3 Limitations

The novel approach introduced in this Master's thesis has some limitations which need to be addressed.

- A limiting property of the novel approach is that it necessitates a lot of computation memory. Further, it requires also a lot of computing time. Even though large parts of the algorithm are parallelized, the novel approach takes approximately a day from the setup of the graph to the computation of the optimal routes when running the algorithm on a EC2 Machine of Amazon with 122 GB Memory. Especially the ground clearance check and the weight computation of the edges in the graph are CPU-intensive. Thus, there is space for improving the novel approach from an algorithmic point of view. Approaches to parallelize Dijkstra's least cost path algorithm could, for instance, be taken into consideration (Jasika et al. 2012, Crauser et al. 1998, Tang et al. 2008).

- The graph was built based on cell centers of a raster with a resolution of 100 meters. Finer resolutions would have provided more precise results. However, the calculation time would have drastically increased, which is the reason why a higher resolution has not been considered in the first place.

- The influence of the technical optimization criteria included in the cost surface, e.g. the terrain suitability and existing linear infrastructures, is not transparent. A separate cost surface for technical criteria would have been necessary in order to discern the exact impact and importance of these criteria with respect to the route computation. The reason why this extension option has not been tested in this Master's thesis, is that the cost surface is the result of Joram Schito's ongoing PhD project at the Institute of Cartography and Geoinformation of ETH Zurich and has been provided as input for this routing analysis. The computation of the cost surface is not subject of this work.

7.4 Outlook

In order to improve the resulting route of the novel approach, various measures for future research could be taken. Different parameter configurations could be tested. For instance, expanding avoidance areas with fens and wetlands would have provided a route, which considers more the environment protection zones near Giswil. For future work it would be interesting to include different heights of transmission towers, as implemented in the different tower siting algorithms (Olbrycht 1982, Mitra & Wolfenden 1968, Viera & Toledo H. 2006, Zheng 1993) and in Rheinert's (1999) algorithm .

Furthermore, this algorithm could be applied on different study areas in order to provide more comprehensive insights into how the algorithm works in different circumstances. Different outcomes are expected in less rough and more settled study areas. As minimizing the intersection with existing linear infrastructures did not provide the expected impact on the route computation, some adaptations of it could be tested. For instance, intersections could be considered according to their importance, i.e. intersections with highways are more important than rural roads.

Moreover, the experts who have been selected for the interviews are mainly project and construction managers of transmission lines. They represent exclusively the private energy sector of Switzerland. Conducting additional interviews with experts from federal offices or representatives of environment and landscape protection organizations would have provided a more comprehensive and more differentiated evaluation of the resulting routes.

The novel approach introduced in this Master's thesis might also be used as basis for future work which aim at modeling underground cables in addition to overhead transmission lines. Underground cables are increasingly taken into consideration as alternative to overhead transmission lines. Underground cabling is beneficial thanks to its low visibility and its comparably low electric and magnetic field. However, only 1% of the Swiss transmission network is underground. The low percentage is mainly due to the construction costs. Underground cables can cost up to 10 times more than overhead transmission lines (Swissgrid AG 2017*a*). In order to include underground cables in the novel approach, additional parameters need to be incorporated in the algorithm. The criteria of cabling differ to those of overhead transmission lines in terms of the spatial planning, the environment and landscape and the technical implementation dimension. The challenge will be to extend the algorithm such that it is able to decide in which case underground cables are more suitable compared to overhead transmission lines. In addition, the graph-based approach will become more complex and thus will require more CPU-time.

As can be seen, various extension options of the novel approach emerge from discussing the findings of this Master's thesis. The firm insights gained regarding the technical criteria, however, will hopefully provide a basis for further studies of routing analysis of transmission lines.

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Appendix A

Maps of the Different Dimensions

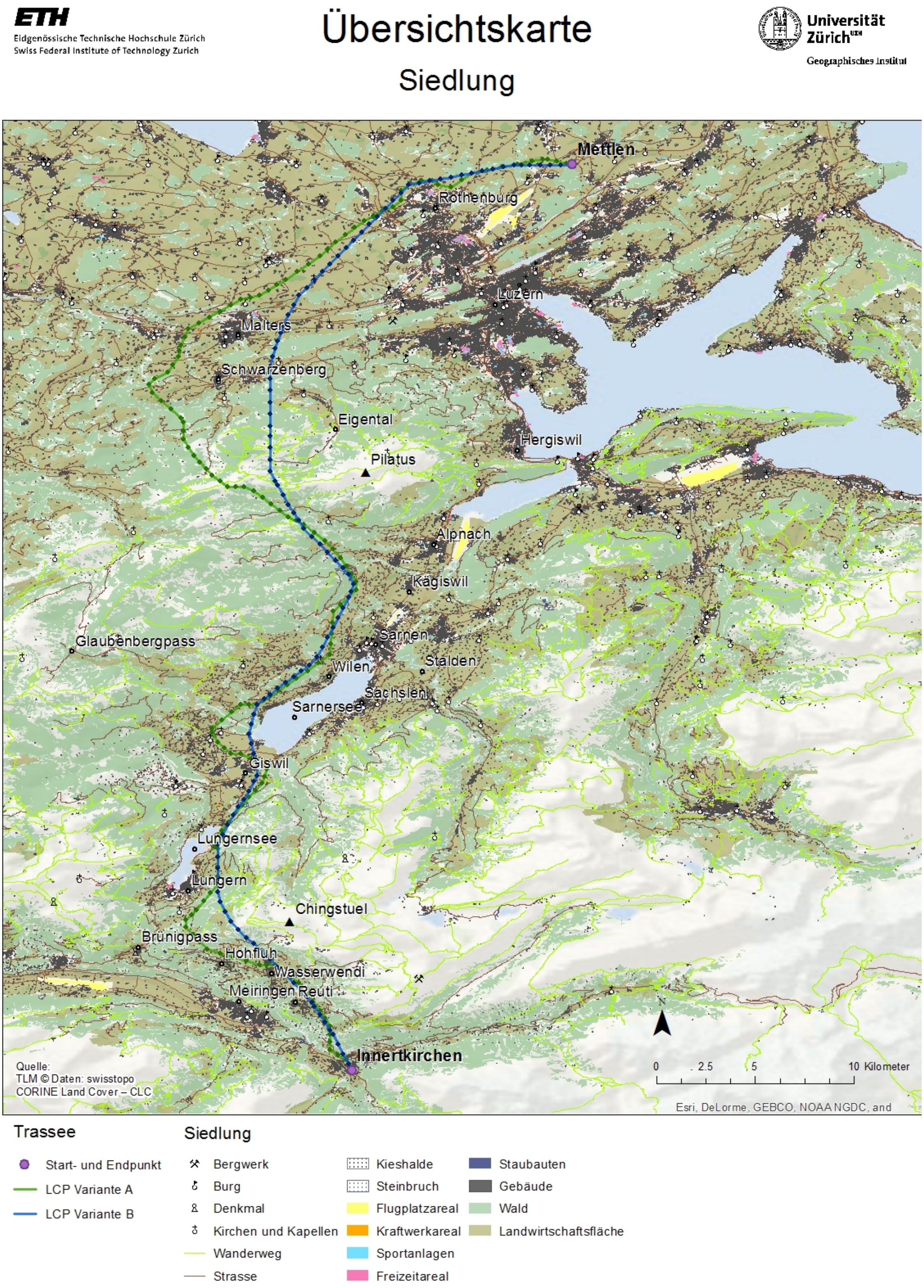


Figure A.1 – Overview map of urban infrastructures. It corresponds to the original map that the experts used to evaluate the routes of the novel approach and the baseline method. That is why the labeling is in German.

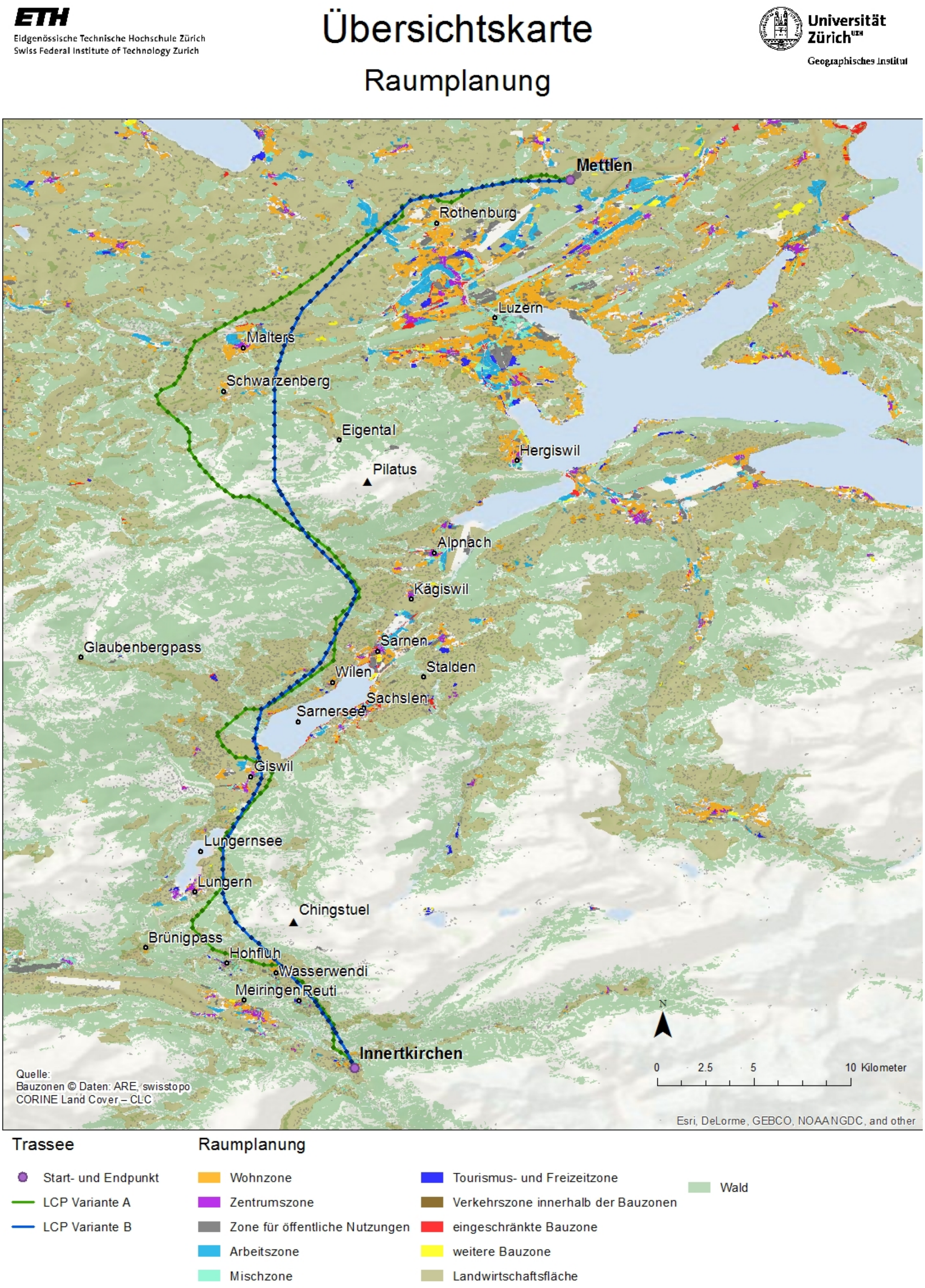


Figure A.2 – Overview map regarding spatial planning. It corresponds to the original map that the experts used as basis of decision-making. That is why the labeling is in German.

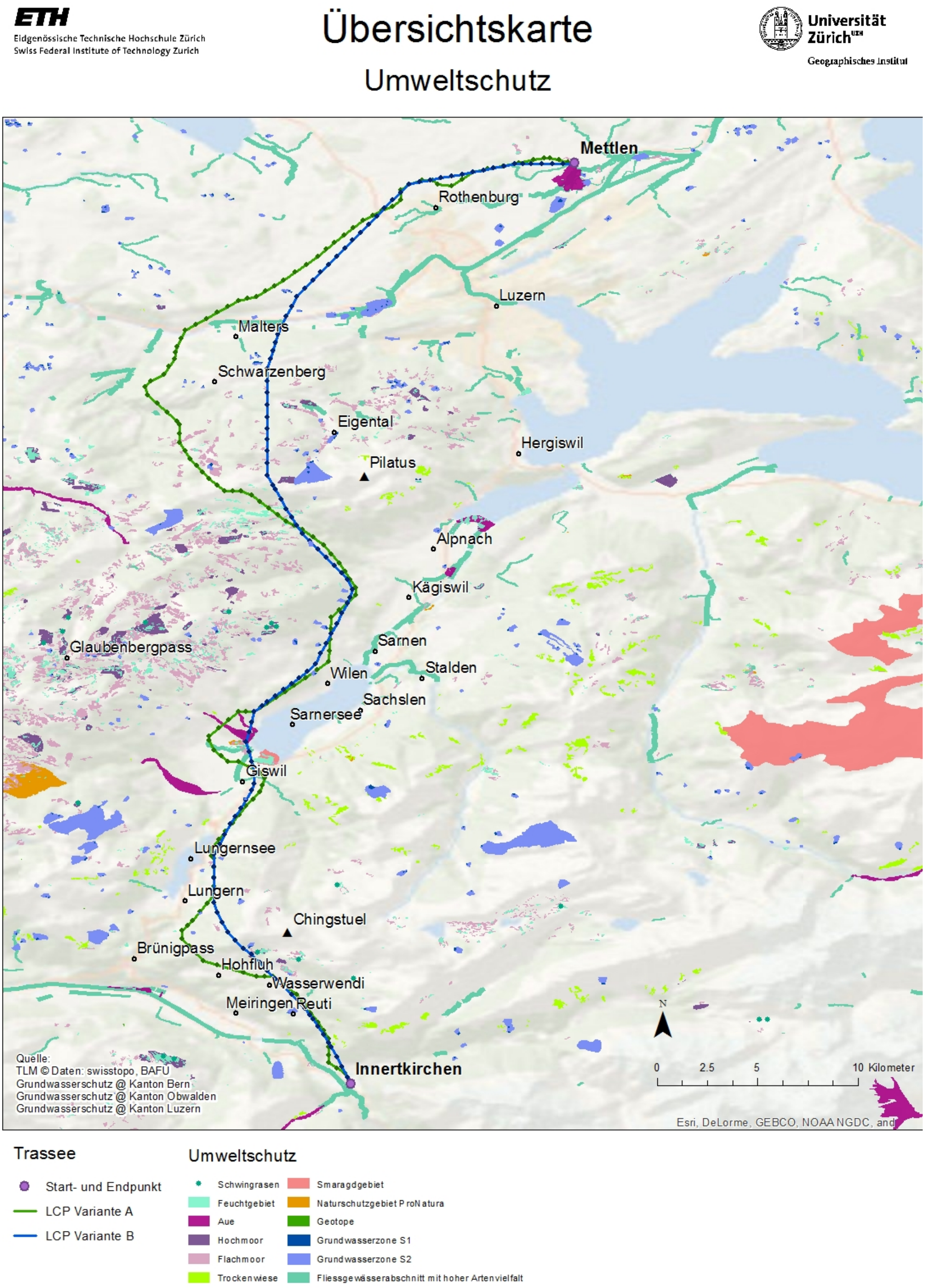


Figure A.3 – Overview map regarding environment protection. It corresponds to the original map that the experts used to evaluate the routes of the novel approach and the baseline method. That is why the labeling is in German.

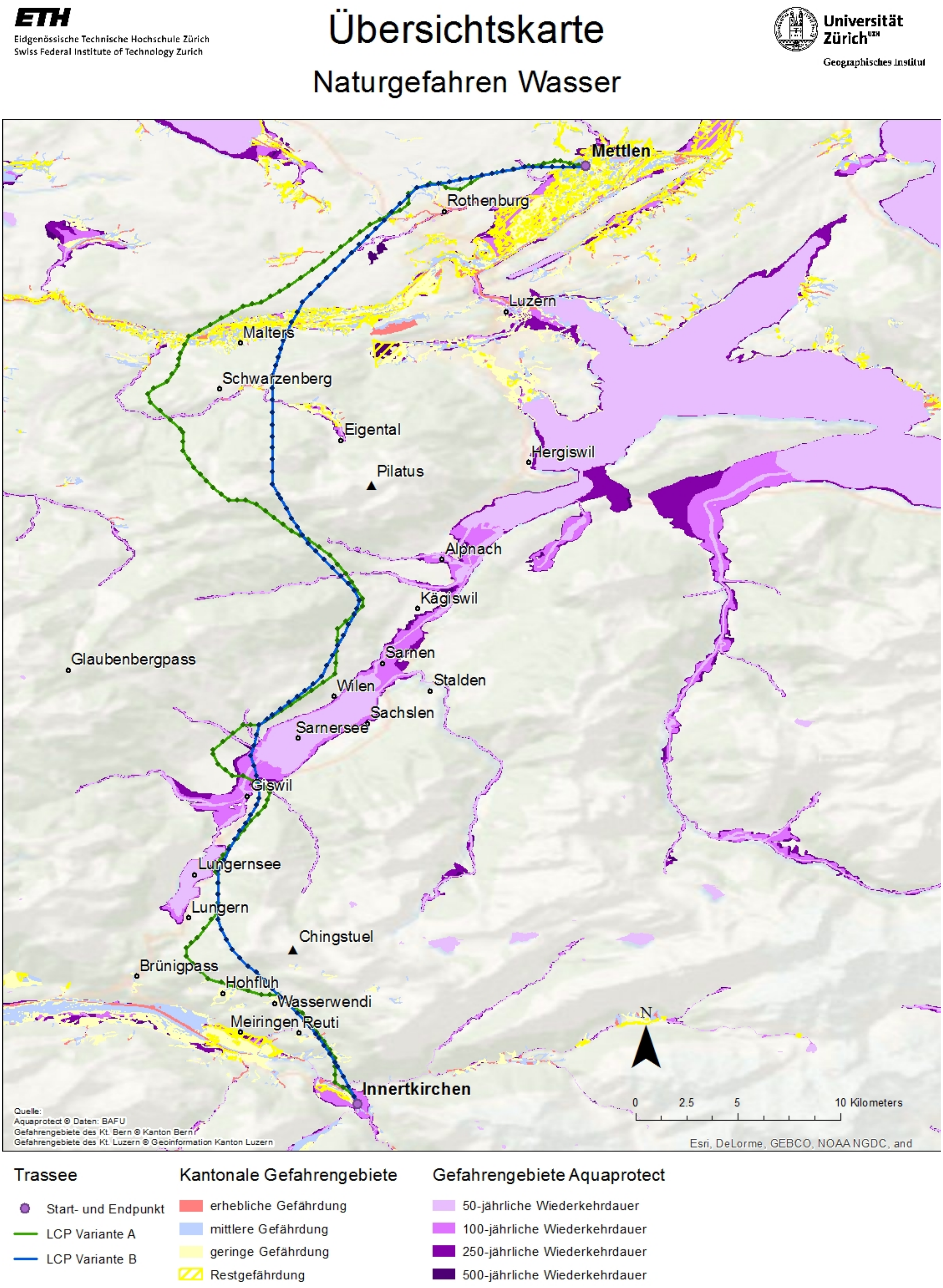


Figure A.4 – Overview map regarding water-related natural hazards. It corresponds to the original map that the experts used to evaluate the routes of the novel approach and the baseline method. That is why the labeling is in German.

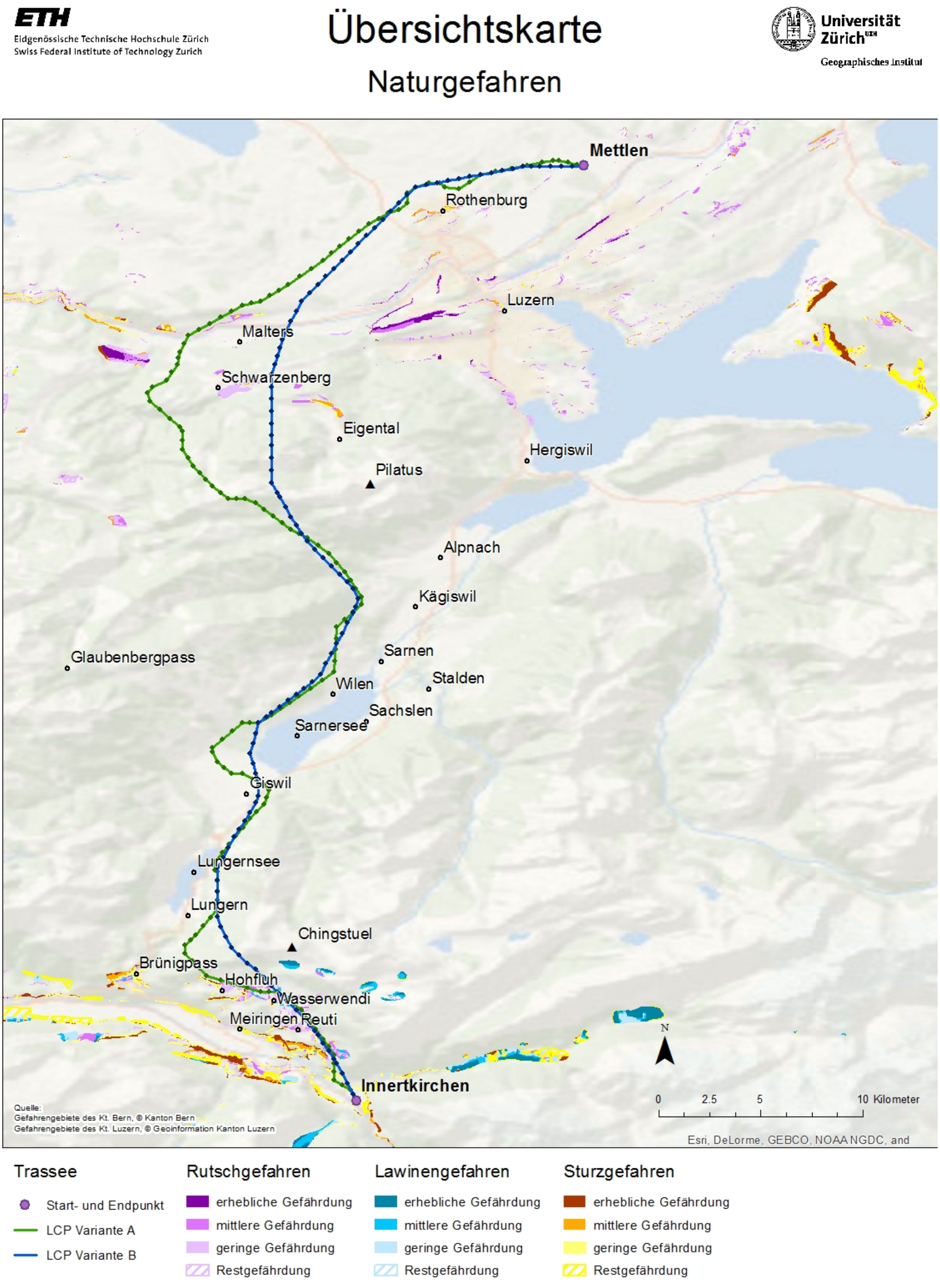


Figure A.5 – Overview map regarding other natural hazards such as landslides, avalanches and gravitational processes. It corresponds to the original map that the experts used to evaluate the routes of the novel approach and the baseline method. That is why the labeling is in German.

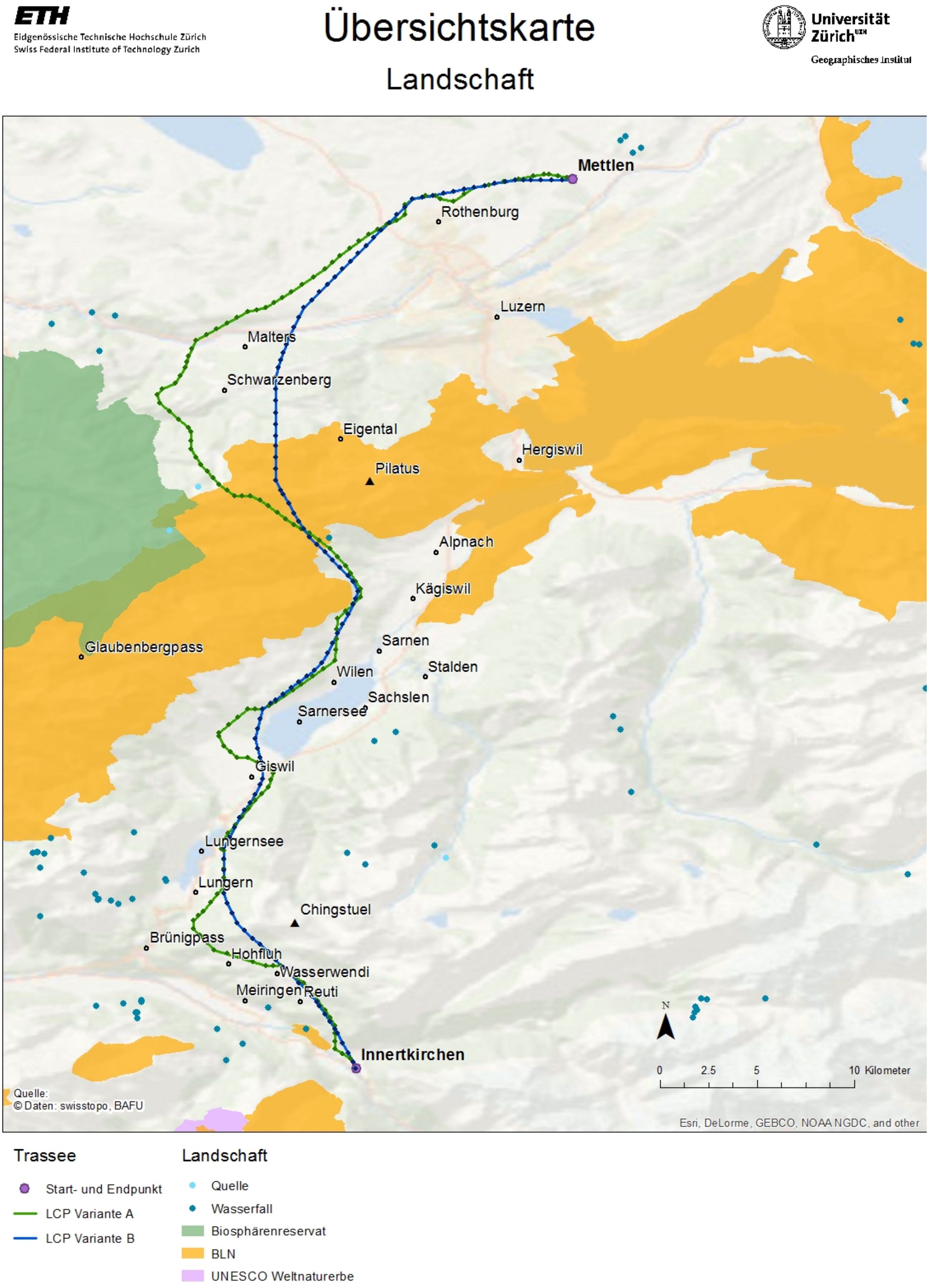
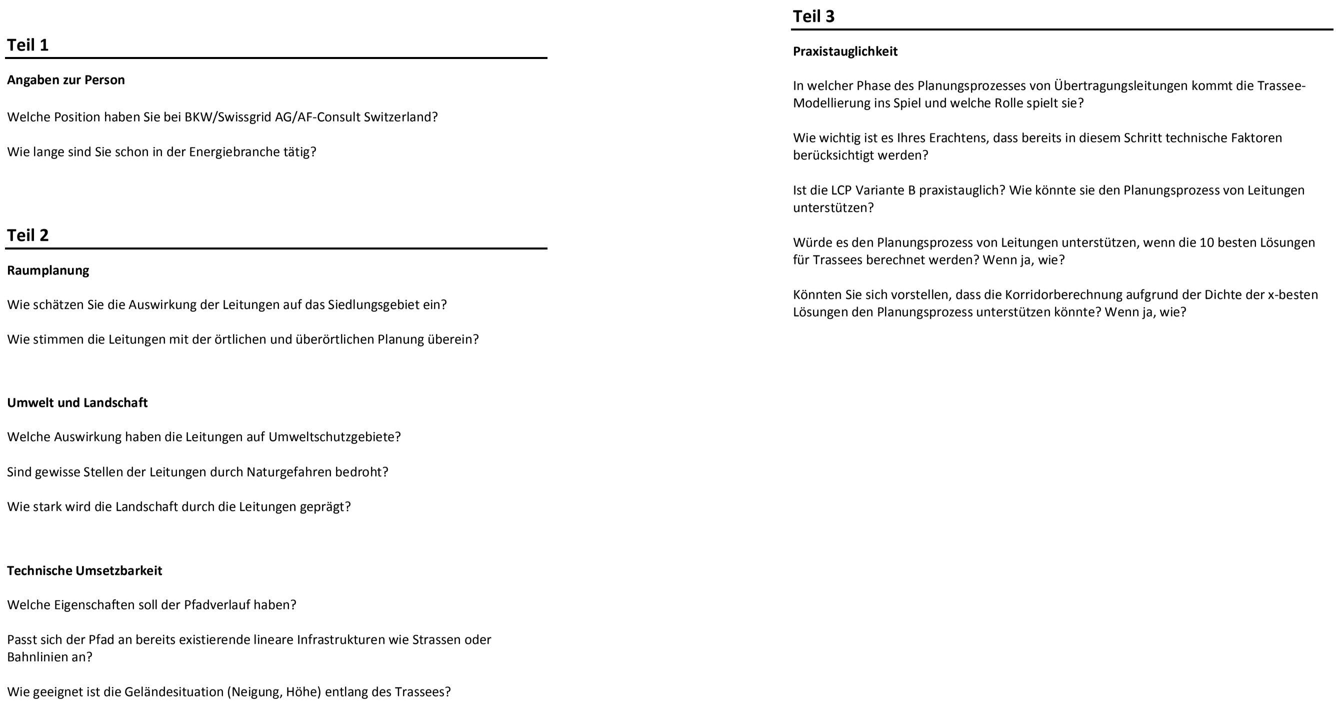


Figure A.6 – Overview map regarding landscape protection. It corresponds to the original map that the experts used to evaluate the routes of the novel approach and the baseline method. That is why the labeling is in German.

Appendix B

Qualitative Evaluation Materials



Teil 1

Angaben zur Person

Welche Position haben Sie bei BKW/Swissgrid AG/AF-Consult Switzerland?

Wie lange sind Sie schon in der Energiebranche tätig?

Teil 2

Raumplanung

Wie schätzen Sie die Auswirkung der Leitungen auf das Siedlungsgebiet ein?

Wie stimmen die Leitungen mit der örtlichen und überörtlichen Planung überein?

Umwelt und Landschaft

Welche Auswirkung haben die Leitungen auf Umweltschutzgebiete?

Sind gewisse Stellen der Leitungen durch Naturgefahren bedroht?

Wie stark wird die Landschaft durch die Leitungen geprägt?

Technische Umsetzbarkeit

Welche Eigenschaften soll der Pfadverlauf haben?

Passt sich der Pfad an bereits existierende lineare Infrastrukturen wie Strassen oder Bahnlinien an?

Wie geeignet ist die Geländesituation (Neigung, Höhe) entlang des Trassees?

Teil 3

Praxistauglichkeit

In welcher Phase des Planungsprozesses von Übertragungsleitungen kommt die Trassee-Modellierung ins Spiel und welche Rolle spielt sie?

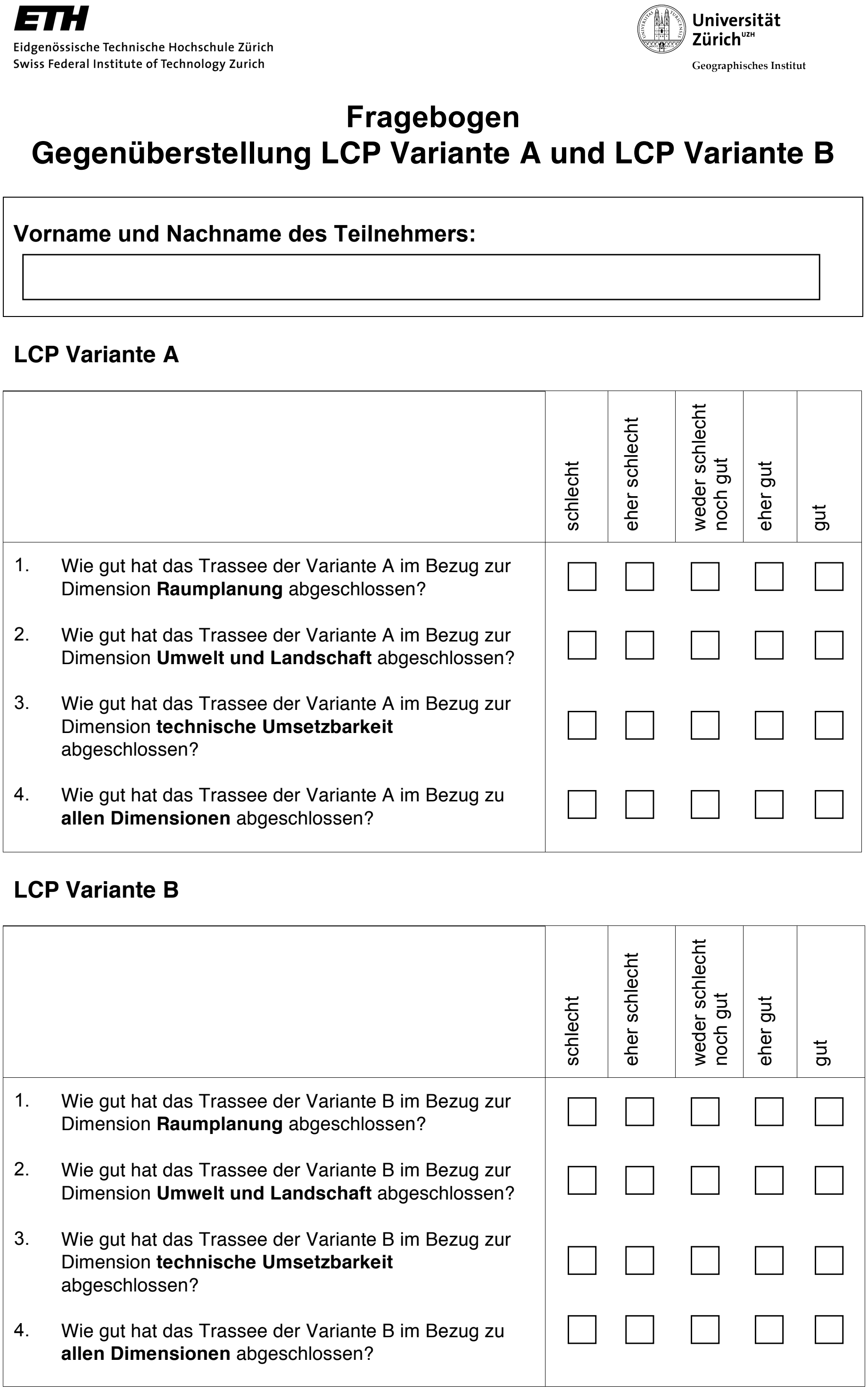
Wie wichtig ist es Ihres Erachtens, dass bereits in diesem Schritt technische Faktoren berücksichtigt werden?

Ist die LCP Variante B praxistauglich? Wie könnte sie den Planungsprozess von Leitungen unterstützen?

Würde es den Planungsprozess von Leitungen unterstützen, wenn die 10 besten Lösungen für Trassees berechnet werden? Wenn ja, wie?

Könnten Sie sich vorstellen, dass die Korridorberechnung aufgrund der Dichte der x-besten Lösungen den Planungsprozess unterstützen könnte? Wenn ja, wie?

Figure B.1 – Guideline of the expert interviews.



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Universität Zürich^UZH
Geographisches Institut

Fragebogen
Gegenüberstellung LCP Variante A und LCP Variante B

Vorname und Nachname des Teilnehmers:

LCP Variante A

	schlecht	eher schlecht	weder schlecht noch gut	eher gut	gut
1. Wie gut hat das Trassee der Variante A im Bezug zur Dimension **Raumplanung** abgeschlossen?	☐	☐	☐	☐	☐
2. Wie gut hat das Trassee der Variante A im Bezug zur Dimension **Umwelt und Landschaft** abgeschlossen?	☐	☐	☐	☐	☐
3. Wie gut hat das Trassee der Variante A im Bezug zur Dimension **technische Umsetzbarkeit** abgeschlossen?	☐	☐	☐	☐	☐
4. Wie gut hat das Trassee der Variante A im Bezug zu **allen Dimensionen** abgeschlossen?	☐	☐	☐	☐	☐

LCP Variante B

	schlecht	eher schlecht	weder schlecht noch gut	eher gut	gut
1. Wie gut hat das Trassee der Variante B im Bezug zur Dimension **Raumplanung** abgeschlossen?	☐	☐	☐	☐	☐
2. Wie gut hat das Trassee der Variante B im Bezug zur Dimension **Umwelt und Landschaft** abgeschlossen?	☐	☐	☐	☐	☐
3. Wie gut hat das Trassee der Variante B im Bezug zur Dimension **technische Umsetzbarkeit** abgeschlossen?	☐	☐	☐	☐	☐
4. Wie gut hat das Trassee der Variante B im Bezug zu **allen Dimensionen** abgeschlossen?	☐	☐	☐	☐	☐

Figure B.2 – Questionnaire with the wrap-up questions that have been asked during the expert interviews.

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

....	....
Place, Date	Signature of the Author