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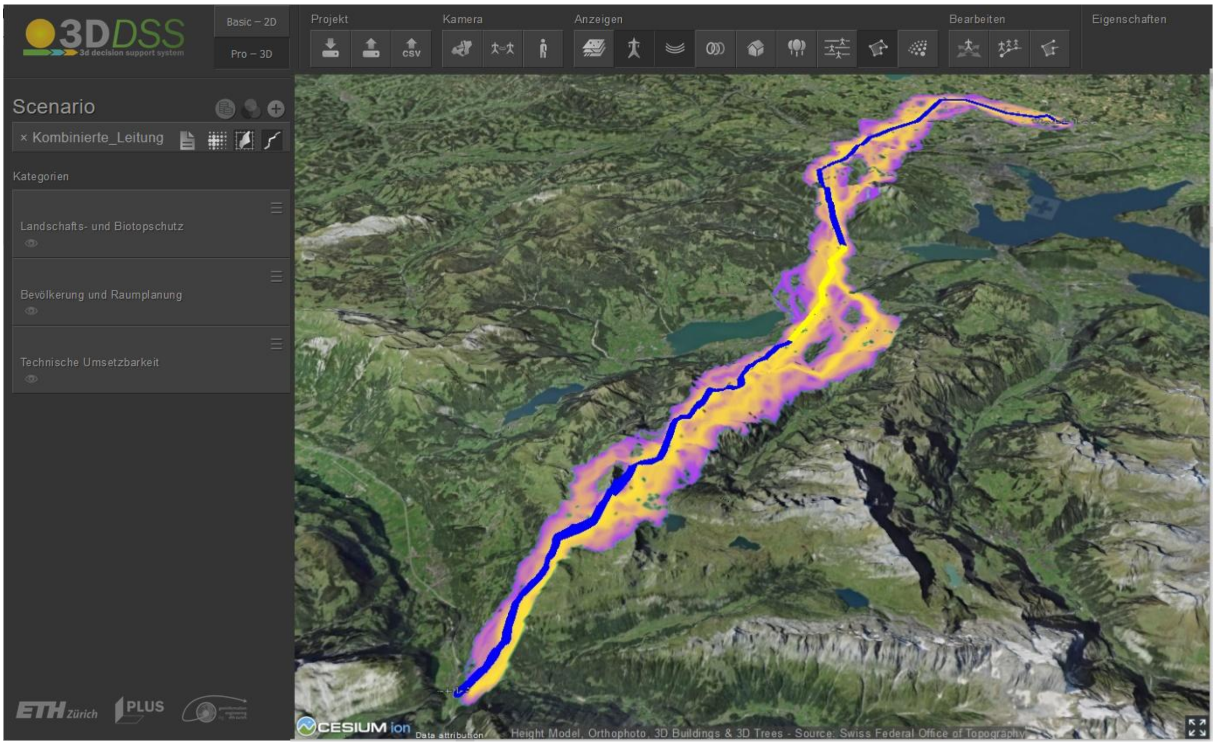
3D DSS – EC

Enhancing the 3D DSS for Supporting the Planning of Electric Power Systems: Integration of Underground Cables



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Zusammenfassung

Im Rahmen des Projekts «3D DSS – EK» wurde ein bestehendes 3D Decision Support System (3D DSS) zur Berechnung und Visualisierung von Planungsgebieten und Korridoren von elektrischen Versorgungsleitungen mit der Integration von Erdkabeln erweitert. Hierzu wurden mehrere Verfahren entwickelt, um mithilfe einer breiten Palette von Ansätzen aus der Multikriteriellen Entscheidungsanalyse, der Geoinformatik und des Operation Research Orte zu bestimmen, die sich für den Bau einer neuen Hochspannungsleitung – sei es über- oder unterirdisch – besonders eignen. Die dabei entwickelten Verfahren vermögen Planungsgebiete, Korridore, Trassees bis hin zu den exakten Positionen der Masten bzw. Muffenschächte zu bestimmen. Im Rahmen dieses Projektes wurde erstmals ein Ansatz entwickelt, der den optimalen Verlauf einer Leitung bestimmen kann, der aus Freileitungs- und Erdkabelabschnitten besteht. Darüber hinaus wurde eine neue Methode erfolgreich getestet, die aufgrund eines definierten Szenarios mehrere Pareto-optimale Varianten generiert.

Die web-basierte Benutzerschnittstelle des 3D DSS wurde bezüglich der Nutzerführung und 3D-Visualisierung der Resultate angepasst. Insbesondere wurde das 3D DSS um die Darstellung von Leitungen im Untergrund erweitert. Des Weiteren wurde eine Augmented Reality-Lösung umgesetzt, die es ermöglicht, Szenarien von Leitungsverläufen in der Landschaft vor Ort über mobile Geräte zu visualisieren. Die Entwicklung erfolgte am Beispiel von Fallstudien auf Höchst- (Innertkirchen–Mettlen), Hoch- (Stadt Zürich) und Mittelspannungsebene, wobei in iterativen Schritten die Feedbacks der Industriepartner und der Bundesämter BFE, ARE und BAFU zur Verbesserung des 3D DSS einbezogen wurden. Das weiterentwickelte Tool kann dazu beitragen, die Entwicklung und Kommunikation von möglichen Leitungsverläufen zu unterstützen und so im Sachplanverfahren Übertragungsleitungen als auch in der Kommunikation mit der Bevölkerung als unterstützendes Werkzeug dienen.

Résumé

Dans le cadre du projet «3D DSS – EC», un 3D système d'aide à la décision sur des problèmes spatiaux (3D DSS) existant pour le calcul et la visualisation des zones de planification et des couloirs des lignes d'alimentation électrique a été étendu avec l'intégration de câbles souterrains.

À cette fin, plusieurs méthodes ont été mises au point pour déterminer les emplacements particulièrement adaptés à la construction d'une nouvelle ligne électrique à haute tension – en surface ou sous terre – en utilisant un large éventail d'approches allant de l'analyse décisionnelle multicritères à la géoinformatique et à la recherche opérationnelle. Les méthodes développées dans ce processus sont capables de déterminer les zones de planification, les couloirs et les itinéraires, jusqu'aux positions exactes des pylônes ou des manchons. Dans le cadre de ce projet, une approche a été développée pour la première fois qui permet de déterminer le tracé optimal d'une ligne composée de sections de lignes aériennes et de câbles souterrains. En outre, une nouvelle méthode pour générer plusieurs variantes Pareto optimales basées sur un seul scénario a été testée avec succès.

L'interface web du DSS 3D a été adaptée en ce qui concerne le guidage de l'utilisateur et la visualisation 3D des résultats. En particulier, le 3D DSS a été étendu par l'affichage de lignes souterraines. En outre, une solution de réalité augmentée a été mise en place, qui permet de visualiser sur place et en utilisant des appareils mobiles, des scénarios de lignes souterraines dans le paysage. Le développement a été réalisé à l'aide d'études de cas aux niveaux à très haute tension (Innertkirchen–Mettlen), haute tension (Zurich) et moyen tension, desquelles les réactions des partenaires industriels et des offices fédéraux de l'OFEN, de l'ARE et de l'OFEV ont été incluses itérativement visant à améliorer le 3D DSS. Le 3D DSS peut contribuer à soutenir le développement et la communication des tracés de lignes possibles et ainsi servir d'outil de soutien dans la procédure de plan sectoriel pour les lignes de transmission et dans la communication avec la population.

Summary

The project «3D DSS – EC» extended an existing 3D Decision Support System (3D DSS) for the calculation and visualization of planning areas and corridors of electrical power lines with the integration of earth cables. For this purpose, several methods were developed to determine locations that are particularly suitable for the construction of a new high-voltage power line – either overhead or underground – using a wide range of approaches from multi-criteria decision analysis, geoinformatics, and operations research. The methods developed in this process are able to determine planning areas, corridors, and routes, right down to the exact positions of the transmission towers or access points. Within the scope of this project, a novel approach has been developed which determines the optimal path of a combined line that consists of overhead line and underground cable sections. Furthermore, a new method was successfully tested which generates several Pareto-optimal variants based on one single scenario.

The web-based user interface of the 3D DSS was adapted with regard to user guidance and 3D visualization of the results. In particular, the 3D DSS was extended by the display of underground cables. Furthermore, an augmented reality solution was realized, which enables the visualization of scenarios of underground lines in the landscape on site by using mobile devices. The development was carried out on the basis of case studies on the extra-high (Innertkirchen–Mettlen), high (Zurich) and medium voltage level, whereas the feedback of the industrial partners and the federal offices SFOE, ARE and FOEN were included in an iterative way to improve the 3D DSS. The enhanced 3D DSS can help to support the development and communication of possible corridors and thus serve as a supporting tool in the sectoral plan procedure for transmission lines as well as in communication with the population.

Contents

Abbreviations

3D DSS	3D Decision Support System	(3D Decision Support System)
AP	Access Point	(Muffenschacht)
AR	Augmented Reality	(Augmented Reality)
ARE	Federal Office for Spatial Development	(Amt für Raumentwicklung ARE)
CL	Combined Line	(kombinierte Leitung)
DEM	Digital Elevation Model	(Digitales Höhenmodell)
DSM	Digital Surface Model	(Digitales Oberflächenmodell)
DTM	Digital Terrain Model	(Digitales Terrainmodell)
EC	Earth Cable	(Erdkabel)
FOCP	Federal Office for Civil Protection	(Bundesamt für Bevölkerungsschutz BABS)
FOEN	Federal office for the Environment	(Bundesamt für Umwelt BAFU)
GIS	Geographic Information System	(Geographisches Informationssystem)
JSG	Hunting Act	(Jagdschutzgesetz, SR 922.0)
MCDA	Multi-Criteria Decision Analysis	(Multikriterielle Entscheidungsnalyse)
LCC	Least Cost Corridor	(Korridor der geringsten Kosten)
LCP	Least Cost Path	(Pfad der geringsten Kosten)
LeV	Ordinance on Electrical Lines	(Leitungsverordnung, SR 734.31)
LP	Linear Programming	(Lineare Programmierung)
ONIR	Ordinance on Protection against Non-Ionizing Radiation	(NISV, SR 814.710)
OKA	Places for Short-Term Stay	(Orte für den kurzfristigen Aufenthalt)
OL	Overhead Line	(Freileitung)
OMEN	Places with Sensitive Usage	(Orte mit empfindlicher Nutzung)
PGV	Planning Approval Procedure	(Plangenehmigungsverfahren)
RPG	Spatial Planning Act	(Raumplanungsgesetz, SR 700)
RPV	Ordinance on Spatial Planning	(Raumplanungsverordnung, SR 700.1)
SFOE	Federal Office of Energy	(Bundesamt für Energie BFE)
SPV	Sectoral Planning Process	(Sachplanverfahren)
SÜL	Sectoral Plan for Transmission Lines	(Sachplan Übertragungsleitungen)
StromVG	Federal Act on the Electricity Supply	(Stromversorgungsgesetz, SR 734.7)
TB	Transition Building	(Übergangsbauwerk)
TL	Transmission Line	(Übertragungsleitung)
TT	Transmission Tower	(Mast)
WFS	Web Feature Service	(Web Feature Service)
WLC	Weighted Linear Combination	(Gewichtete Linearkombination)
WMS	Web Sap Service	(Web Sap Service)

1 Introduction

1.1 Background information and current situation

The planning of transmission lines (TLs) is a complex endeavor because technical, legal, political, economic, and ecological aspects must be considered. The fact that the major part of the spatial evaluation is done manually requires even more time. Furthermore, affected citizens criticize that the planning process is not sufficiently transparent. This leads them to object a TL project, which in turn causes delays and thus, higher costs.

In the previous 3D-GIS project (Raubal et al. 2017), which was carried out from 2014–2017, two research teams of ETH Zurich developed a 3D-Geographic Information System (3D-GIS) to shorten the "planning and approval process based on the sectoral plan for electricity transmission lines" (SÜL). The developed application, the 3D Decision Support System (3D DSS), fosters transparency by applying Multi-Criteria Decision Analysis (MCDA) as, on the one hand, stakeholders' subjective assessments are quantified and, on the other hand, different opinions can be accounted for during the decision-making process (Zheng, Egger, and Lienert 2016). By defining how much weight a factor should have regarding the protection of a specific area, stakeholders can compute maps visualizing optimal corridors and TL paths in a short time.

The approach of the former 3D DSS has only a limited applicability for modeling earth cables (ECs), as many particular factors for planning underground lines were not considered. However, social pressure on laying high voltage cables underground, has been increasing for years (Jullier 2016; Lienert, Sütterlin, and Siegrist 2017). Furthermore, according to the SÜL and to a court decision (Swiss Federal Supreme Court 2011), the option of implementing ECs and to carrying out a balancing of interests has to be proved for projects with a high impact on the landscape (UVEK 2001).

For this reason, the current project aimed at investigating methods that model and visualize ECs by taking the special conditions of underground lines into consideration. Furthermore, previous methods allowed to model only lines of the same transmission technology whereas combined lines (CLs), which consist of overhead and underground sections, were not possible to model. For this reason, we investigated two novel methods to tackle this issue (Schito 2020) and present in the current report the method that experts determined to provide more realistic results.

1.2 Purpose of the project

As approaches for modeling ECs were missing in the former 3D-GIS, a new approach needed to be developed which extends the existing 3D DSS in a way that also corridors for ECs and CLs can be modeled. Thereby the specific requirements for different grid levels, the extra-high voltage (N1), high voltage (N3), and medium voltage (N5) voltage level), needed to be taken into account.

1.3 Objectives

This project is based on the Electricity Grid Strategy (Swiss Federal Council 2013) and aims to support renewing and expanding the existing grid. It takes up the findings from the previous project «Application of 3D Geographic Information Systems for transparent and sustainable planning of electric power systems (3D-GIS)» and extends it towards finding a solution for modeling EC corridors. In order to fulfill these requirements, this project aims at developing a solution that automatically models the optimal corridor for an EC and for a CL.

Specific objectives are:

- Developing a decision model that calculates ECs on the grid levels N1-N5. The advanced decision model should take into account factors that are specifically relevant for underground cable construction. The optimal EC corridor is calculated based on a multi-criteria decision analysis (MCDA).
- Complementing the existing 3D DSS. The new approach shall combine overhead lines (OLs) and EC segments, since CLs most likely represent a realistic alternative. For this purpose, suitable locations shall be automatically identified which are suitable for the construction of transition buildings.
- Adaptation of the existing 3D DSS user interface. The interface will be adapted and completed in such a way that overhead lines and ECs can be modeled and visualized.
- Developing a mobile 3D DSS user interface. The modelled power line shall be displayed location-dependent using Augmented Reality. By using a tablet, the users should be able to interactively see the visual impact of a possible power line at a certain location.
- Evaluating the advanced 3D DSS. Whether and to what extent the 3D DSS supports the planning process of power lines will be evaluated by means of case studies (rural and urban) and workshops.

The reliability of the modeled corridors and paths shall be further increased compared to the current 3D DSS by comparing the resulting corridors with the expectations of experts. The extended 3D DSS is ought to become more versatile by integrating the criteria specific to each grid level (N1-N5) and to each spatial characteristic (rural vs. urban) into the decision model.

Specifically, the following results are expected:

- An approach that calculates the ideal corridor for ECs on the grid levels N1-N5. The approach takes into account the special decision criteria for the construction of ECs, spatial planning conditions, and data uncertainty. Furthermore, the approach is integrated into the existing 3D DSS and combined with the approach for calculating OL corridors.
- A user-friendly 3D DSS user interface for desktops and notebooks that uses current techniques to visualize basic data and calculated corridors for OLs, ECs, CLs, and electricity infrastructure facilities.
- A user-friendly solution for mobile devices that uses augmented and virtual reality to display the results of the calculated corridors in relation to the current position coordinates of the mobile device.
- Feedback from stakeholders from practice, to what extent and under which conditions the advanced 3D DSS is able to support the planning process of power lines according to the SÜL.

2 Procedures and methodology

2.1 Workshop with project partners

In January 2019, a series of four workshops was conducted with the project partners. Three workshops were with the individual partners, whereas the fourth workshop organized by Swissgrid involved key stakeholders of the process for the SÜL. The goal was to get a common understanding of the ideas and requirements of the project partners, ewz[1], Swissgrid[2], and Elia[3], with regard to the advancements of the 3D DSS. Therefore, the needs concerning the visualization of information in the 3D DSS, as well as the approaches for calculating ECs, were discussed. Furthermore, the individual case study areas of the respective partners were defined.

In the preparation of the workshops, programs with guiding questions were set up (see Annex 10.1). Major topics discussed in the workshops were:

1. Case study and data sources
2. Data model and AR / VR
3. Decision model
4. MCDA method

The answers to the questions were documented and analyzed w.r.t. the requirements concerning the modeling and the visualization of information in the 3D DSS (see Annex 10.2).

2.2 Case Studies

The project partners defined three different case studies. For Swissgrid, the case of Innertkirchen–Mettlen, which was already used in the previous development of the 3D DSS, should be taken into consideration for further analyses. The focus in Innertkirchen–Mettlen lies on power line planning on the extra-high-voltage level (220–380 kV).

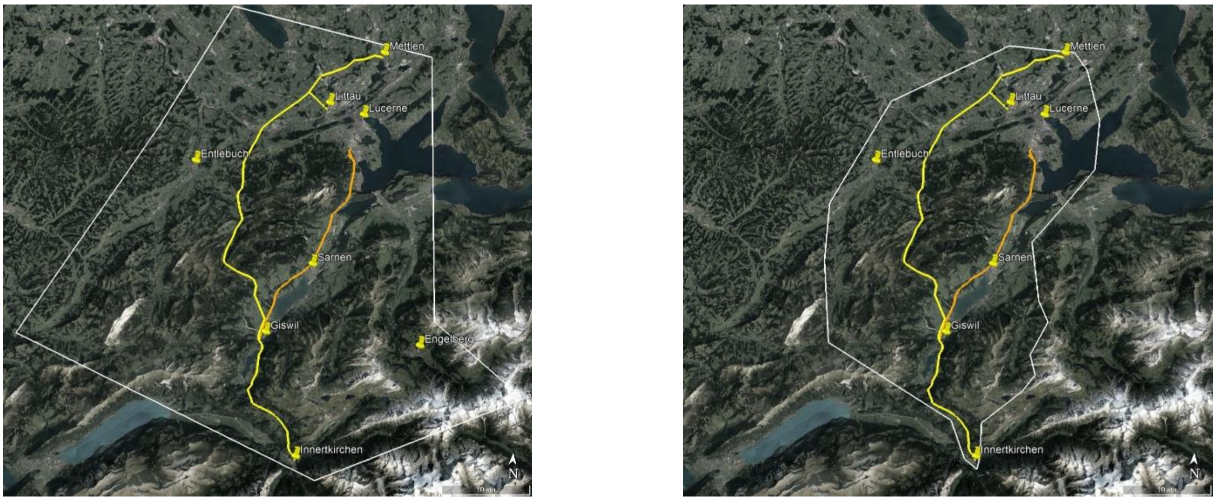


Figure 1: Extra-high voltage level: Study area «Innertkirchen–Mettlen» in central Switzerland, including existing extra-high voltage (yellow) and high voltage power lines (orange). Left map: old study area extent (2014–2018). Right map: new study area extent (since 2019).

[1] Distribution System Operator of the city of Zurich, Switzerland.
[2] Transmission System Operator of Switzerland.
[3] Transmission System Operator of Belgium.

Elia suggested a region in Flanders in Belgium as case study, where the high voltage level (150 kV) should be considered. On this level, the choice between the grid technologies is limited to ECs.

The distribution system operator ewz defined a study area in the western part of Zurich city between the substation Waldegg and the substations Altstetten Neu, Binz, and Sihlfeld. The case aims at connecting the newly built substation Waldegg with one of the other three substations by a high voltage EC (150 kV). The distance between the substations and the number of crossings with other lines and tubes is ought to be kept as low as possible. Feasible locations for laying an EC are limited to public places and streets. Moreover, existing, but unused pipe blocks should be preferred whenever possible. The study area comprises of the neighborhoods *Altstetten* and *Albisrieden* (district 9), *Hard*, *Langstrasse*, *Werd* (district 4), and *Sihlfeld*, *Alt-Wiedikon,* and *Friesenberg* (district 3).

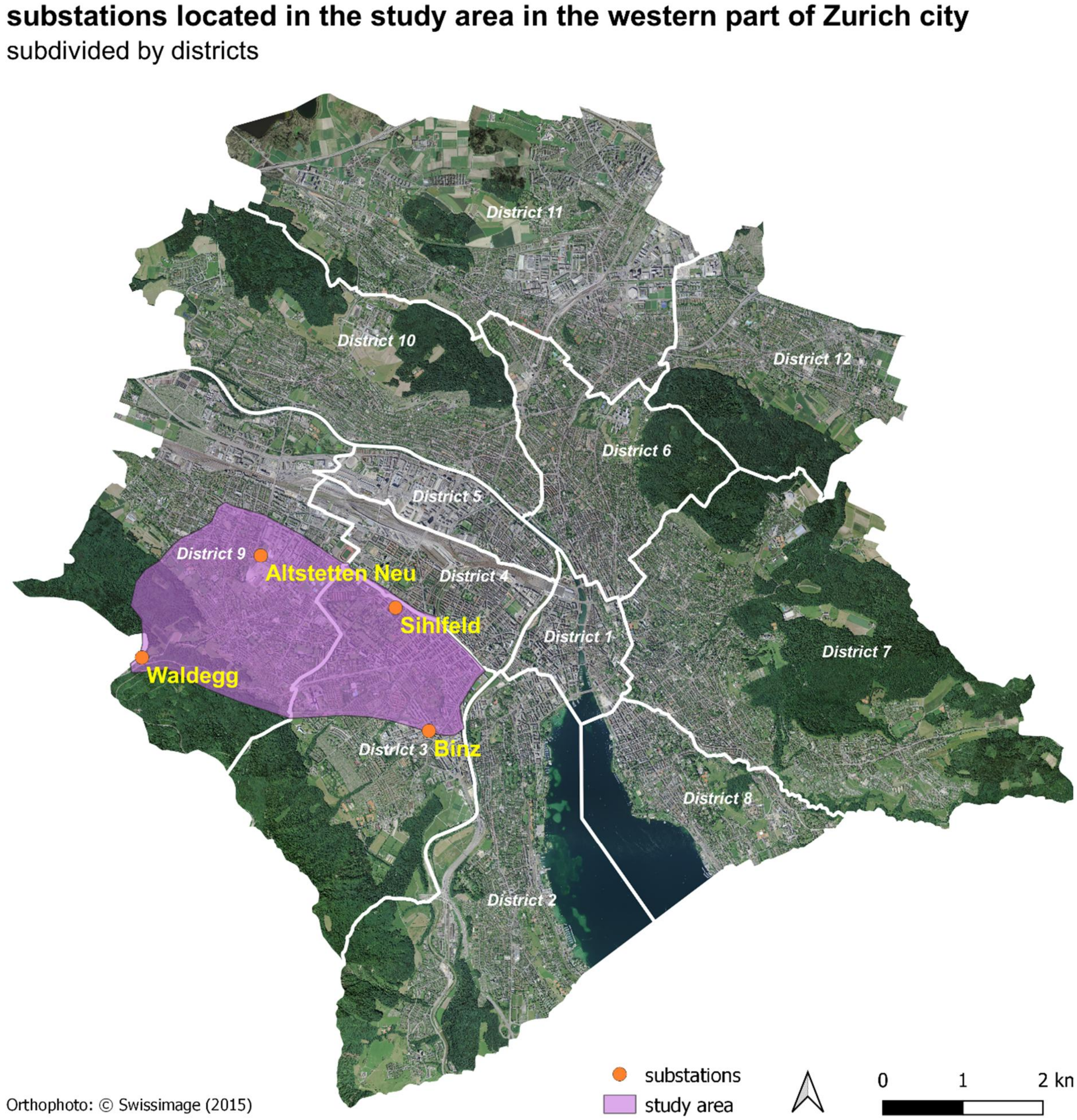


Figure 2: High-Voltage Level: Study area «Zurich City», Switzerland.

2.3 Theoretical background

2.3.1 Use of Multi-Criteria Decision Analysis for supporting rational decision-making

As a basic preliminary, we assume that decisions are made on a rational basis, and in turn, that rational decision-making might solve a decision problem adequately, although not optimally in every case. If multiple criteria have to be considered for making a decision, Multi-Criteria Decision Analysis (MCDA) is a way how decision-makers can be supported to organize and synthetize conflicting information “in a way which leads them to feel comfortable and confident about making a decision, minimizing the potential for post-decision regret” (Belton and Stewart 2002, 2). MCDA is a set of mathematical, strategical, and communicative techniques that are applied to structure and conduct a decision-making process. According to Belton and Stewart (2002), the typical MCDA process is structured as follows:

1. Identify the problem issue.
2. Structure the problem: Define the problem, values, objectives, constraints, stakeholders, alternatives, and uncertainties.
3. Build the decision model: Specify the alternatives, define the criteria, elicit the values.
4. Use the decision model to inform and challenge thinking: Synthesize information, create new alternatives, and conduct a sensitivity analysis to rank the alternatives.
5. Develop an action plan based on the obtained results.

2.3.2 The concept of costs

MCDA works either by determining a suitability score in favor of or by calculating costs against a specific alternative. In our case, we decided to work with the concept of costs, as it resembles human thinking regarding the question, how TLs are perceived, better than the suitability approach. Thus, we assume that the acceptance of TLs is generally low and that perceiving them often affects negative feelings, such as fear or discomfort due to health concerns or property value losses (Cain and Nelson 2013). As a consequence, we assume that citizens assess the worthiness of a location of being protected from building a TL differently, depending on, for example, the beauty of a landscape, nearby cultural assets, or the underlying laws that enforce this protection. In this regard, costs can be summed, which may yield higher costs if a location is protected by several ordinances at the same time compared to another location that belongs only to one protected area. Therefore, costs are defined as follows:

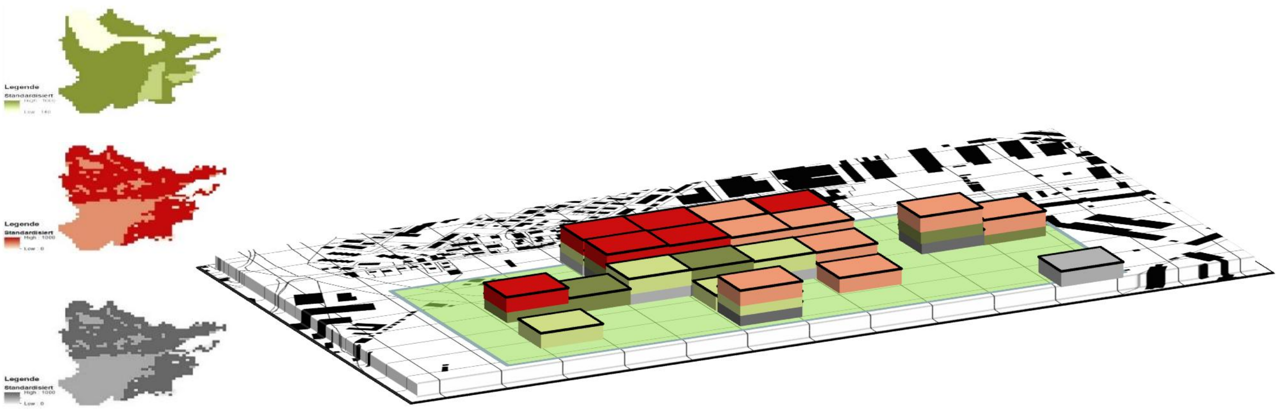


Figure 3: Concept of costs. Each layer (green, red, grey) is assigned specific costs. These costs are summed if the areas that correspond to these layers overlap each other.

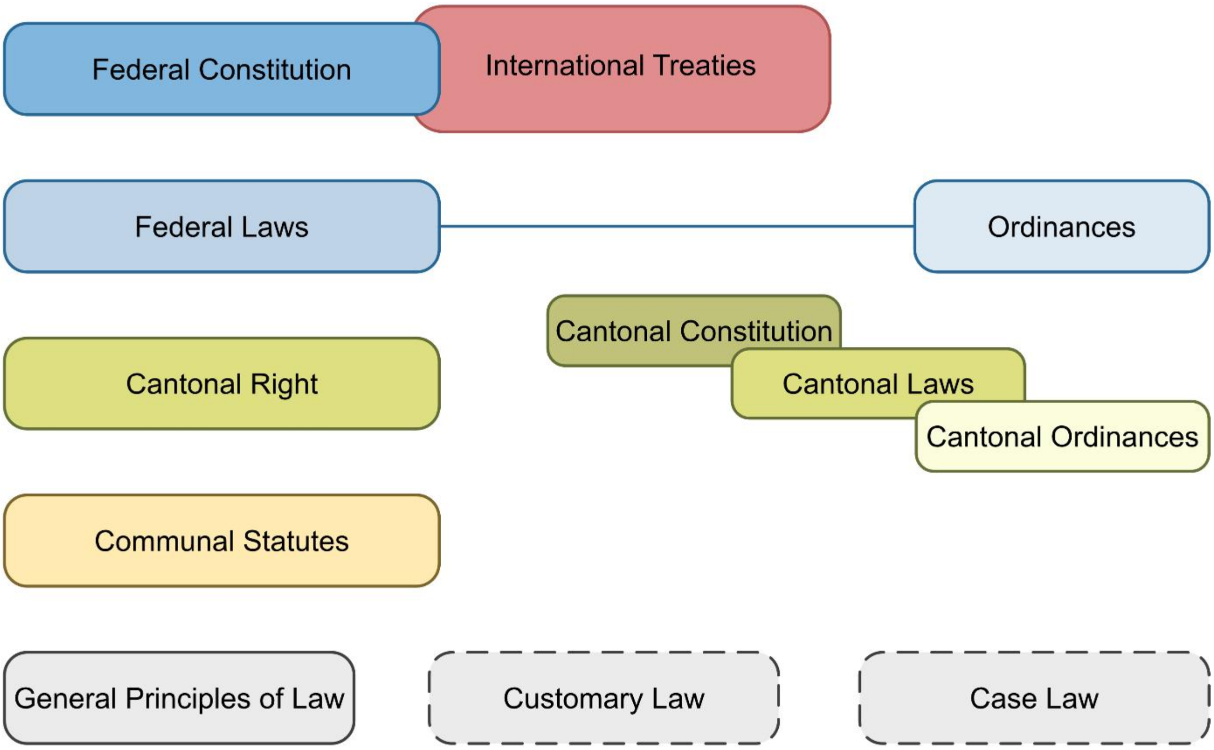


Figure 4: The hierarchy of laws in Switzerland according to Mosimann and Winsky (2012).

Costs are frictions in terms of virtual costs that must be overcome to cross an area. In case of OLs, costs represent frictions to span the according area while for ECs, they represent frictions that must be overcome to lay the cables into the ground. Costs are assigned to each layer, on the one hand, based on the importance of the underlying laws, which represent a higher importance the higher they are located in the hierarchy of laws (Figure 4). On the other hand, costs refer to the "Assessment Scheme for Transmission Lines" (SFOE 2013a) and the corresponding manual (SFOE 2013b), whereas both consider experts' knowledge regarding technical and practical issues.

2.3.3 Parameters that affect costs

Based on the concept of costs, we define four parameters that affect the calculation of the total costs:

- Resistances
- Criteria weights
- Category weights
- Objective weights

Let us further define that each layer represents one spatially-explicit[4] *criterion* with a spatial extent. The criteria that are considered in the *decision model* are organized in *categories* and are assigned to a specific *main objective* (see Table 3 and criteria specifications in section 10.5). The importance of these parameters can be adapted by specifying them numerically, as described in the following sections. We

[4] The term "spatially-explicit" means that a feature can be clearly located in space.

urge the reader to consider the **technical instruction of the 3D DSS** (Schito and Wissen Hayek 2020) or the **chapter that describes the working principles of the 3D DSS** (Schito 2020) for further information regarding the calculation of costs and of how all parameters interact with each other.

Resistances

Each criterion was assigned a resistance band based on the legislation and by considering expert knowledge. For example, mire biotopes were assigned the highest possible resistance, without any possibility to decrease it as they are protected by the Swiss Constitution. Resistances can be either positive or negative, whereas positive resistances repel TLs and negative resistances attire them. Resistances contribute to the calculation of costs on an objective basis.

Criteria weights

Criteria weights aim at enhancing the resistance on a subjective basis, leading to more negative weights if applied to negative resistances and to higher resistances when applied to positive resistances[5]. Thus, stakeholders can assign criteria a weight based on their interests and their beliefs. Thus, criteria weights contribute to the calculation of costs on a subjective basis.

Category weights

Since each criterion belongs to a specific category, a weight applied on all criteria of the corresponding category allows stakeholders to balance the importance of the categories against each other. Thus, category weights contribute to the calculation of costs on a subjective basis. However, although category weights would be possible to be applied, we deactivated this feature in the 3D DSS in order to emphasize another approach in which criteria are weighted based on objectives instead of categories.

Objective weights

The application of weights on objectives is the last parameter that affects the calculation of the total costs. An approach that allows stakeholders to weight objectives may be promising as we found out that experts preferred to discuss and negotiate about the fulfilment of objectives than weighting attributes, which is due to their more practical and less abstract nature. Therefore, each criterion is assigned to one of the seven main objectives shown in Figure 5 and contributes to the calculation of costs on a subjective basis.

The working mechanism of how objective weights work is simple: The higher the objective weight is set, the higher the costs for passing through a corresponding area become. Consequently, the path-finding algorithm tries to avoid areas that correspond to objectives with a high weight. The more these areas are avoided, the more the corresponding main objective is fulfilled.

In order to quantify the degree to which the main objectives have been fulfilled, an algorithm measures the distance over which the calculated optimal path crossed areas that correspond to a specific objective. This distance is then normalized with the total path length, which results in an *indicator* ranging from 0–100%. Therefore, an optimal solution regarding specific interests is a path that yields high indicator values for with regard to these objectives.

[5] This is done by applying specific weighting functions to the resistances. See Schito and Wissen (2020) and Schito (2020) for further information.

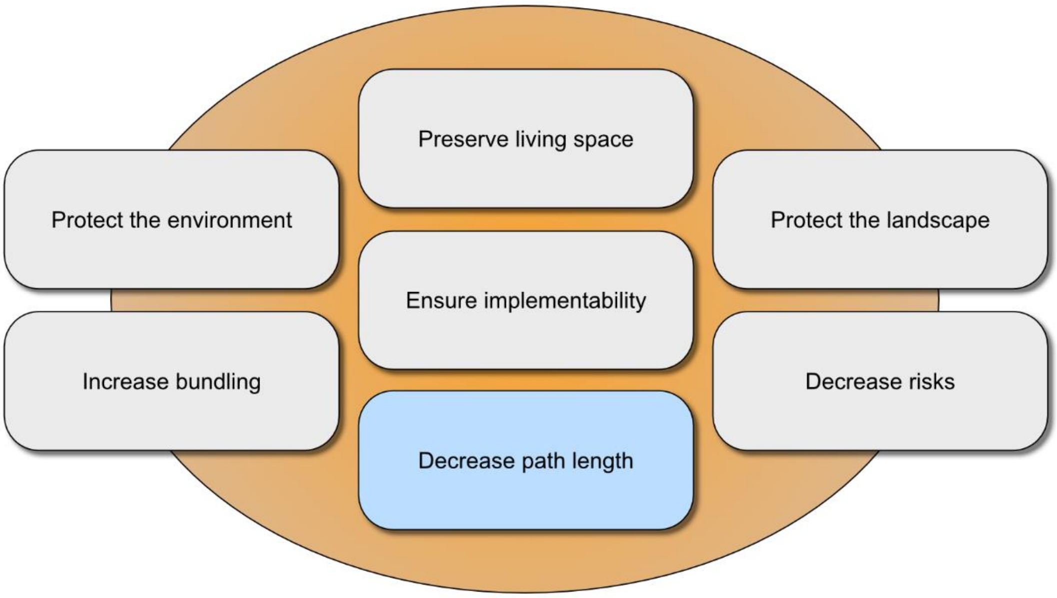


Figure 5: The seven main objectives. The blue objective has a dual function, as it might be that no spatial criterion exists that allows to determine its contribution to the total costs. The accomplishment of all objectives can be measured post-hoc by determining the corresponding indicators.

2.3.4 General modeling workflow

Within the scope of the 3D DSS project, we developed several algorithms that aim at narrowing down the area of interest step by step from the study area to the exact positions of the transmission towers (TTs) or access points (APs) (Figure 6). The workflow is split into an overhead and an underground branch as the planning requirements for OLs and ECs differ from each other.

Applying different planning rules depending on the transmission technology, however, causes a problem when trying to determine an optimal route for a CL that consists of both, overhead and underground sections. From a logical perspective, the number of possibilities of locating two transition buildings for *one* partial underground cabling section, is high[6] and becomes even more massive if *two or more* such sections should be determined. As first approach worldwide, we offer a solution that reduces the complexity of this problem by a hands-on approach that considers the planning procedure applied in the SÜL, which is represented as purple arrow in Figure 6.

The planning modalities for proposing a new TL according to the SÜL require that at least one transmission line corridor (TLC) is suggested that contains at least one feasible transmission line path (TLP). In order to balance different interests adequately, it is recommended to propose, based on the judgement 1C_398/2010 from 5 April 2011 (Swiss Federal Supreme Court 2011), also at least an alternative that includes a partial underground cabling section. Finally, the exact positions of the TTs and APs must be determined within the scope of the Planning Approval Procedure (PGV).

[6] In fact, it is the number of raster cells on the cost surface to the square minus the number of raster cells, thus, $(n-1) \cdot n = n^2 - n$.

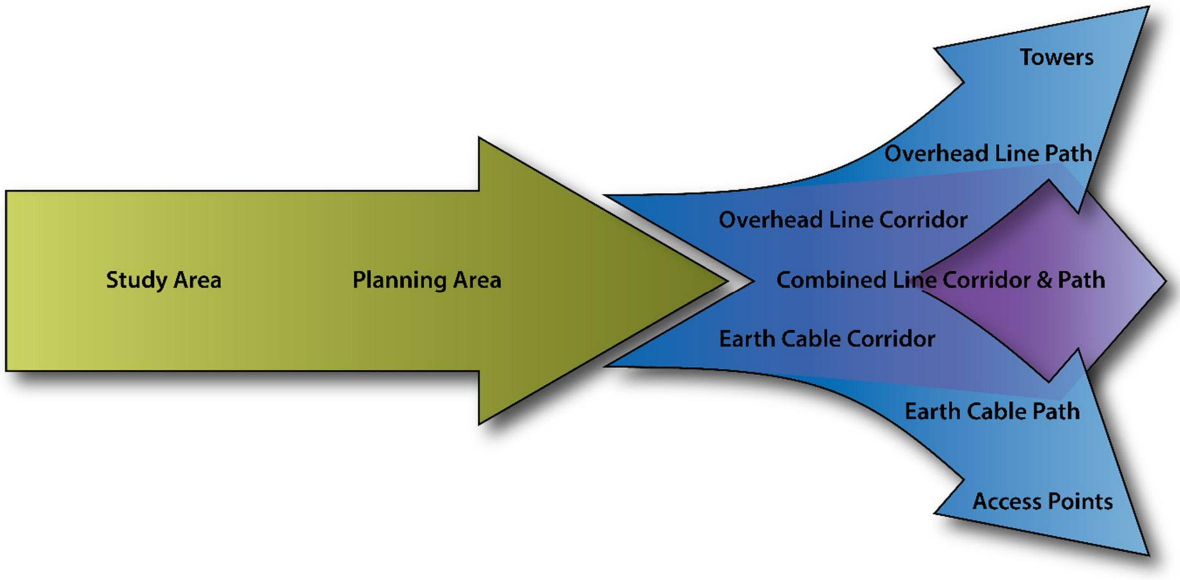


Figure 6: Workflow that narrows down the area of interest step by step.

2.4 Visualization requirements

The project partners' requirements provided the basis for developing the detailed concept of enhancing the user interface and the visualization functions of the 3D DSS. In the following sections, these requirements are first summarized. Then, in section 2.4.4, the overall concept is presented how the interface and the functions were adapted to meet these requirements.

The requirements of the project partners concerning the enhancement of the visualization functions of the 3D DSS concern different processes supported by this tool: (1) Selecting the modeling task; (2) Weighting of criteria; and (3) Analyzing the modeling results. In the following, the requirements regarding these three topics are presented.

2.4.1 Selecting the Modeling Task

Compared to the 3D DSS for the modeling of overhead lines, for the case of Innertkirchen–Mettlen, the extended 3D DSS should also model corridors for ECs and for the combination of OLs and ECs. Thereby, in case of the modeling of only one type of TLs, this should apply to the entire planning area (all OLs or all ECs). These alternatives are required for analysis by the advisory board group of the process for the SÜL. For the case studies in Belgium and the city of Zurich, only the calculation of ECs was defined as relevant.

2.4.2 Weighting of Criteria

In the context of supporting the planning on the extra-high-voltage level, potential users criticized the way of setting resistances and criteria weights in the existing 3D DSS. Discussing and assigning a resistance towards TLs and weights to each of the criteria turned out to take a long time and to be very tiring. Hence, the process should be improved in terms of its overall duration and the presentation of the selected settings in order to allow for comparison with alternative settings. A suggestion was to use clear objectives as basis for the weighting, and assign the criteria to the objectives. The weighting of the objectives should then, as described in section 2.3.3, be translated into the total costs. This procedure would also prevent settings from being made that do not comply with legal requirements.

2.4.3 Analyzing the Modeling Results

Extra-High-Voltage Level (220 – 380 kV; Case: Innertkirchen–Mettlen, CH)

The resistance map of the study area, the planning area, the corridor, and the approximated costs are the major modeling outputs to be presented in the 2D view. The costs should be displayed as implemented already in the 3D DSS. The value of the calculated approximated costs of the ECs and CLs («Indikative Baukosten») should be provided. Further, a color coded corridor providing information on segments of the corridor probably causing low, medium, or high costs for building the power line should be displayed.

In the existing 3D DSS, the corridor width was an issue as it is no line but a corridor with varying width. An idea was to take the mean value of a section of the planning area as width for the corridor. Further requirements were that an overlay of alternative corridors and paths should be enabled and that own solutions can be uploaded.

In the 3D view, a function for setting the terrain transparent should be implemented in order to view the ECs. The ECs should be visualized with single cables below ground. APs should be displayed as 3D boxes below ground. The TTs and TBs should be visualized with more detail and represent the respective type of these infrastructures generally used in the study area.

When calculated EC corridors cross forested areas, the area should be highlighted to show that the trees would be felled and only low growing vegetation would be allowed here in the future. These are so-called clearance zones («Freihaltezonen»).

Another suggestion was to provide further information layers, e.g., cantonal landscape concepts. Such concepts include polygons with designated landscape types on cantonal scale and further qualitative information on development goals of these landscapes types. This information would be valuable in the context of the discussion of alternative corridors by the advisory board of the SÜL process.

High-Voltage Level (150 kV; Case: Flanders and Wallonia, BE)

TL planners at Elia defined that the 3D DSS should be suitable to display several earth cable projects in the regions of Flanders and Wallonia. Therefore, they suggested that it should be rather simple. Generally, in these regions, the ECs are built in the roads and displaying the information on existing underground cables is valuable. However, the access to data of existing underground cables for the case study area is problematic, because this information is distributed and not always available in digital form.

Besides calculated alternative paths, the 3D DSS should provide further information in form of indicators such as length and percentage of public and private roads, private land, agricultural land, and forests crossed, of Natura 2000 area crossed, the amount of people affected, as well as the amount of communities located next to the path. A buffer of 50 m on both sides of the path would be a suitable area to calculate and display these indicators. This would be a heat map of the path's quality. Further relevant information is, for example, areas with risk of high-rise water. In such areas, no TBs can be built. In addition, the regional zoning plan (Gewestplan[7]; Plan de secteur en viguer[8]) is an important information

[7] http://www.geopunt.be; WMS: https://metadata.geopunt.be/zoekdienst/apps/tabsearch/?uuid=0e7f5e73-df16-43b2-9c82-03a4f429d84a
[8] http://geoportail.wallonie.be/walonmap; WMS: http://geoportail.wallonie.be/catalogue/7fe2f305-1302-4297-b67e-792f55acd834.html

layer because areas for community and public utilities (Gebieden voor gemeenschapsvoorzieningen en openbare nutsvoorzieningen) are suitable for building transition buildings. The latter should be presented as 3D model in the 3D DSS.

High-Voltage Level (150 kV; Case: City of Zurich, CH)

For the case study of the city of Zurich, potential users of the 3D DSS at ewz mentioned specific requirements for the information visualization. First, the grid of existing underground infrastructure (water, wastewater, gas, district heating, existing ECs) should be visualized below ground. Thereby, the EC with its diameter as well as the pipe block or trench should be visualized. For ECs a width of 1.25 m should be used to represent double pipe blocks («Doppelrohrblöcke»).

Furthermore, the buildings should be displayed in 3D and it should be possible to show their basic use. The latter information is helpful to see whether the buildings belong to *places with sensitive use* (Orte mit empfindlicher Nutzung, OMEN[9]), which are, e.g., apartments, schools, hospitals, hotels or permanent workplaces. This is relevant in the context of the Ordinance on protection against non-ionizing radiation (Verordnung über den Schutz vor nichtionisierender Strahlung, ONIR (Swiss Federal Council 1999)). To support the evaluation of possible EC paths, buffers according to the ONIR around buildings (10m, 5m, 3m) should be integrated into the 3D DSS.

For analyzing the quality of the resulting paths of the ECs and comparing the alternatives, different indicators were suggested. These were, e.g., the approximation of costs, the length of cable segments, the amount of segments, the amount of APs, the amount of curves (straightness of the path), the expected traction, the amount of parallel running infrastructure, as well as the amount of conflicts with defined buffers around buildings or the violation of OMEN.

2.4.4 Concept for enhancing the user interface and visualization functions

Concerning the visualization functions of the 3D DSS, the user requirements differ in some parts according to the voltage level of power line planning. However, the existing user interface is a feasible basis for implementing the new functions for all three case studies. In the user interface of the 3D DSS, the results of the modeling can be displayed generically. The visualization of the results is done in the viewer of the 3D DSS, in which the digital open source 3D globe Cesium[10] is integrated. According to the specific user requirements, certain functions had to be customized, which are briefly described in the following.

Case Studies

Whereas the cases of Innertkirchen–Mettlen and of Zurich city are both in Switzerland and use the same basic geodata such as the DEM and orthophotos, for the case of Flanders and Wallonia other basic geodata are required. For Switzerland, the basic geodata provided by Swisstopo are streamed directly from their server. As this data has a higher resolution as the open source basic geodata available for the Cesium globe, the areas outside Switzerland are not displayed. This means that the 3D DSS for the Belgian case needs to be stored in an individual network path providing access to the respective Belgian geodata. In the scope of this project, we focused on the Swiss case studies because essential data for meaningful visualization of the Belgian case study, e.g., existing underground lines, was not available during the project. However, with the results of the Swiss case studies we demonstrate how the functions of the 3D DSS can be adapted. These developments are generally applicable on the Belgium case, too.

[9] https://www.bafu.admin.ch/bafu/de/home/themen/elektrosmog/fachinformationen/massnahmen-elektrosmog/orte-mit-empfindlicher-nutzung--omen-.html
[10] https://cesium.com/cesiumjs/

Creating or Loading Scenarios

Compared to the 3D DSS for the modeling of OLs only, the extended 3D DSS additionally models corridors for ECs and for the combination of OLs and ECs. The user is able to choose, which of the alternatives are calculated. Further, the user is guided through the procedure of setting the resistances and weighting of the criteria to speed up this process and make it more transparent. As many resistance settings are not freely selectable due to legislation restrictions, a default setting is provided. However, in order to allow for extreme scenarios, e.g., for testing purposes, interactively changing these settings is still possible. The weighting is now assigned to objectives. For implementing these functions, a scenario wizard was developed. Additionally, this wizard offers the possibility to load previously calculated scenarios. When selecting scenarios from a list, indicators for an easy comparison of alternatives are provided, such as the degree of achievement of the objectives or estimated approximate costs («Indikative Baukosten»).

Visualizing the Modeling Results

In the existing interface, buttons for displaying resulting maps were directly assigned to the individual calculation steps that were performed one after the other. With the introduction of the scenario wizard, the results are now calculated in one step. Therefore, a field was added in the user interface to display the results of a respective scenario. This field provides buttons for the individual display of the cost map, the planning area, and the corridor. The width of the corridor is displayed with a varying width according to a new attribute «width» of the resulting data file, which provides the calculated mean width of a certain segment of the corridor. As in the existing 3D DSS, the corridor can be colored according to a further attribute called «costs», and for further analysis, the spatial maps of the individual criteria of the three categories «Landscape and Biotope Protection», «Population and Spatial Planning», and «Technical Feasibility» (Table 3) can be switched on and off.

When switching to the 3D mode, according to the respective scenario, a possible TL path is visualized with 3D models of TTs and cables above and below ground, as well as TBs and APs. For 3D visualization, a new button for changing the basic display functions («Darstellung») has been implemented. With this button, new functions for changing the basic layer (the Swisstopo orthophoto or the OpenStreetMap or both in transparent overlay), for setting the terrain transparent, and for creating sections through the 3D model are available. A further button comprises all functions concerning 3D buildings, such as displaying the 3D building models, displaying calculated NISV-buffers around the buildings, and showing the basic land use (ÖREB-Kataster – Grundnutzung). Another button concerns the 3D vegetation. With this, it is possible to display 3D vegetation models, and, in 3D mode of the 3D DSS, highlight the areas in the forest, where calculated ECs run through («Freihaltezonen»).

For the case of the city of Zurich, the existing underground cables can be displayed in the 3D DSS. To this end, a workflow for processing the available data has been developed in order to integrate them into the Cesium globe viewer. Further, visualization functions were developed for showing sections of the street in order to analyze the available space below ground for new pipe blocks.

The implementation was made by adapting the interface script, by graphical additions to the web-based graphical user interface (GUI), by programming new visualization functions, and by integrating further data layers and 3D models into the 3D viewer. The implementation of the enhancements of the interface is described in more detail in the results section.

2.5 Requirements for the augmented reality solution

For the visualization of TTs with Augmented reality (AR), we have used existing 3D models of TTs and cables provided by project partners and generated by exporting the 3D objects in the following formats: Collada, object and FBX. Additional requirements are mobile devices compatible with AR applications. Android and iOS of last generations are in principle compatible since the deployed technology allows the usage of such an app. List of compatible mobile devices can be found here:

- For Android devices: https://developers.google.com/ar/discover/supported-devices
- For Apple devices: https://developer.apple.com/library/archive/documentation/DeviceInformation/Reference/iOSDeviceCompatibility/DeviceCompatibilityMatrix/DeviceCompatibilityMatrix.html

ARkit and ARcore are the main existing frameworks for mobile devices respectively provided by Apple and Alphabet. The major differences between the two frameworks lie in the accessibility and the frequency of update and development. ARkit is more developed but is a closed framework, whose development, debugging and updates depend on Apple strategy. The community of developers is more active with such framework compared to ARcore. ARcore is an open framework which underwent a major review of the technology, some technical issues and apparently not part of the priorities of Alphabet.

As agreed on the project proposal, it was decided to develop the first prototype for iOS products. Additional requirements are a Digital Terrain Model (DTM) or a Digital Surface Model (DSM) to model the occlusion effect of terrain and objects on it such as vegetation and buildings. Such data must be converted into text files. As an additional option, data of 3D buildings provided by Swisstopo can be also used to model the size and volume of buildings in Switzerland.

2.6 Workshop with stakeholders from practice

In the final project workshop, the enhanced 3D DSS was presented to the project partners as well as further stakeholders from practice. The participants discussed the modeling approaches and visualization enhancements developed for the different grid levels. In a questionnaire, they were asked to rate the usability of the 3D DSS and the suitability of the 3D visualizations. Further, the participants focused on four questions to provide feedback on the enhanced 3D DSS concerning its suitability for implementation in practice:

- In which processes could the 3D DSS be used from a practical point of view?
- Where and why is there resistance to its use?
- What are the practical benefits of the 3D DSS?
- How could the 3D DSS be further developed to better meet practical requirements?

Further details on the workshop program and the questionnaire are provided in the Appendix 10.3. The results presented in section 4 provide an evaluation of the enhanced 3D DSS as basis for further development and implementation of the tool in planning practice.

3 Results regarding the enhanced 3D DSS

In this section, the advancements of the modeling algorithm as well as the enhancement of the 3D DSS user interface are presented. For the 3D DSS of the case studies “Innertkirchen–Mettlen” and “Zurich city” also a technical guide (Schito and Wissen Hayek 2020) is available, which explains the general functionalities of the online platform in more detail.

3.1 Advanced modeling components

3.1.1 Improved decision model

Criteria specified more distinctively

As stakeholders criticized in the former project that the decision model could have been improved in terms of declaring some criteria more precisely, we decided to specify some of them as separate ones. As a consequence, the number of criteria increases from 33 in 2017 to 62 in the current model (Table 3). Compared to the previous model, some biotope inventories, subject to a specific protection act, were split into biotopes of national or cantonal importance. As a consequence, compound criteria, such as ‘landscapes worthy of protection’ or ‘characteristic objects’ were redefined since some objects could be assigned inventories of cantonal importance. Furthermore, natural hazard zones were not regarded as aggregated areas any longer. Instead, they were split by the natural hazard type, which led to a distinction between areas under risk of avalanches, floodings, landslides, rockfalls, and, though not listed in each canton, of sink holes. Furthermore, stocked areas, which include vineyards and orchards, were separated from arable land. Finally, airports, military sites, and cableways were listed as separate entities.

In particular, the decision model was extended by underground entities or criteria that are located on the surface, but affect the construction of an EC. In this regard, the decision model was extended by inappropriate geologic underground, underground facilities, special railways, tunnels, and gravel pits. Another criteria that complements the decision model is those of ‘inappropriate aspect,’ which was proposed by Schoinas (2018) since zones with an aspect of 111.5° to 292.5° azimuth deviation from the North Pole can lead to higher power losses when transmitting electricity through an EC due to increased ground heating.

Valleyness – a criterion for straightening the TLP based on the relief

The valleyness states, as a quantifiable unit, to what extent a location can be characterized as a valley (Straumann 2010). Since valleys are geomorphological units of great importance for planning a path along a given geodeterministic structure, we included three valleyness parametrizations, which were investigated by Monchecchi (2020), that resemble the valleyness of the terrain in different granularities. These depend, in turn, on the defined size of the catchment area, on the model for calculating the valleyness, and on a critical slope angle (Moncecchi 2020).

The results of Moncecchi’s study (2020) revealed that TL planning experts assessed OLs which were computed by considering a moderate weight for the valleyness more realistic than by neglecting the valleyness. Obviously, punishing the crossing of mountain ridges due to this criterion enhances the quality of TL modeling. For this reason, we considered three different granularities (Figure 7), leaving it up to the stakeholders to what extent greater or finer geomorphological structures should be followed by a potential new TL.

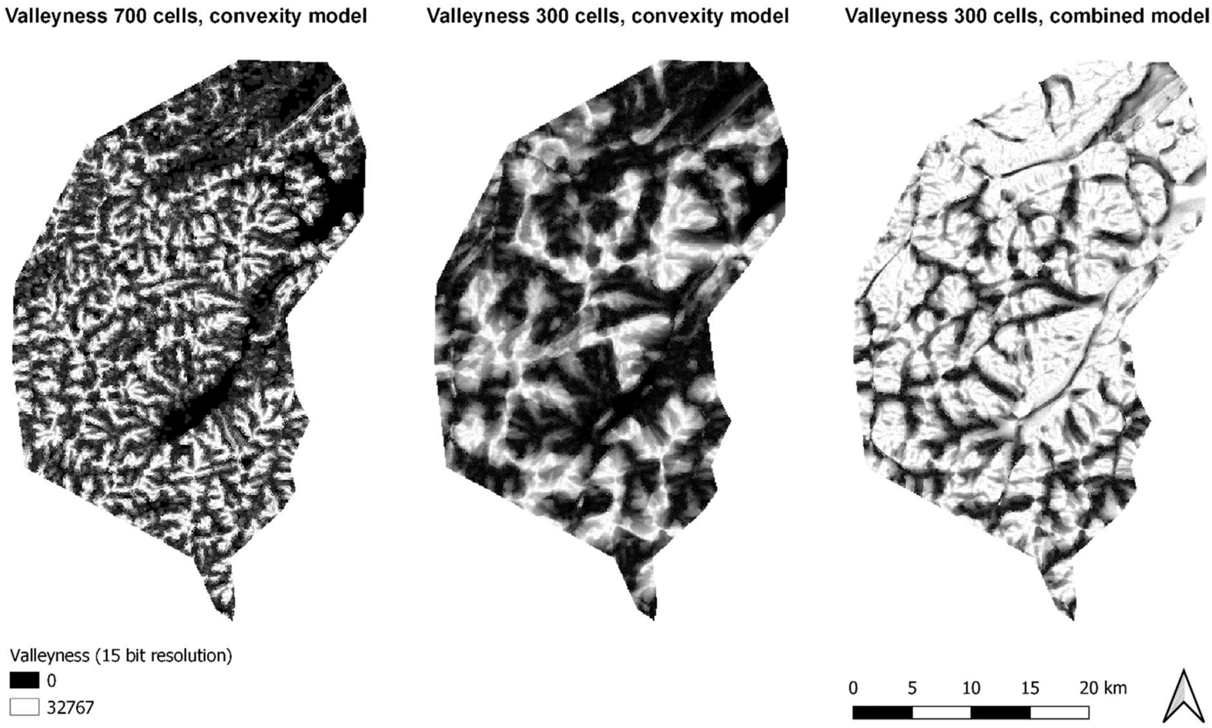


Figure 7: Used valleyness models. 0 = valley floor; 32767 (16 bit) = maximum cost for crossing a ridge. Each model used a critical slope of 1.5°.

3.1.2 Novel modeling approaches for TLs

Since the case studies differ among each other regarding the used transmission technology, the legislation, and the voltage level, we must adapt the modeling approaches to these requirements while trying to generalize the workflow so that it could be applied also to other study areas. Therefore, the 3D DSS must be regarded as a set of algorithms that can be applied to solve a specific problem given the planning circumstances and according to the workflow shown in Figure 6.

Figure 8 shows the main characteristics of the developed approaches. Approach Z is the resulting method that emerged from the previous 3D-GIS project. Approach A is an improved version of Approach Z that is adapted to ECs. Approach B makes use of Approach Z and Approach A while considering the planning rules applied in the SÜL. On the right half, Approaches C, D, and E use network optimization for determining the optimal alternative. Approaches C and E use the same geometric rules for building the network graph while differ in the purposes for what they are used: Approach C is used to identify Pareto optimal path alternatives by using the same scenario (Schito, Moncecchi, and Raubal 2021) while Approach E identifies the optimal locations for TTs by considering the topography (Piveteau 2017). The following sections describe the approaches in more detail.

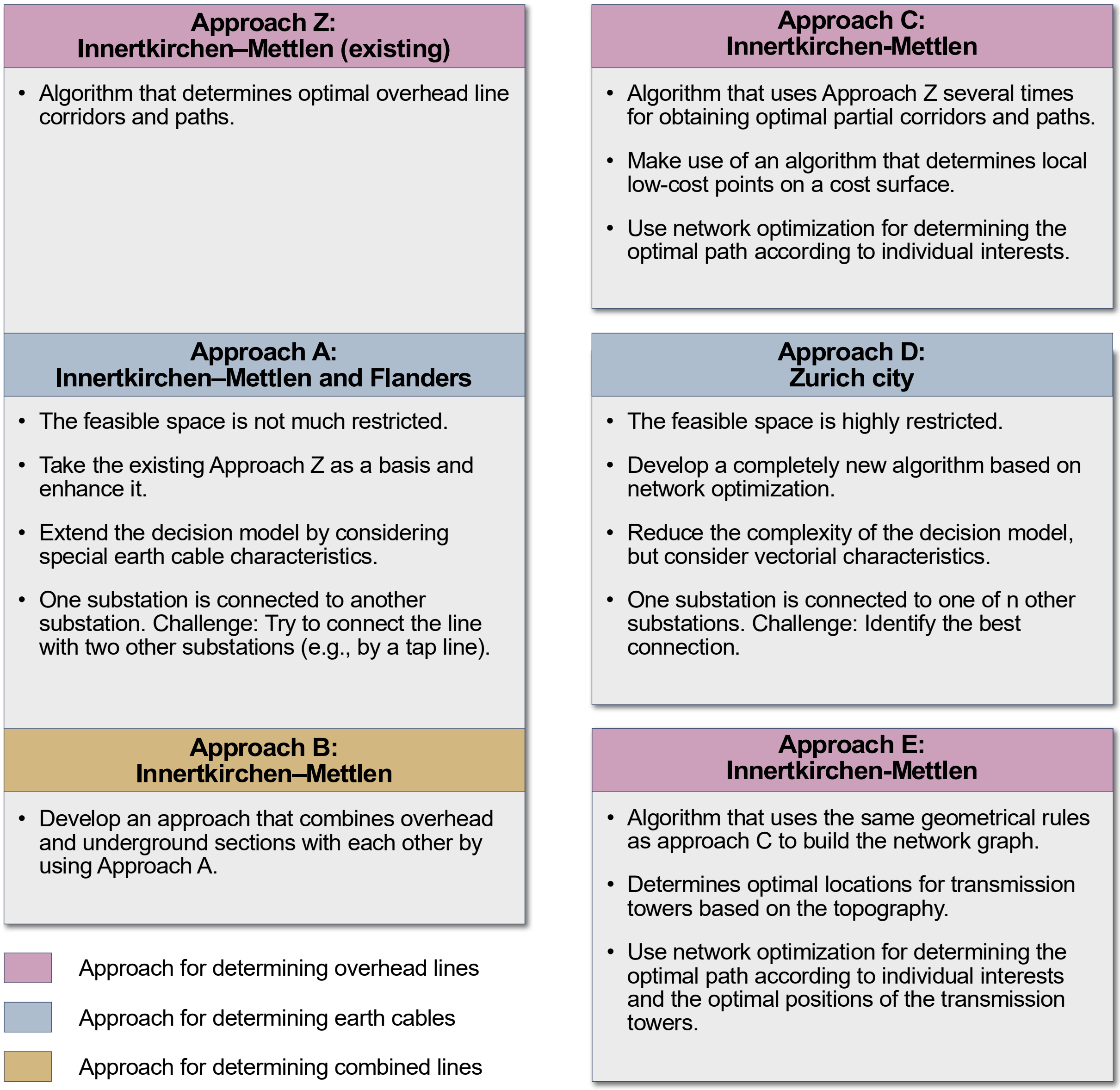


Figure 8: Main characteristics of the novel developed approaches.

Approach Z: existing approach for modeling OLs

Approach Z is the basic approach that was developed within the scope of the former 3D-GIS project (Raubal et al. 2017). It aims at identifying optimal OL corridors and paths by considering the costs of various influential factors, as described in the sections 2.3.2 and 2.3.3. Hereby, the partial costs of all influential factors are summed, for each discretized location and over all layers, to a *total cost surface*, which is represented as a raster with a cell width of 100 x 100 m. In other words, the total cost surface is calculated by a *Weighted Linear Combination* of all influential factors of the decision model. This total cost surface forms the basis for obtaining an optimal OL by means of this approach. Again, **the higher the costs, the less suitable the corresponding area is to build a TL on its surface**.

The following step considers this relation as the optimal path corresponds to the path with least *accumulated costs* from the start to the end point, which is called *Least Cost Path* (LCP). The concept of accumulated costs is important to understand as the costs for passing through a specific area increase with the costs for each cell that must be crossed. Thus, an algorithm seeks the path with least accumulated costs from the start to the end point, which can be compared to a stream that follows the steepest slope when flowing down a relief. Analogously, approach Z uses the same principle whereas it conducts Dijkstra's algorithm (1959) for doing so.

The MCDA method applied by using Approach Z is, as mentioned above, a *Weighted Linear Combination*, which is also called *Simple Additive Weighting* (Churchman, Ackoff, and Smith 1954). This means that the MCDA is carried out by assigning each criterion a weight (as explained in section 2.3.3), which is summed to a total cost surface. As, at this point, the resulting cost surface contains a LCP as an optimal solution (provided that the start and the end point are known), the cost surface can be regarded as the outcome of a set of preferences (= weights), which is also called an *alternative*. Applying Dijkstra's algorithm on that cost surface for identifying the LCC and LCP is only an additional step that yields a better comprehensible map in order to support decision-making across several alternatives.

Approach A: adapted for modeling ECs

Approach A uses the same principle as Approach Z with the difference that special decision rules have been applied for determining ECs. Approach Z and Approach A differ mainly regarding the rules that have been defined for each criterion. For instance, spanning a lake might be forbidden whereas laying a cable through it might be allowed. Since Approach A can be regarded as an improved version of Approach Z, it differs regarding the following parameters from the latter:

- Approach A uses a more precise method for calculating the continuous boundary model.
- Approach A is more versatile as it can model OLs as well as ECs by considering special planning rules, straightening methods and different searching patterns for determining the cost surface.
- Approach A is more versatile regarding data handling as the automation of data pre-processing has been improved, which allows stakeholders to run a model with any parametrization without it being necessarily pre-processed.
- Approach A uses a more complex decision model and focuses on objectives.
- Approach A can be forced to pass through specific points.

Approach B: determines optimal CLs according to the SÜL

Approach B is one of the major achievements of this research as it was determined reliable for modeling CLs according to the SÜL (Schito 2020; Schito and Wissen Hayek 2020). The underlying algorithm carries out the following steps:

1. Assume to build a continuous OL between the start and the end point. On this basis, use Approach A for calculating a continuous OL.
2. Intersect the obtained path with critical areas that have been defined in advance, such as settlements, residential areas, or nature reserves. For each intersected line section, determine the center point.
3. Calculate the Average Nearest Neighbor (Clark and Evans 1954) for each point and use it as independent variable when calculating the Getis-Ord Gi* (Getis and Ord 1992) index for each point. Then, put all continuous points with positive z-scores in separate lists. Then, order these lists by

the sum of the z-scores for the corresponding connected points. While beginning with the list with the largest sum of z-scores, select as many point lists as partial ECs should be laid underground.

4. From the start to the end point of these clusters, buffer the OL sections generously and eliminate all critical areas. If no corridor for a continuous line can be determined within these areas, increase the buffer width.
5. Within the obtained areas, determine all partial areas that are large enough for building a transmission building (TB).
6. From the set of all possible TB locations, select those that are located next to the border points of each cluster. These points are considered to be TBs.
7. Model an EC between both TBs for each obtained area in which a partial underground cabling should be realized.
8. For all sections that do not belong to a critical cluster, connect the TBs with each other or with the start or the end point.

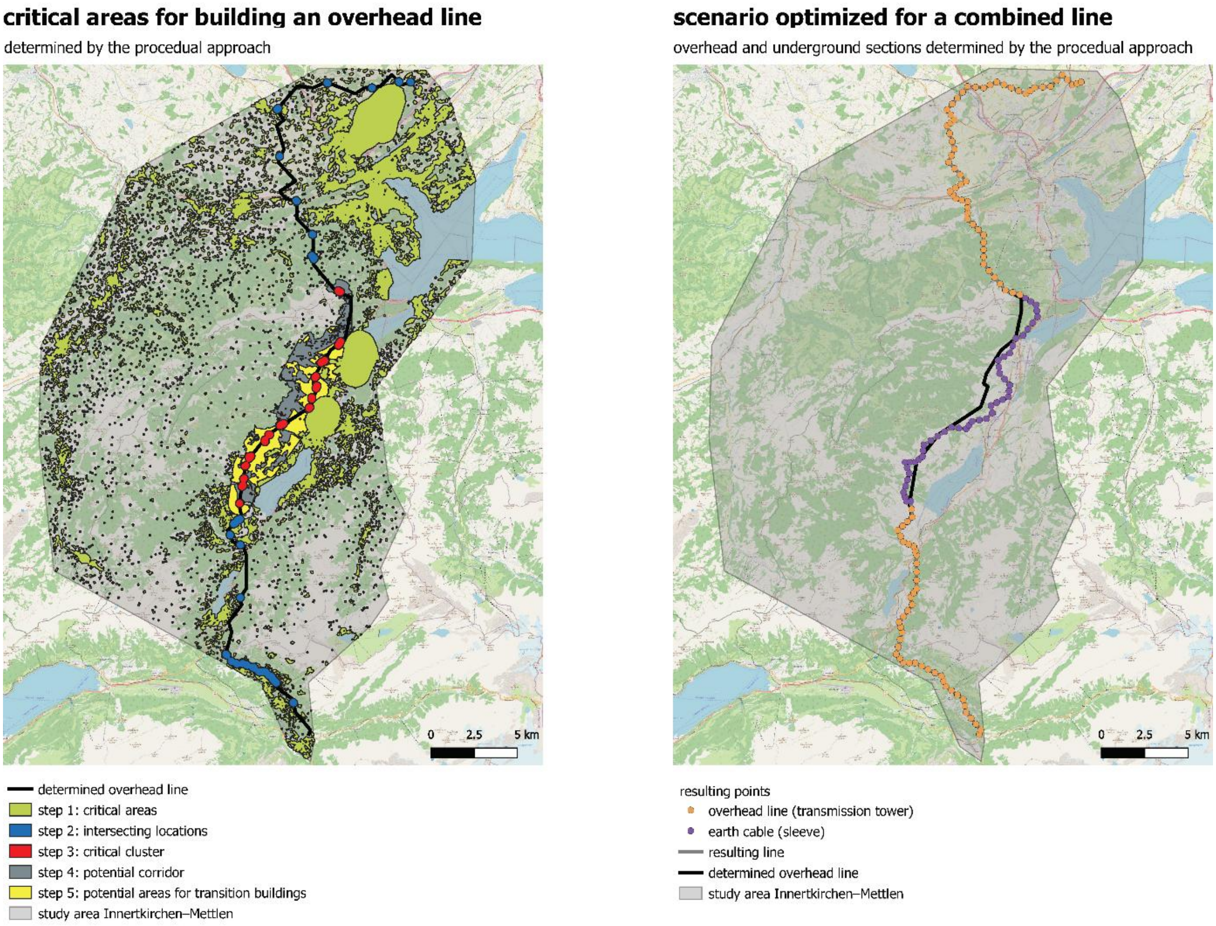


Figure 9: By-products (left panel) and final map (right panel) when carrying out the procedural approach. The black line represents the modeled OL in case only this transmission technology would be considered for construction. The procedural approach identifies the area with many scattered settlements in the mid-section as the most critical cluster in which an EC would come into question.

Approach B is synonymously called the *procedural approach* as it follows a specific procedure according to the SÜL for determining optimal locations for a partial underground cabling. It shows a high flexibility as it can determine a varying number of critical clusters whereas it allows to adapt the decision rules for selecting appropriate TBs. A further advantage is that the critical clusters are ranked based on the impact an OL would have. The evaluation of a study (Schito 2020) showed that Approach B was able to successfully determine the scattered settlements in the mid-section of the study area as critical areas. Furthermore, pre-studies with two partial underground cabling sections revealed that the areas around the substations in Innertkirchen and Mettlen were determined to be critical as well, mainly due to limited available space for a new TL.

Approach C: determines Pareto optimal alternatives based on LCP analysis

Approach C aims at identifying Pareto optimal path alternatives based on the same cost surface, meaning by considering the same scenario. In order to do so, one must derive several low-cost paths based on the same cost surface, however, by considering different objectives.

The approach starts by identifying local low-cost points, which is carried out by Straumann's algorithm (2010) for determining valleys. The mid-points of each valley basin represent local low-cost points, which are meshed to a network graph by applying the geometric decision rules shown in Figure 10 and described by Schito et al. (2021). Approach A serves as basic method for determining the partial LCPs for each edge on the graph, including its indicators. When determining all possible full path alternatives by combining all edges within a defined cutoff distance with each other, these indicators are summed up proportionally to their partial length, which leads to a set of full path alternatives that describe, to what extent they fulfill the given objectives.

On these basis, dominated alternatives can be excluded from the solution space. What remains is a set of Pareto optimal alternatives that can be used for determining the optimal alternative based on the preferences of a stakeholder by applying an objective function.

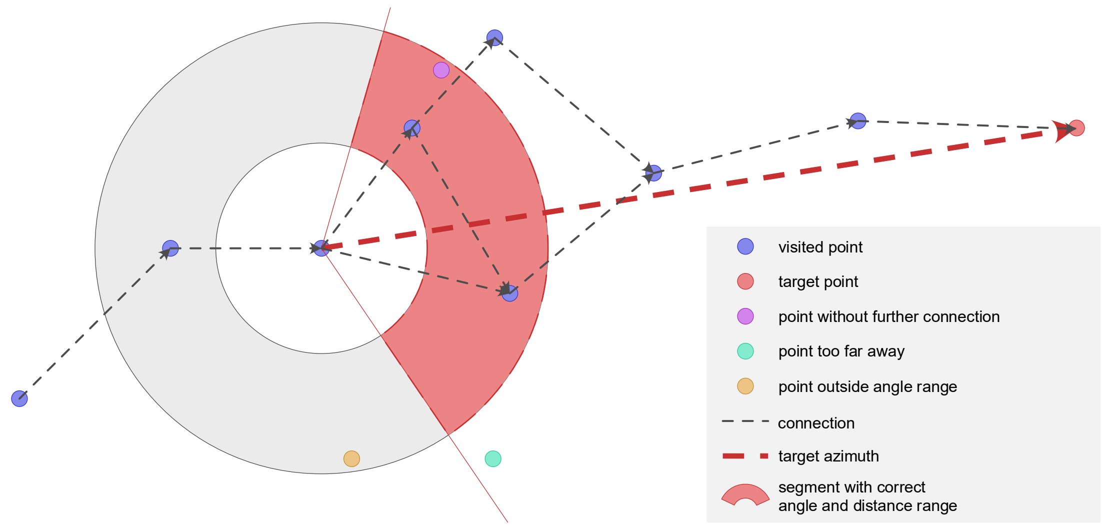


Figure 10: Geometric decision rules for building the network graph.

Approach D: determines Pareto optimal alternatives based on a vector approach

Approach D was built to determine optimal EC paths on a network of possible routes, which in our case was applied on a street network[11] (Figure 11 left panel). Furthermore, Approach D allows decision-makers to find the optimal alternative given a set of different targets. Analogous to Approach A, stakeholders can define their interests by setting the weights as described in section 2.3.3. The approach builds then a network graph by combining all edges between the start and the end points with one another, whereas the number of edges lies below a defined cutoff distance. As a result, the obtained network graph may contain several TLP alternatives between a start and one or more end points (Figure 11 right panel), including an indicator for each objective that represents the extent to which the corresponding objective has been fulfilled.

On this basis, an objective function that represents the stakeholders' interests best is applied to the set of alternatives (Figure 11 right panel), aiming at identifying the optimal EC path alternative with regard to individual interests. Apart from this linear programming approach, Approach D further allows analysts to use the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon 1981), which is method often used when solving an MCDA problem.

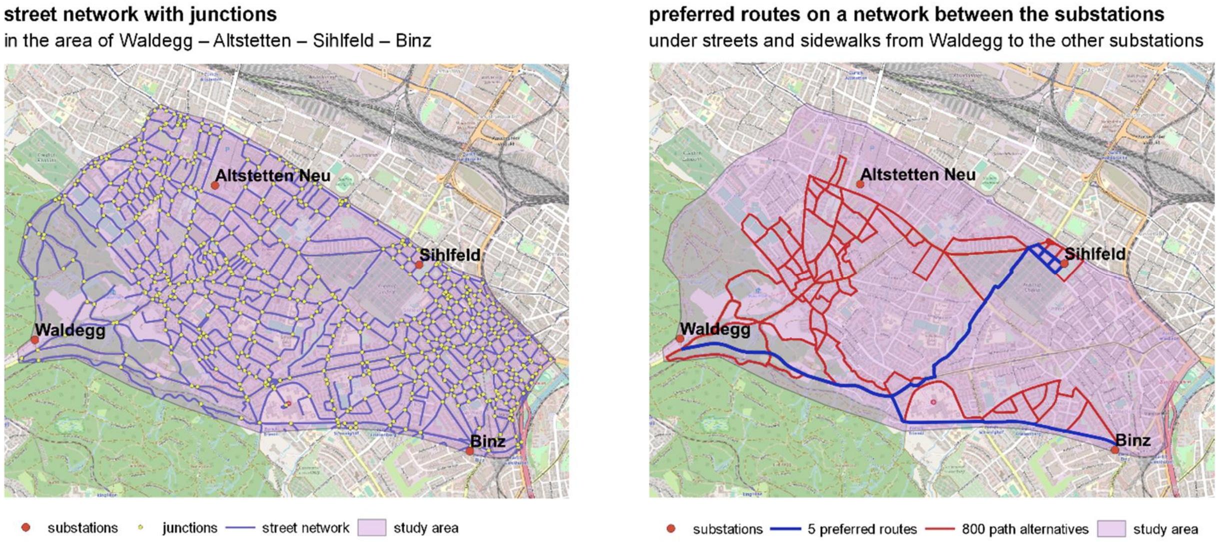


Figure 11: Left panel: All streets that connect two junctions with each other were assembled to a network graph, leading to a street network in the study area "Zurich city." Right panel: Network graph of 800 connections between the substation "Waldegg" with the three other substations, including five preferred alternatives with highest achievement of the objectives (based on a random scenario). The figure shows that several routes can connect the substations with each other, as, for instance, the substation "Sihlfeld" can be reached from the west or from the southwest.

Approach E: determines optimal locations for TTs

Approach E aims at determining the optimal locations for TTs which comply with the ONIR in terms of keeping the minimum distance between the cable and the ground. In particular, it calculates the sag at every point of the OL and compares it to the elevation provided by a Digital Elevation Model (DEM). Analogous to Approach C, it uses similar geometrical rules for determining, for each cell, a set of potential cells that the current cell could be connected to. For each connection, an algorithm checks, whether

[11] See 'street meshing' (Schito 2020, 91) for further information.

or not the sag complies with the minimum required distance according to the ONIR. Thus, valid connections are maintained whereas invalid connections are disregarded. A network graph between the start and the end point is then built based on the set of all valid connections (Rheinert 1999; Piveteau 2017).

Pivetau (2017) found out that Approach D calculates more realistic TT positions than Approach Z. Experts acknowledged its capability of limiting the alternatives that come into question for constructing an OL only to those that comply with the minimum distance between the cables and the ground according to the ONIR. Despite its reliability of modeling TT positions accurately, one shortcoming of Approach D is that it requires a high computational effort, which makes it a good tool to be used in a late stage during the SÜL or in an early stage during the subsequent PGV. For this reason, we improved the computational efficiency of the original code, which was originally developed in the scope of a Master's thesis (Piveteau 2017), and integrated Approach D into the 3D DSS script collection.

3.2 Enhancement of the 3D DSS user interface

3.2.1 Extra-high-voltage level: Case «Innertkirchen–Mettlen»

Scenario wizard

A workflow wizard was developed to facilitate the setup of a scenario. The wizard provides a logical, user-friendly interface for creating and calculating a new scenario and for loading existing scenarios. The wizard is started in the web interface and guides the user through the necessary steps. The steps are presented below.

Selection: Load scenario or create new scenario.

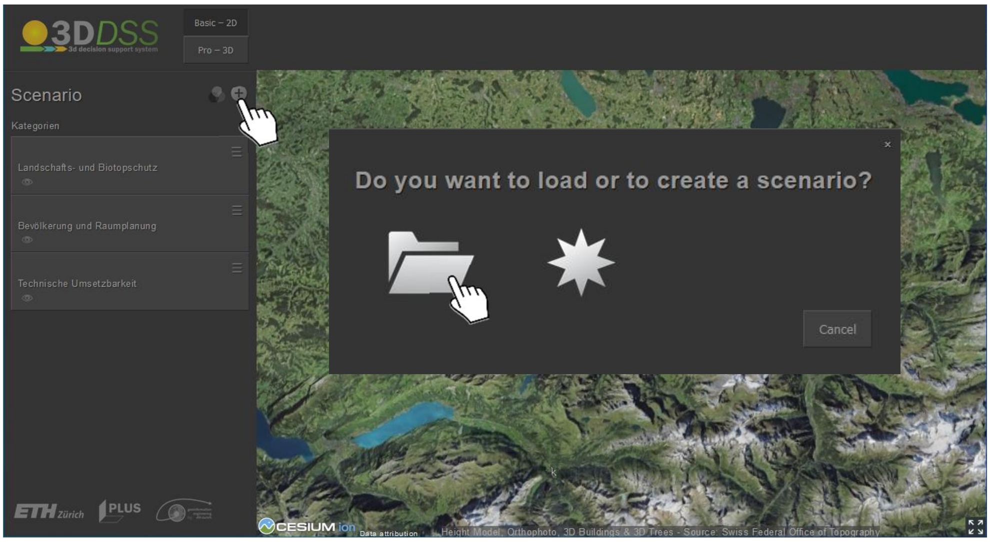


Figure 12: The first dialog box after starting the wizard: Select whether to load an existing scenario ("Folder" icon, left) or create a new scenario ("Star" icon, right).

Load an existing scenario

If a scenario is to be loaded, a list of existing scenarios appears. Each scenario is represented by a spider web diagram, which reflects the achievements obtained when running the respective scenario. These characteristics show in a clear form which objectives the scenarios are based on.

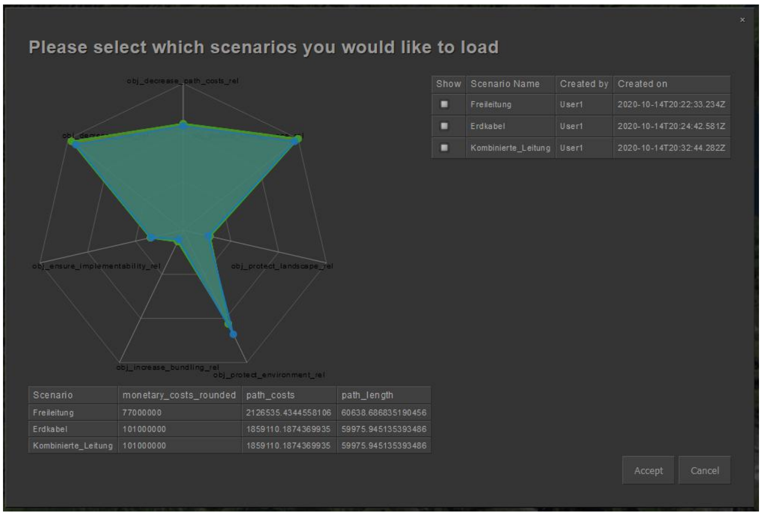


Figure 13: Loading existing scenarios.

Create a new scenario

First step: «Enter the name for your new scenario»

A name for the new scenario and the name of the author is entered in the fields provided. Further, the TL type to calculate – all OLs, all ECs, CLs, or a special algorithm to calculate the kernel density with variable sensitivity – is selected.

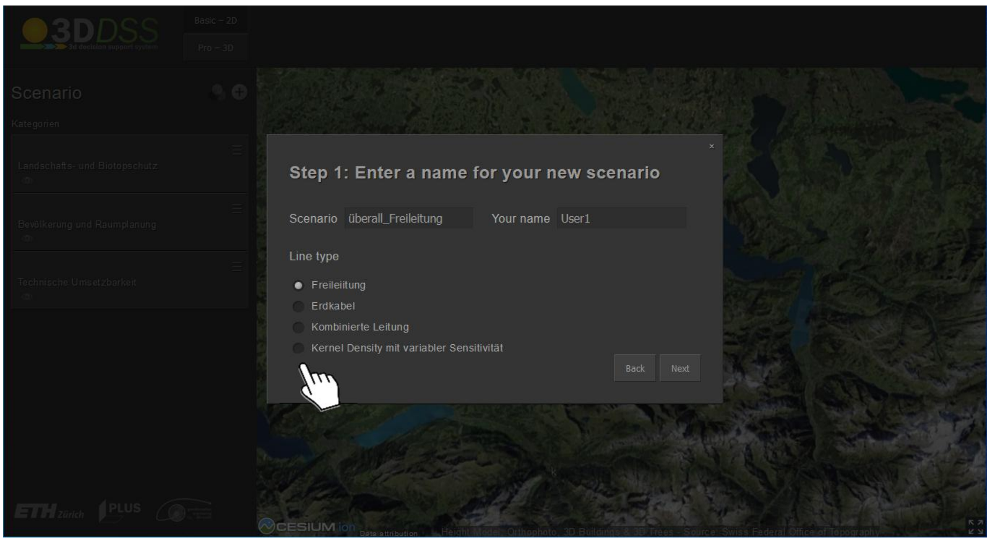


Figure 14: For a new scenario the name of the scenario is defined, the author is specified, and the line type is chosen.

Second step: «Do you agree with the settings of the resistors and buffer distances?»

This step is used to check the resistance settings with regard to the construction of TLs assigned to the criteria. Default values are set, which are based on expert experience or legal requirements. Additionally, the distances for the buffers that are placed around the polygons of criteria layers can be adjusted. This is one way to reduce or increase the protection of areas of a certain criterion. The resistance values and buffer distances should normally not be changed, even though this was possible (Figure 15). It needs to be scrolled down to the end of the list, where the button is provided to proceed to the next step.

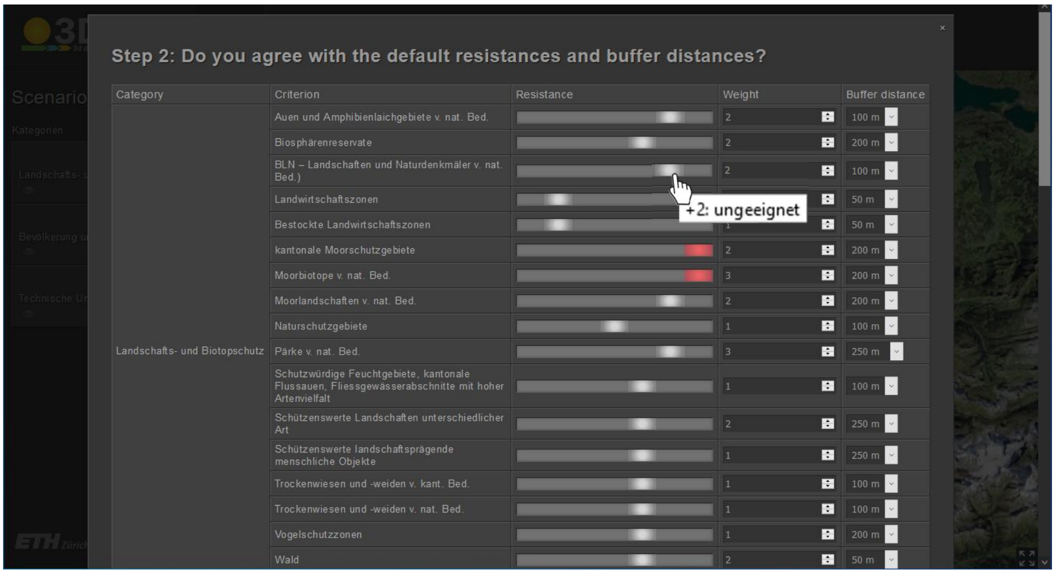


Figure 15: Check resistances and buffer distances for defined criteria. For getting an impression, which areas are affected by the criteria, respective criteria layers can be switched on in the 3D DSS viewer for spatial visualization of the corresponding areas (Figure 16). The color of the layers can be adjusted by clicking with the cursor in the grey area below the colored line in the navigation bar and choose the color from the appearing color palette.

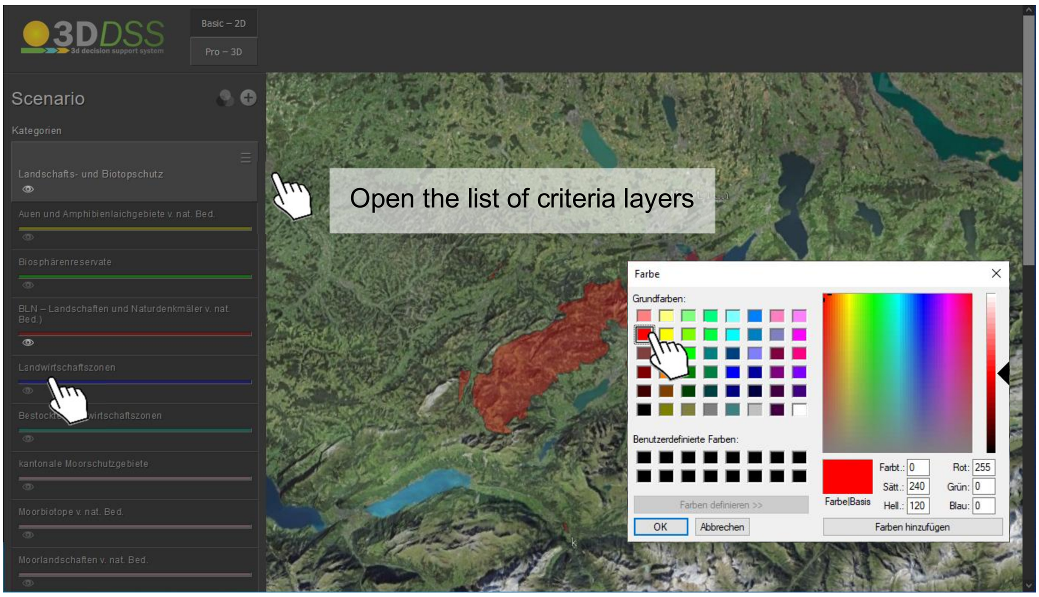


Figure 16: Display of criteria layers. In the example image, the areas of «Landscapes and natural monuments of national importance» (BLN) from the category «Landscape and biotope protection» are displayed, as can be seen from the white highlighted eye symbol in the navigation bar on the left side. The function for assigning a new color is activated.

Third step: «What criteria do you want to include?»

By not selecting all the criteria in a category, the remaining criteria get a higher weighting and thus, a higher influence on the result. As default setting, all criteria are selected and this should normally not be changed. However, the option for selecting criteria is regarded as useful for an expert mode. It needs to be scrolled down to the end of the list to view the button for proceeding to the next step.

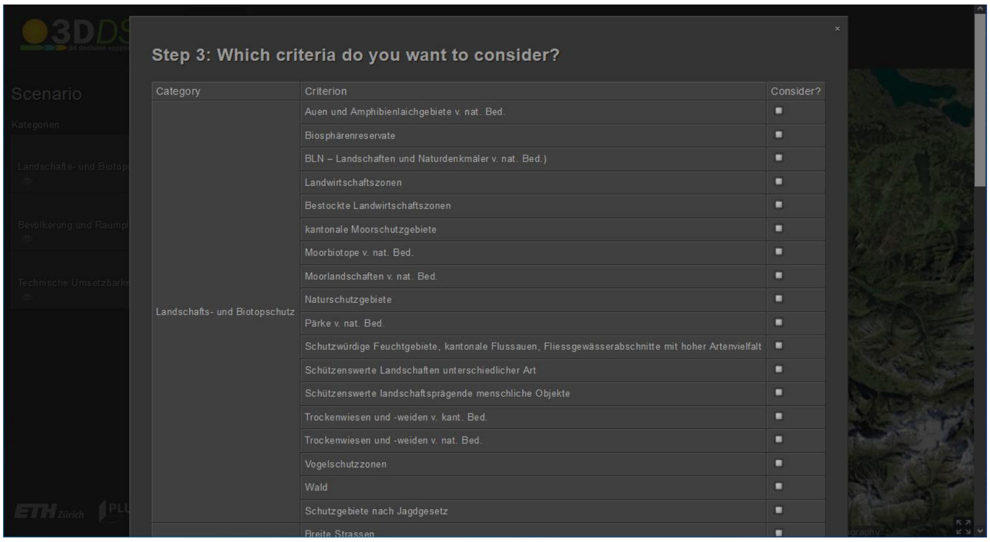


Figure 17: Customizable selection of individual criteria of the three categories.

Fourth step: «Define the weight for each objective»

Weighting the objectives is the first active step for general users. The criteria with the settings from the second or third step are assigned to the objectives. The user sets the weights according to the importance of the individual objectives.

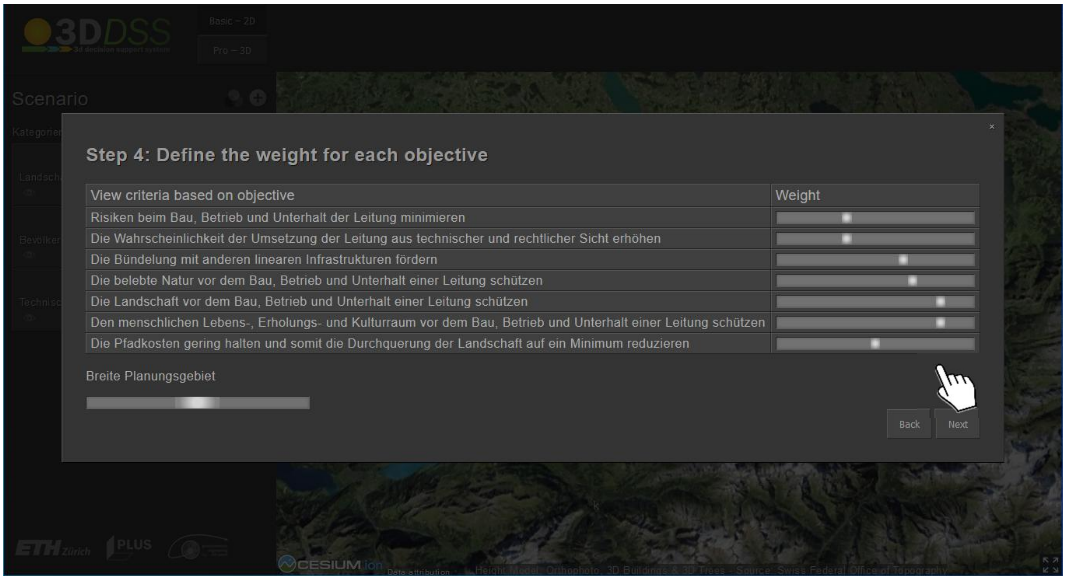


Figure 18: The weighting of objectives determines how important the criteria assigned to the individual objectives are.

Fifth step: «Which scenarios should be selected for further analysis?»

In the fifth step, the option is prepared to include further scenarios in the modeling in order to calculate an optimized scenario. However, this function is not yet available as the developed approach was not as good as the procedural approach already implemented (see modeling approaches in section 3.1.2).

As soon as the «Finish» button is clicked, the results for the new scenario are calculated and automatically saved.

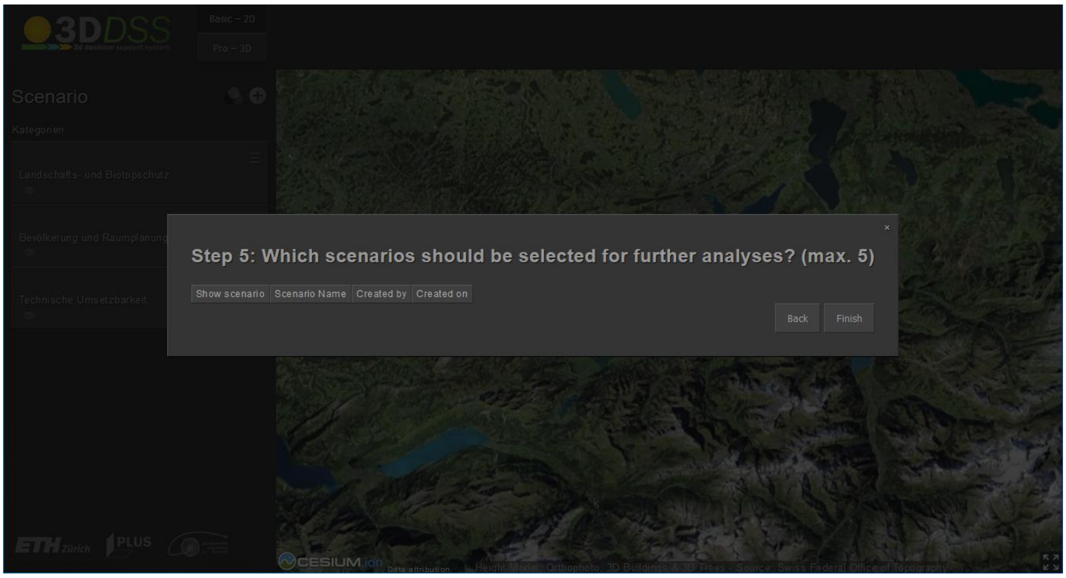


Figure 19: Start the calculation of the new scenario with the «Finish» button.

3.2.2 Visualization of modeling results for the extra-high-voltage level

For the implementation of the new functions in the 3D DSS, the version of the Cesium globe was updated to CesiumJS 1.70[12]. The programming of the functions was done in JavaScript.

Swiss terrain and orthophotos

The terrain and the orthophotos of Switzerland are retrieved directly from a server of Swisstopo (Micheletti, Gasser, and Terral 2018). Swisstopo has processed their data into the format «3D Tiles» and provide a web access to this data: https://www.Swisstopo.ch/webaccess. The Swisstopo web access-inscription form needed to be completed to enable the access. The terrain and orthophoto of Switzerland are available with the following link: http://api3.geo.admin.ch/services/sdiservices.html#terrain-service. In the viewer of the 3D DSS the copyright of Swisstopo was added.

[12] https://cesium.com/downloads/cesiumjs/

Topographic basemap

For a better orientation, a function has been implemented that shows the layer "OpenStreetMap". This layer is a topographic basemap provided as tiled imagery and hosted by OpenStreetMap[13]. The OpenStreetMap and the Orthophoto layer can be switched on and off, and by slider bars, the transparency of these two layers can be defined interactively. In this way, e.g., the street names, place names, and land use classes (forest, settlement, agriculture etc.) become visible on top of the orthophoto. In the 3D DSS, the layer can be activated by clicking on the "Display" button in the opening window and the transparency can be adjusted with the slider.

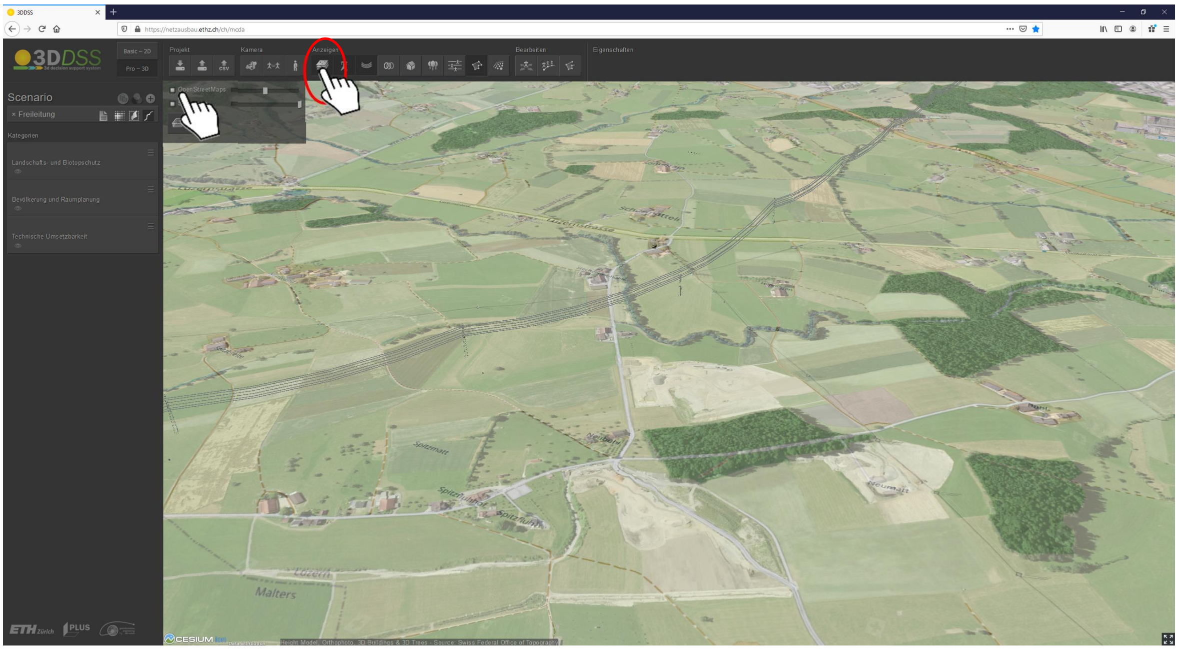


Figure 20: Displaying the OpenStreetMap on top of the terrain and the orthophoto in the 3D DSS.

3D buildings and 3D trees

A function was added to the interface to display 3D buildings and 3D trees. As a first approach, the vector data set swissBUILDINGS3D 2.0 (Swisstopo[14]) provided the basis for processing the 3D models suitable for integration in Cesium. The swissBUILDINGS3D 2.0 data contain detailed shapes of roof forms and roof overhangs. The vector data were exported in the format b3dm («**b**atched **3d** **m**odel»). For this purpose, the shapefiles of the swissBUILDINGS 2.0 were imported into Esri ArcMap[15] and transformed into the WGS 1984 (EPSG: 4326) format using the «Project» tool. The transformed shapefiles were then used in the FME Workbench[16] program as input for the «CESIUM 3D Tiles» writer and converted into the b3dm format. In the process, all shapefiles were combined into one file in the Writer. The resulting building data in b3dm format are divided into tiles that can be displayed on the Cesium globe (Lilley 2017).

Since the 3D buildings processed in this way were not very performant and they did not include color for roofs and facades, a different approach was implemented as final solution. In addition to the terrain

[13] https://cesium.com/docs/cesiumjs-ref-doc/OpenStreetMapImageryProvider.html
[14] https://shop.Swisstopo.admin.ch/de/products/landscape/build3D2
[15] http://desktop.arcgis.com/de/arcmap/
[16] https://www.safe.com/

and orthophotos, Swisstopo also offers the buildings and vegetation of Switzerland as 3D tiles via its web access service[17]. Thus, in the 3D DSS these 3D objects are now streamed directly from the Swisstopo server.

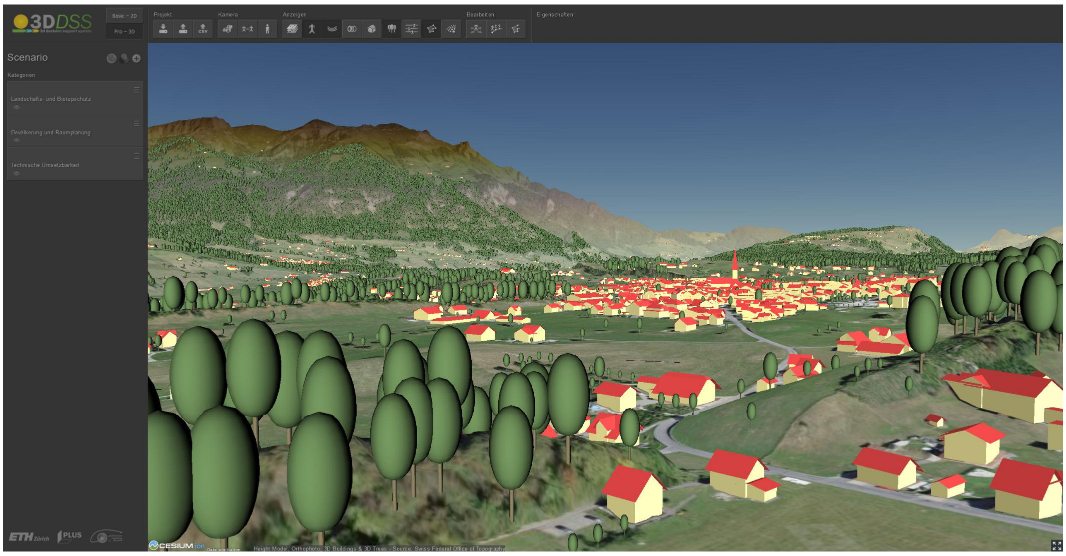


Figure 21: 3D visualization of buildings and trees.

Planning area, resistance map, corridor

For each scenario, the calculated spatial resistance map (Raumwiderstand), the planning area (Planungsgebiet), as well as the corridor (Korridor) for OLs and ECs are displayed in the 3D DSS as 2D maps on the 3D globe. For the visualization of results, new fields for toggling the maps on and off have been added to the navigation bar on the left side of the graphical user interface (GUI).

Spatial resistance map: Result of the summation of the resistances and weighting of all factors.

Planning area: The map shows spatially the relative spatial costs for the construction of TLs based on the spatial resistance map.

Corridor: Area in which the construction of a TL causes the lowest relative spatial costs according to the selected scenario. (blue = OLs; yellow = underground cable)

The legend for the spatial resistance map as well as the map of the planning area can be shown and hidden with the keyboard key "R".

[17] http://api3.geo.admin.ch/services/sdiservices.html#d-tiles

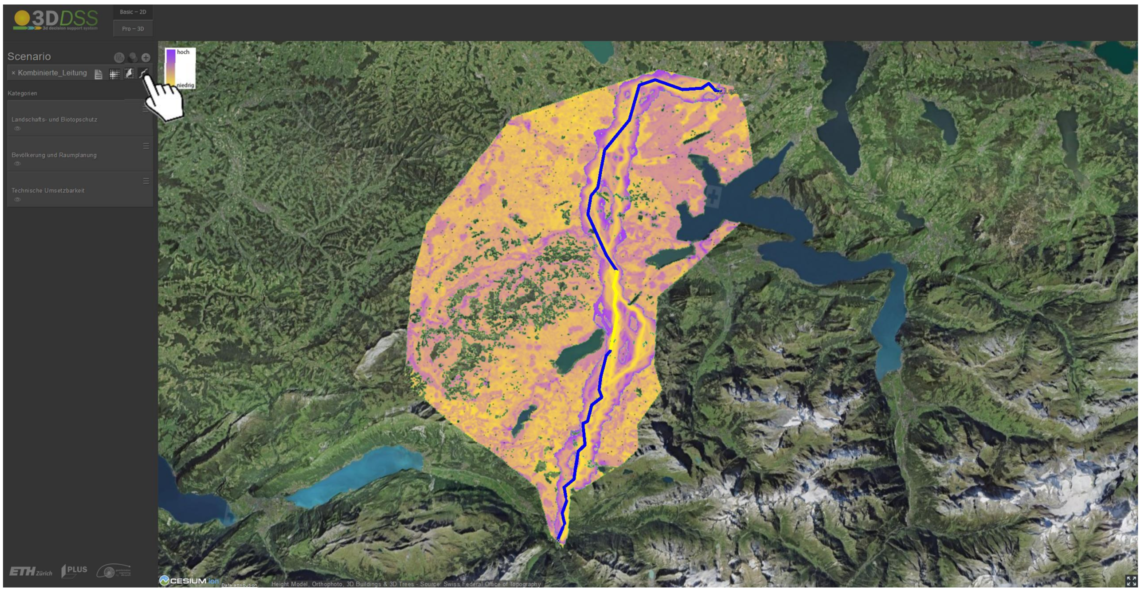


Figure 22: 2D visualization of the scenario results: Overlay of the spatial resistance map, the planning area, and the corridor (blue = OLs, yellow = ECs).

Corridor – Approximated costs

With a mouse click on the circular button with the coin symbol, the corridor is displayed classified in three levels (low, medium, high) according to the calculated approximated construction costs per kilometer. With the keyboard key "K" the legend can be shown or hidden respectively. To return to the original coloring by line type (blue = OLs; yellow = ECs), it needs to be clicked again on the coin symbol.

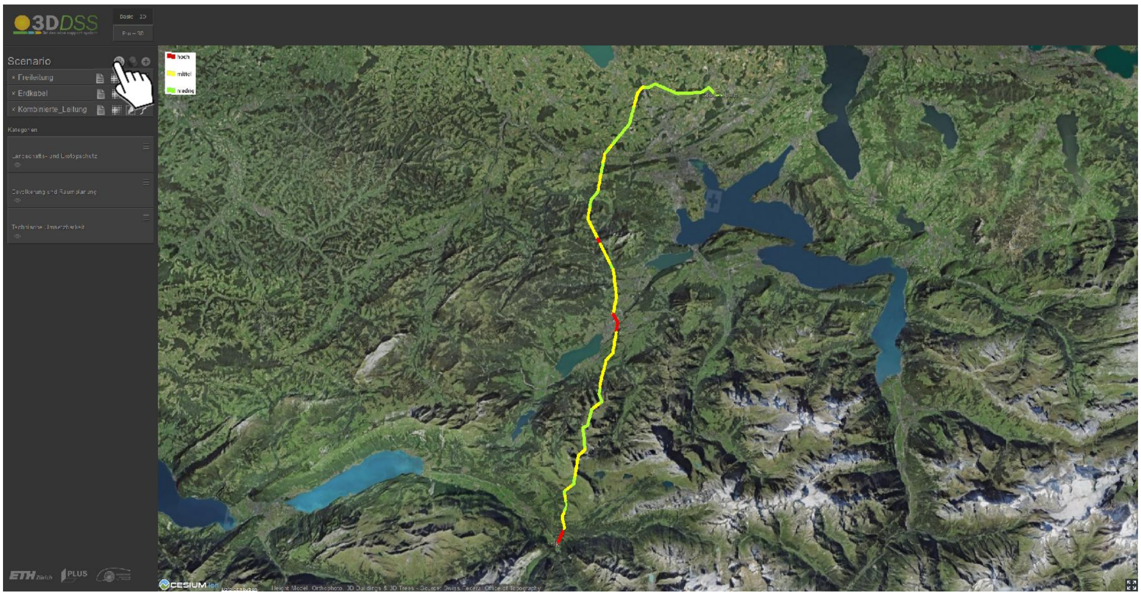


Figure 23: Colorizing the corridor by approximated construction costs.

Comparing corridors of alternative scenarios

If several scenarios are to be compared, the different corridors can be colored differently by clicking on the button with the three circles: 

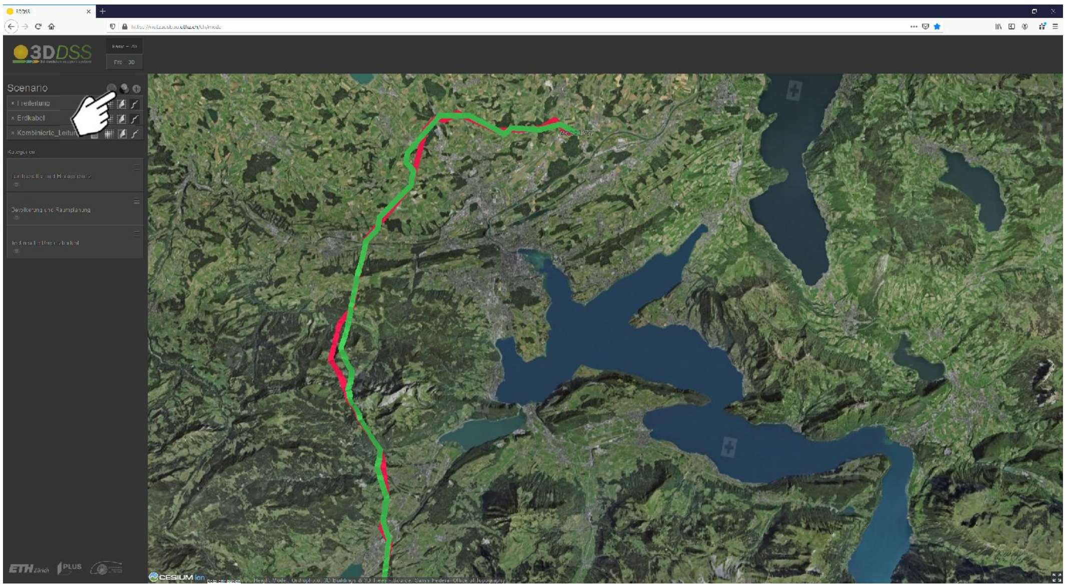


Figure 24: Colorizing the corridors of alternative scenarios differently for better comparison.

Transmission towers, transition buildings, earth cables, and access points

For the 3D visualization of objects, such as TTs and TBs (Figure 25), common dimensions for Switzerland were compiled from literature in an overview. In Switzerland, TTs can have varying heights depending on the topography, e.g., between 47–80 m in the case of Beznau–Birr[18] or 60–90 m in the case of Chamoson–Chippis[19]. We decided to display the TTs with a general height of 80 m (see also Song (2017)). Pipe blocks (Rohrblöcke) for ECs also can have different dimensions depending on their type (single or double, one or two layers). We decided to use pipe block models of the type double and with two layers, which are 0.6 m high and 1.25 m wide (ewz 2019). Transition buildings require an area of approximately 50 m by 80 m, whereby the transition building can have 52.5 m length x 30 m width x 25 m height (Swissgrid 2018, 27; 2019). APs can have dimensions of 10 m length, 2.5 m width and 2.1 m height (plus 0.4 m above ground for the access) (Rendigs 2016, 84). According to this information, in the Cesium code it was defined how large the corresponding 3D models are displayed in the 3D DSS (Table 1).

[18] https://www.swissgrid.ch/dam/swissgrid/projects/project-overview/beznau-birr/190328-flyer-gaebihuebel-de.pdf
[19] https://www.swissgrid.ch/de/home/projects/project-overview/chamoson-chippis.html

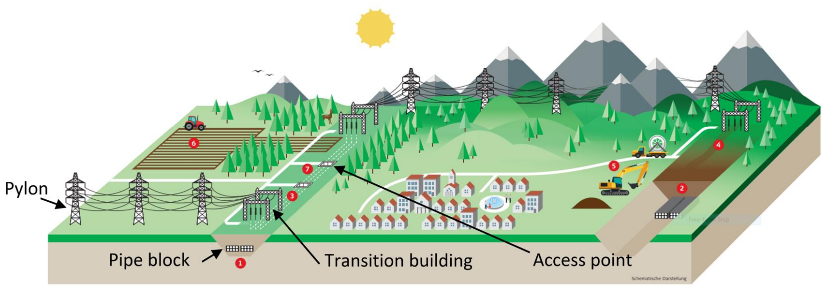


Figure 25: Overview of 3D objects for visualization of a TL. (Image source: Swissgrid)

Table 1: For 3D visualization defined dimensions of the different infrastructure types.

Infrastructure type	Height [m]	Width [m]	Length [m]
Transmission tower	80	-	-
Transition Building	25	30	52.5
Pipe Block	0.6	1.25	-
Access Point	2.1	2.5	10

Depending on the data formats, different approaches were applied to prepare the 3D models so that they can be displayed in the Cesium viewer. Digital CAD models (in DWG format) of pylons and transition buildings, which correspond to the types of these infrastructures commonly used in Switzerland, were obtained from Swissgrid. The model of the transition building was first imported in the CAD program Vektorworks[20] and exported in the DAE (Collada) format. The DAE file was then imported into the graphics program Cinema4D[21], simplified to minimize the number of polygons and exported again in DAE format. Using the command-line tool «COLLADA to glTF converter[22]» the DAE file was converted into the format glTF (GL Transmission Format[23]). The resulting file of the 3D model is now loaded into Cesium at the points calculated by the respective scenario.

The transition buildings are placed between OLs and ECs. The calculated first point for the beginning of an earth cable or the first point of an OL at the end of the EC is used as the point for the placement of this building.

[20] https://www.computerworks.de/produkte/vectorworks.html
[21] https://www.maxon.net/en-us/products/cinema-4d/overview/
[22] https://github.com/KhronosGroup/COLLADA2GLTF
[23] https://www.khronos.org/gltf/

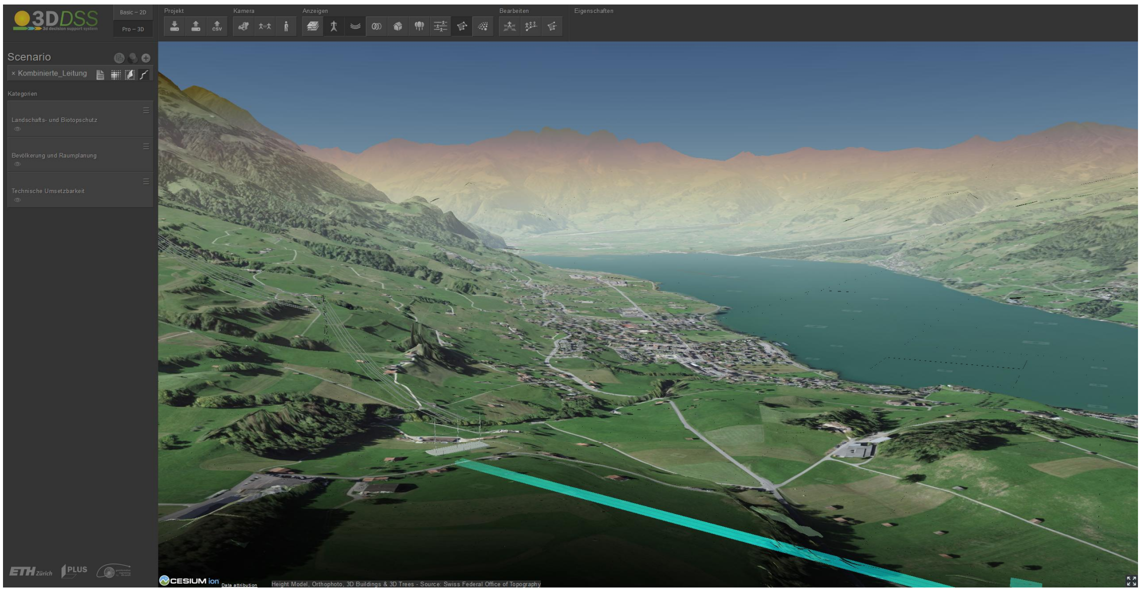


Figure 26: 3D visualization of a transition building between an OL and an earth cable.

The 3D model of a 'Barrel shape' pylon (Figure 52) was used in the same way as the 3D model of the transition building. However, the colors assigned to the model in the program Cinema4D could not be displayed in Cesium. In order to display the coloring, the 3D model was imported into the open source 3D graphics program «Blender[24]» to assign a color before its export to the glTF format.

Figure 27: 3D model of the pylon and the cables of the OL.

The calculated ECs are shown as eight tubes (4 x 4 tubes) at a depth of ten meters below the surface of the terrain. The depth can be adjusted in the code according to further specifications. When trying to display more tubes (6 x 6 tubes) for the visualization of the EC, display problems occurred due to graphics card bottlenecks. In order to be able to display the modeling results on as many computers as possible, even in the 3D mode of the 3D DSS, the generalization of the representation of ECs in the form of eight tubes is necessary. In order to view the ECs in the 3D mode, a button was added to activate transparent display of the terrain. This is activated by mouse click on the "Display" button and then on

[24] https://www.blender.org/

the lower left button "toggle translucent terrain" in the window that opens. If one now zooms further into the view, the terrain becomes transparent and the ECs become visible.

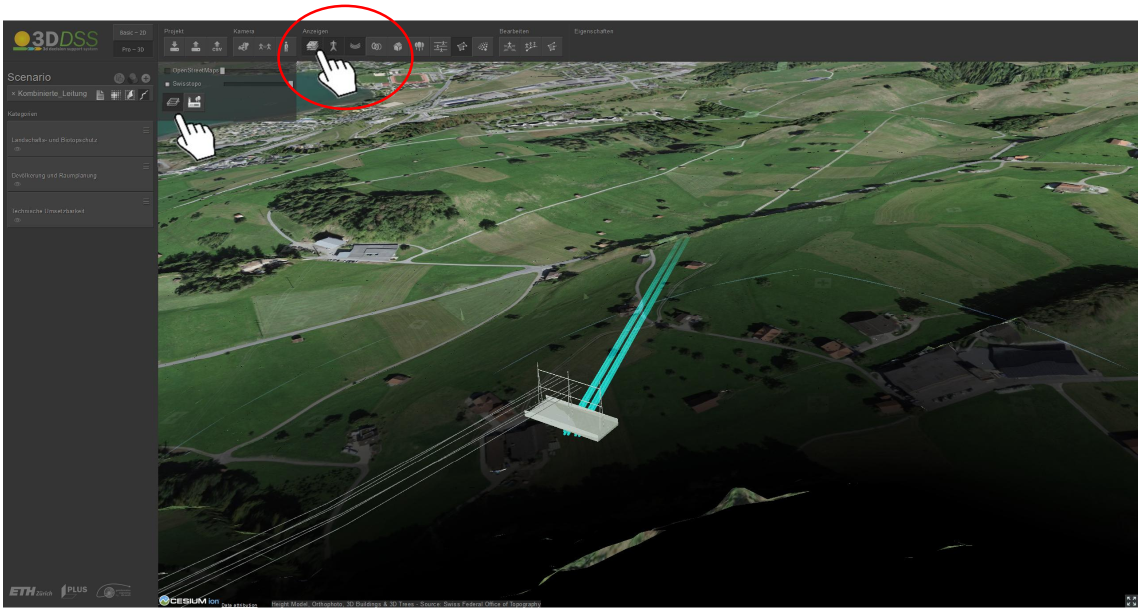


Figure 28: Display settings to toggle translucent terrain in order to see the ECs below ground.

APs are visualized as boxes (2.5 m x 10 m x 2.1 m), which are placed at calculated points provided by the result files of a scenario at a regular distance of 1000 m and when the cables change direction.

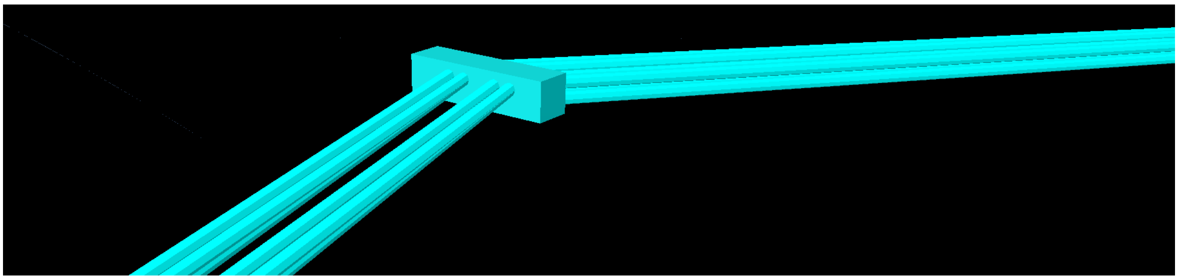


Figure 29: 3D visualization of APs.

Electromagnetic field

The display of the electromagnetic field around the wires has been improved. This function provides important information, especially in residential areas where greater distances to buildings are required. The electromagnetic field of the immission limit is displayed as a «tubular field» around the OLs.

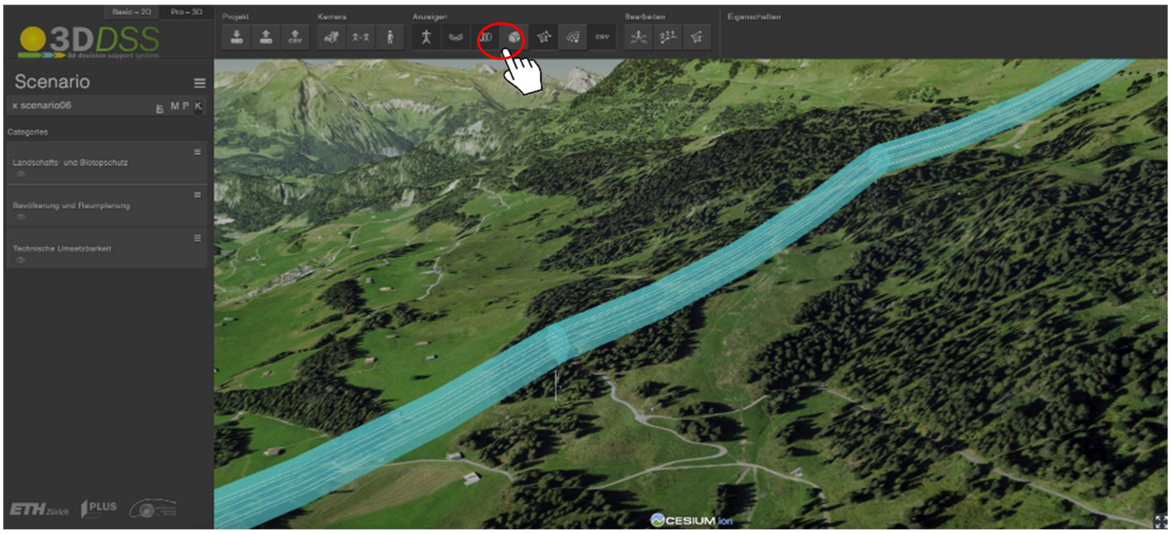


Figure 30: Improved 3D visualization of the electromagnetic field of OLs.

Clearance zones

Areas in the forest, which are crossed by ECs, need to be cleared from high vegetation. The visualization of these so-called 'clearance zones' («Freihaltezonen») is based on the calculated scenario results, whereby segments of the resulting path are attributed whether they belong to these zones or not. Clearance zones can have a width between 12 m and 25 m (Rendigs 2016, 84). We decided that segments of the path belonging to the clearance zones are displayed with a total width of 25 m (= buffer of 12.5 m around the earth cable path). The polygons (AISLES.json) are resulting from the modeling process and are added automatically when displaying the results of a scenario.

The 3D tiles of the buildings and vegetation can change their colorization based on the color of a vector data file. This function is used to highlight the clearance zones of a scenario in the 3D mode. When the 3D vegetation is switched on, the 3D trees falling in that zone are highlighted in the color of the clearance zone layer.

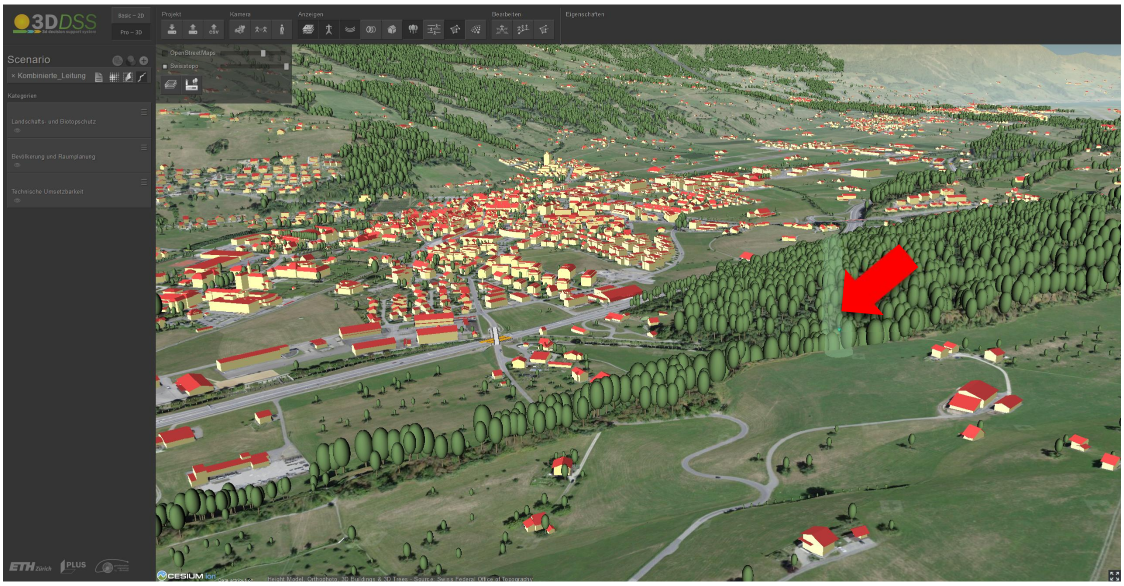


Figure 31: Example of the visualization of clearance zones («Freihaltezonen») in 3D mode.

3.2.3 High-voltage level: Case «Zurich city»

Visualization of existing underground infrastructure

In this section, the preparation and visualization of existing underground cables for the case of the city of Zurich is briefly described. The detailed processing and visualization of the data is documented in an individual report (Wissen Hayek et al. 2020).

The available data of existing underground cables belong to the underground infrastructure cadaster («Leitungskataster») of the city of Zurich (Stadt Zürich 2020a). They comprise digital information on gas, water, district heating, telecommunication, and TLs (with inexact position). Furthermore, ewz provided a data set on TLs below ground, which are for the most part exactly positioned. This data had to be processed for 3D visualization below ground in the 3D DSS (Table 2).

Table 2: Overview of the data sets of underground infrastructure available for the 3D DSS.

Data owner	Data set	Format	Content
AWEL, Kanton Zürich	EN_STROMANLAGEN_P.shp	Esri Shapefile	Strominfrastrukturanlagen (inexact position)
ewz	Strom_alle_Trassentypen_Flächen.shp …Beschriftungstexte.shp …AchsenRohre.shp Strom_Erdungssystem.shp Strom_Schacht.shp Strom_Station.shp Strom_Trassebauwerk.shp Strom_Ueberdeckung.shp Strom_Verteilstelle.shp	Esri Shapefile	Strominfrastrukturanlagen (exact position)
Energie 360° AG	gas-2019-0104-1	DXF	Werkleitungsdaten Gas
Erdgas Ostschweiz AG	AV_261-zuerich-gds.itf DM01AVZH24LV95.ili	INTERLIS 1 (.itf)	Rohrleitungen (Hochdruck); *Leitung im Datensatz «gas-2019-0104-1» enthalten*
Wasserversorgung Zürich	Wasserleitungen_ Hauptleitungen	DXF	Wasserleitungen
AWEL, Kanton Zürich	EN_KVA_WAERMENETZ_L	Esri Shapefile	Fernwärmeleitungen *Keine Leitung im Studiengebiet enthalten*
Swisscom AG	Stadt-Zürich_LK-Swisscom_20190604	DXF / DWG	Kommunikationsleitungen
UPC	8048_Zürich_Projekt 3D_DDS	DXF	Internet-/TV-Leitungen

First, the width and depth of the different underground infrastructure types was identified. Therefore, the data was inspected regarding their attribute values. Most of the data contained information on the tube diameter. However, the depth of the tubes below ground and the width and depth of the pipe trench was not provided. In an internet search, values for the dimensions of the pipe trenches commonly used in practice were determined. Thereby, inter alia, the standards for the construction of drainage systems and roads of the civil engineering and waste disposal department provided helpful information (Stadt Zürich 2020b).

For visualization in the 3D DSS, the cables as well as the trenches should be displayed. The cables should be displayed in the assumed depth of the upper edge of the cable and with the determined width. The possible trenches of the tubes should be displayed as 3D boxes, which start at the assumed depth of the upper edge of the trench and end at the assumed depth of the bottom of the trench (Figure 32; please note that the trenches start at the surface level as it is assumed that in most cases no other underground infrastructures can be placed above another infrastructure).

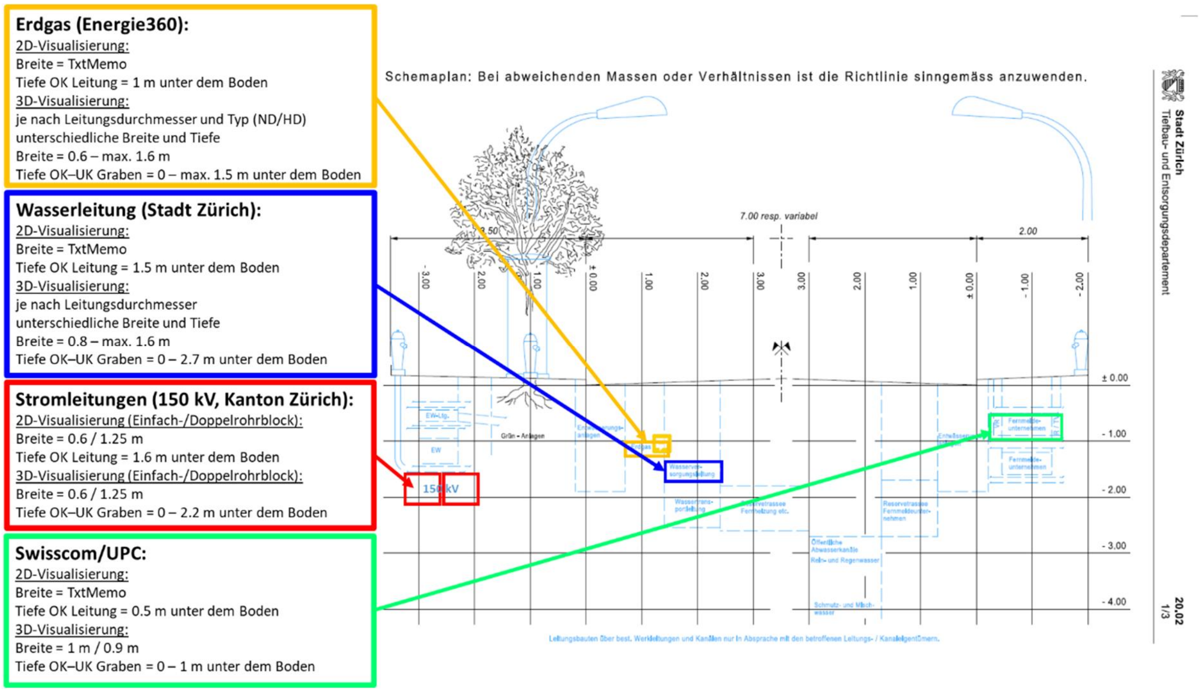


Figure 32: For the visualization assigned values of the dimensions of tubes and trenches for different underground infrastructure types.

The data provided by ewz already contained polygons with the width of the pipe blocks and further information in the attribute table on their depth below ground. However, the latter information was too detailed to use it for preparing the data in the format for 3D visualization in the Cesium viewer. Hence, the polygon and line segments respectively were assigned to six classes of depth. Thereby, the classes in the first two meters below ground are divided into smaller units, whereas the units are increasing between two and eight meters (see Wissen Hayek et al. (2020) for further details).

The data was converted, if necessary, and imported in Esri ArcMap 10.5[25] for further processing. First, polygons with the width of the tubes and the trenches of the respective infrastructure types were generated. In order to assign the depth of the polygon below ground, the tool «Interpolate Shape[26]» was used for the cables, and the tool «Extrude Between[27]» for the trenches. «Interpolate Shape» adds a z-value from a Digital Terrain Model (DTM) to the polygon. With the tool «Raster calculator[28]», using the DTM with the actual height of the terrain as input, we created surfaces, which are on the respective assumed depths of the upper edges of the tubes. These surfaces provided the input for interpolating the shape of the polygons of the tubes, resulting in Polygon Z-Shapefiles.

For generating the 3D box models of the trenches, two surfaces had to be created in the described way. Additionally, the resulting surfaces were converted to TIN Layers (tool «Raster to TIN»), the required input format for the tool «Extrude Between». These two TINs provided the surfaces for extruding the respective polygons between, resulting in MultiPatch-Shapefiles.

Finally, the 3D polygons had to be converted to CESIUM 3D Tiles, the format to load data efficiently in the Cesium viewer. As the CESIUM globe uses the World Geodetic System 1984 (WGS 84, EPSG

[25] https://desktop.arcgis.com/de/arcmap
[26] https://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/interpolate-shape.htm
[27] https://desktop.arcgis.com/en/arcmap/latest/tools/3d-analyst-toolbox/extrude-between.htm
[28] https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/raster-calculator.htm

4326), the Polygon Z-Shapefiles and the MultiPatch-Shapefiles were projected in ArcMap into that co-ordinate system (tool «Project»). Then, the shapefiles were converted with FME Workbench (Version 2020.0) to the format CESIUM 3D Tiles, which can be displayed in the Cesium viewer.

With the new button «Leitungen», the underground infrastructure can be visualized in the 3D DSS (Figure 32). The ending «3D» refers to the prepared 3D Tiles of the trenches, the ending «2D» to the 3D Tiles of the tubes.

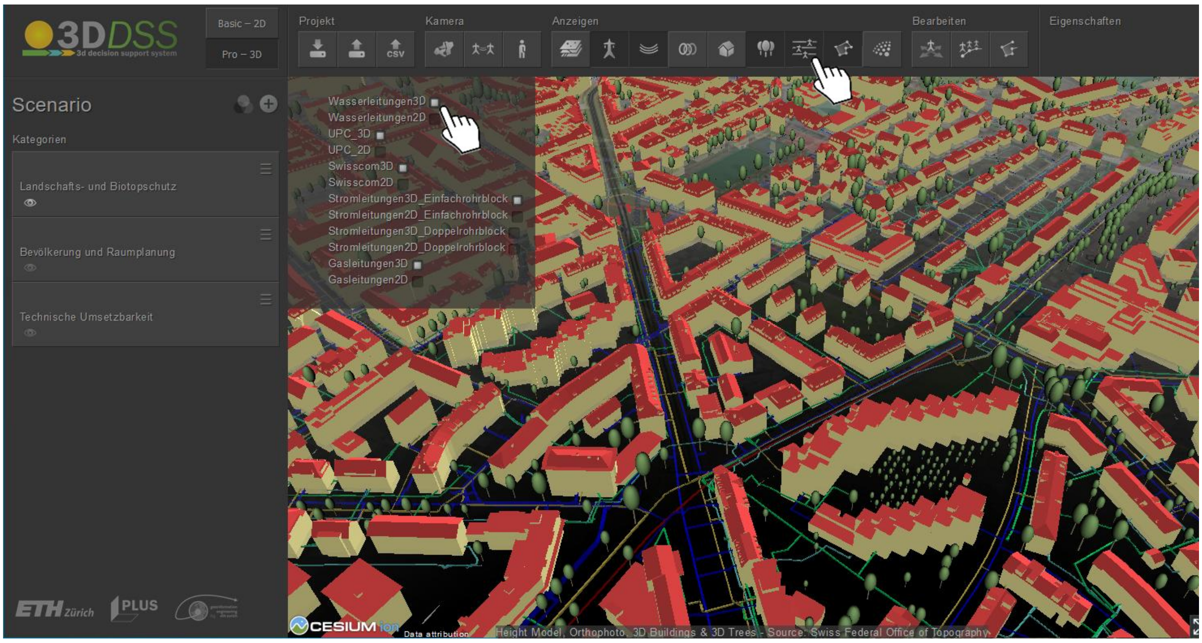


Figure 33: 3D visualization of ECs below ground. The terrain is set to transparent.

For better orientation, and in order to get an impression of the varying depth of the different tubes and trenches, new display functions were programmed. In addition to displaying the layer «OpenStreetMap» on top of the orthophoto (see section 3.2.2), we developed a section tool. When clicking on the button «Clipping plane», the tool is activated. The terrain should be displayed in the opaque mode. Then, with a first click on the ground, the beginning, and with a second click to the left side, the direction of the clipping plane is defined. As result, all features in front of this virtual clipping plane are hidden. Now, the terrain transparency can be activated. The «Clipping plane» function is helpful to provide a view on the underground infrastructure in the different depth (Figure 34).

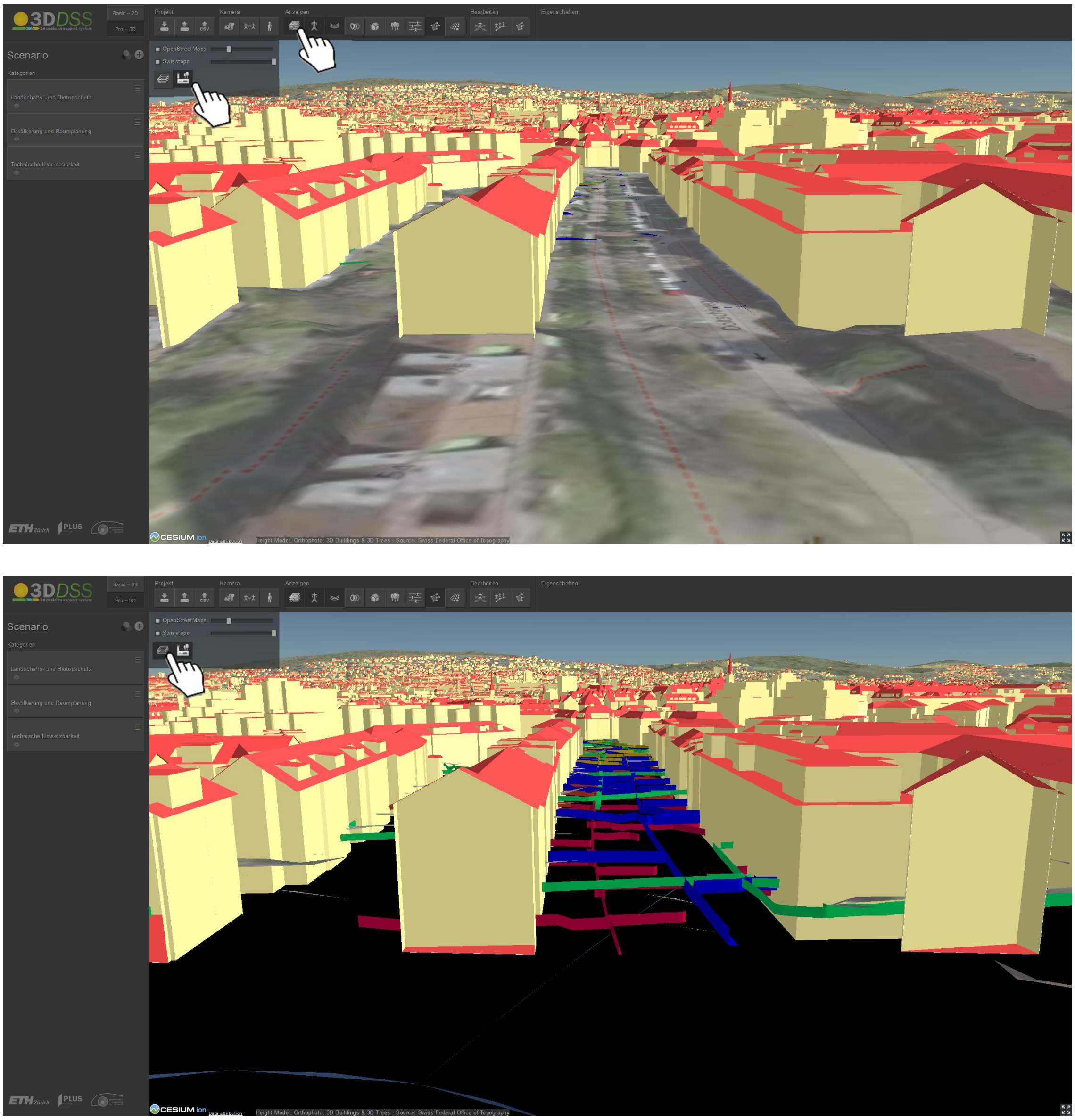


Figure 34: Section view of a street with 3D buildings and underground infrastructure below ground.

The data of ewz contain detailed information on the occupancy of the pipe blocks. There are attributes specifying whether pipe blocks are empty or how many pipes are still available in a pipe block. Additionally, the depth value can be used to make the visualization of this information clearer than with the extruded polygons only. Hence, we programmed the function to colorize the ewz-3D data according to these three attributes (Figure 35).

The other ewz data set «AchsenRohre» comprises rather detailed information on the position of tubes. This is another layer, named EWZ_2D, which can be displayed in the 3D DSS (Figure 36).

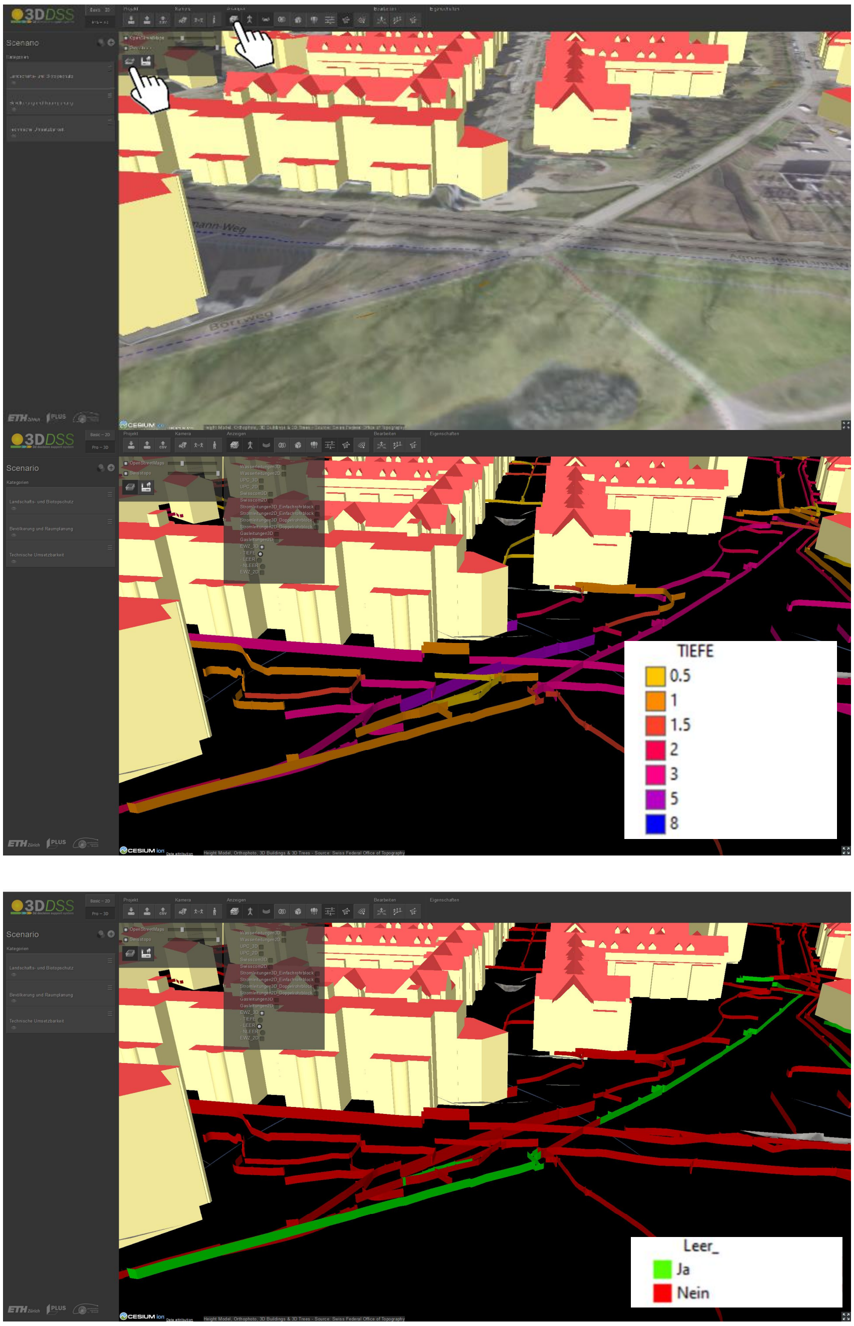
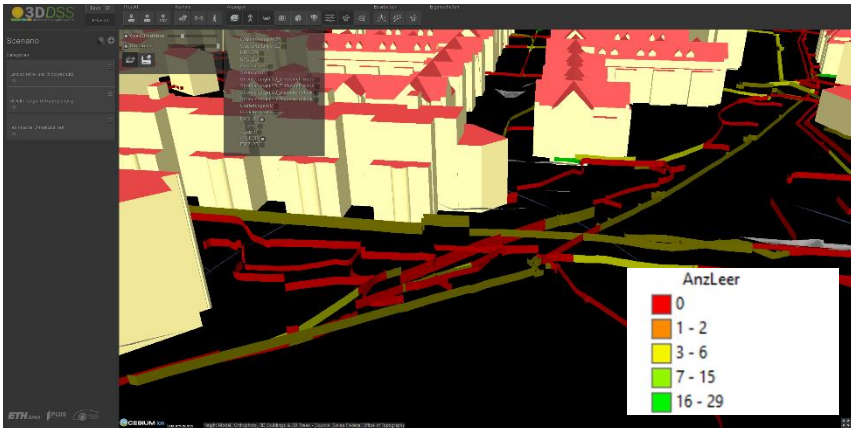


Figure 35. ewz data «Flächen»: Coloring by the attributes «TIEFE» (depth), «LEER» (empty pipe blocks), and «NLEER» (number of empty pipes).



The "ewz 2D" data derived from the "Strom_alle_Trassentypen_AchsenRohre.shp" data set shows the location of the lines.

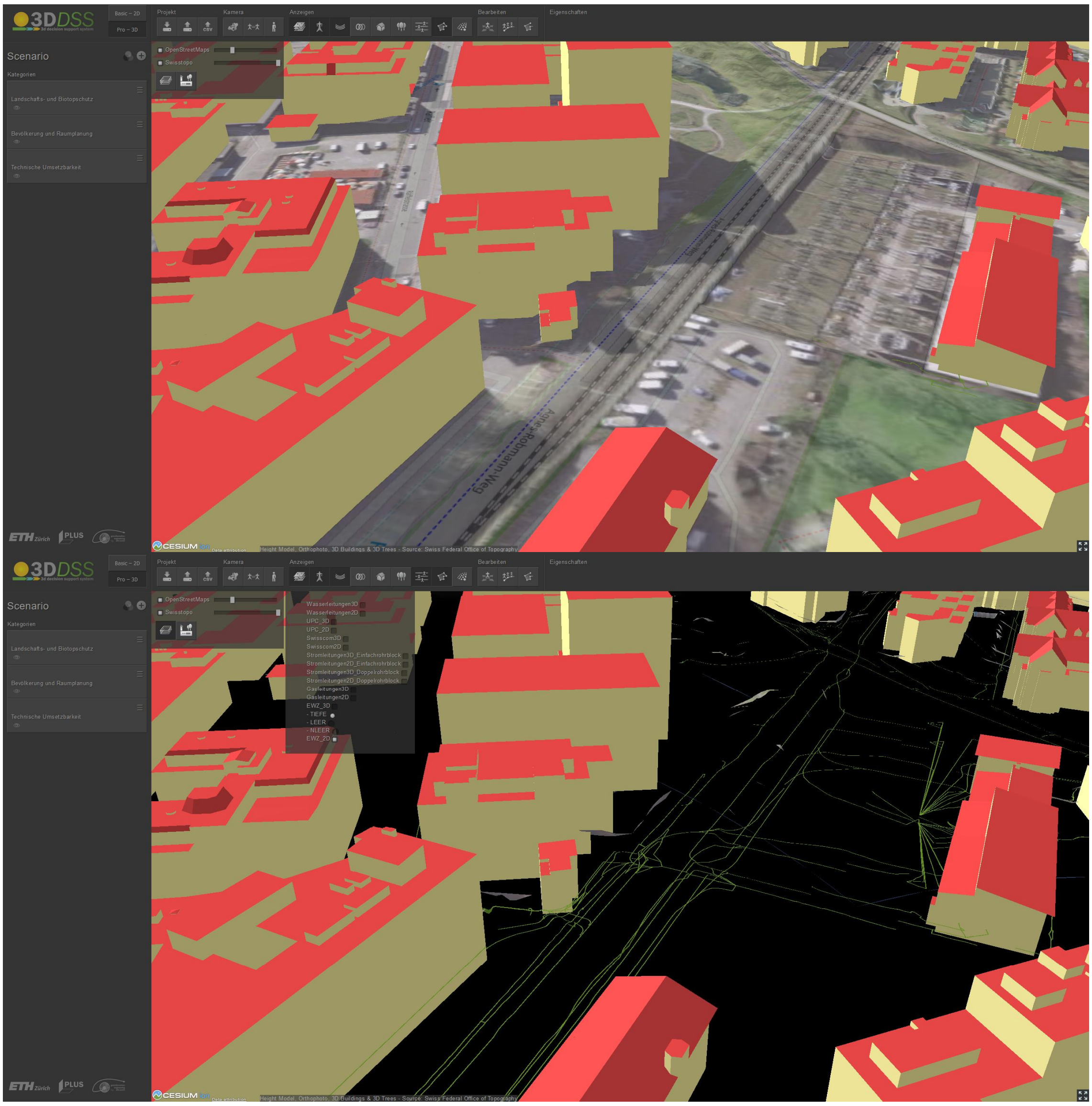


Figure 36: EWZ-data «AchsenRohre»: Visualization of the position of tubes.

Network path alternatives

The modeling for the case study «Zurich city» results in a large number of different network paths between the substation Waldegg (UW) and the substations Altstetten, Binz and Sihlfeld. For the visualization, all network paths between the start UW Waldegg and the respective target substation were aggregated. Thus, the possible network paths for a target substation (UW Altstetten = blue; UW Binz = green; UW Sihlfeld = red) can be displayed.

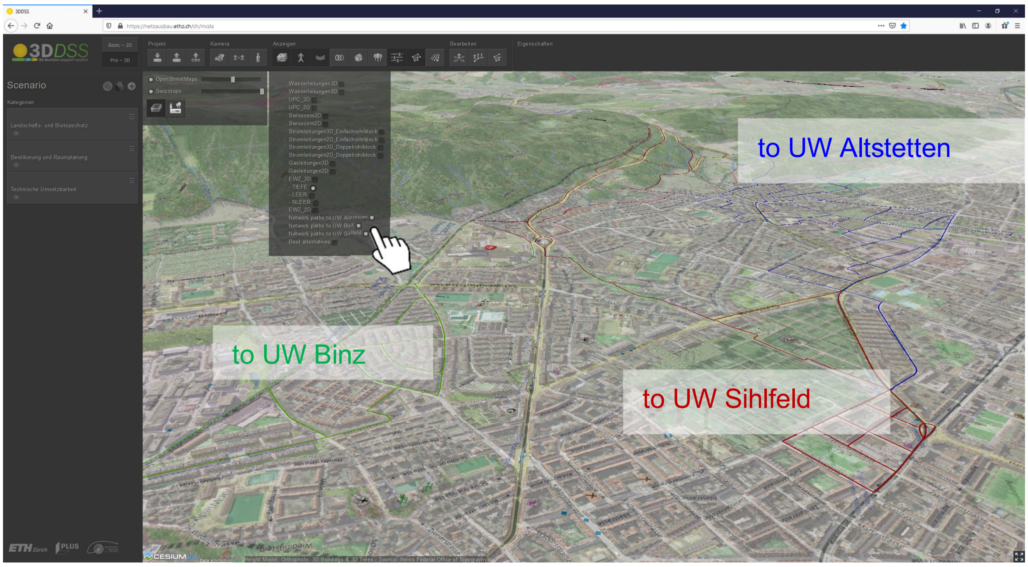


Figure 37: Displaying possible network paths for the different target substations (UW) for the case «Zürich».

In addition, the five best network path alternatives can be visualized. When the mouse is moved over the paths, the respective alternative is highlighted in violet and the name of the alternative is displayed in a black box. Since the paths of the different alternatives overlap, the path appears dark blue in some parts.

By clicking on the path, the attributes of the data set for the selected alternative are displayed in a box at the top right of the 3D DSS. This box contains various information for assessing the quality of the alternative, such as the length, the number of intersections, and further attributes.

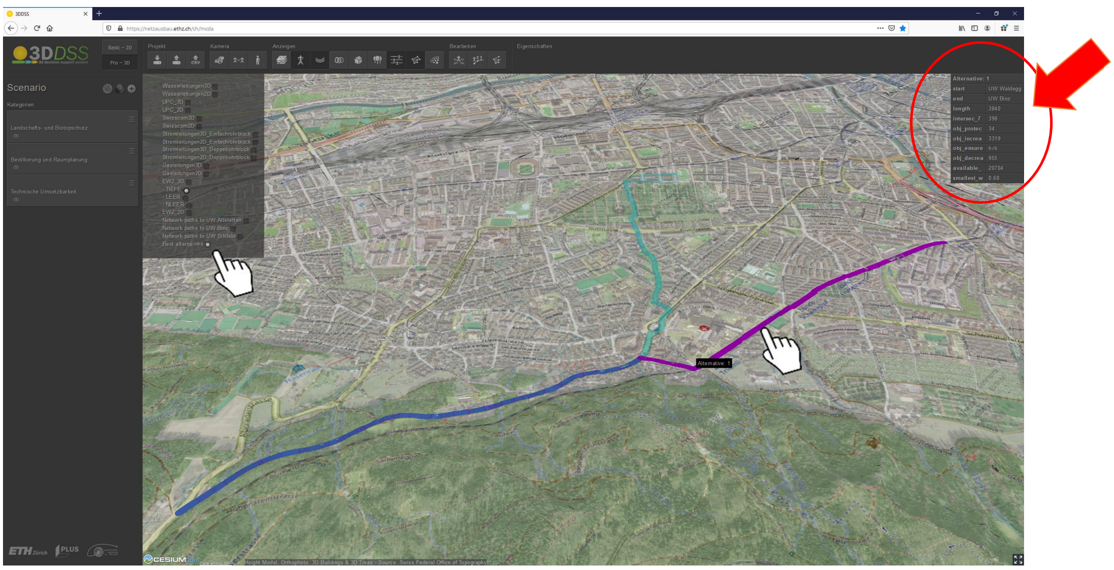


Figure 38: Visualization of the five best network path alternatives.

Further information layers

In the case of Zurich city, further information layer can support the analysis of modeling results in order to decide if a calculated alternative is suitable or not. For example, the zoning plan information comprising, inter alia, living, industrial, central or recreational zones etc., is an important information. This data of the cadaster of public-law restrictions on ownership (Kataster der öffentlich-rechtlichen Eigentumsbeschränkungen, ÖREB-Kataster) is available as web feature service (WFS) layer from the geographic information system of the Kanton of Zurich (GIS-ZH; https://www.geolion.zh.ch/geodatensatz/2281). In the 3D DSS, with a new button, the data including the legend is directly called from the cantonal server (Figure 39). Accessing the data in this way also ensures that the data layer is always up to date.

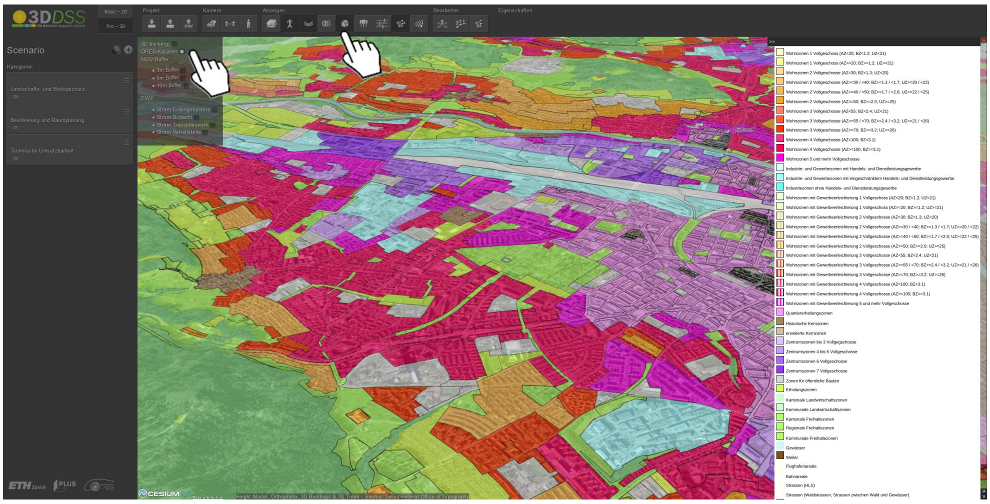


Figure 39: Information layer ÖREB-Kataster: Cadaster of public-law restrictions on ownership.

For analyzing whether there might be conflicts with the NISV, three different buffer (3 m, 5 m, 10 m) around the buildings of the study area were calculated using Esri ArcMap. These were included as vector data into the 3D DSS (Figure 40). The buildings take the color of the respective vector polygon layer.

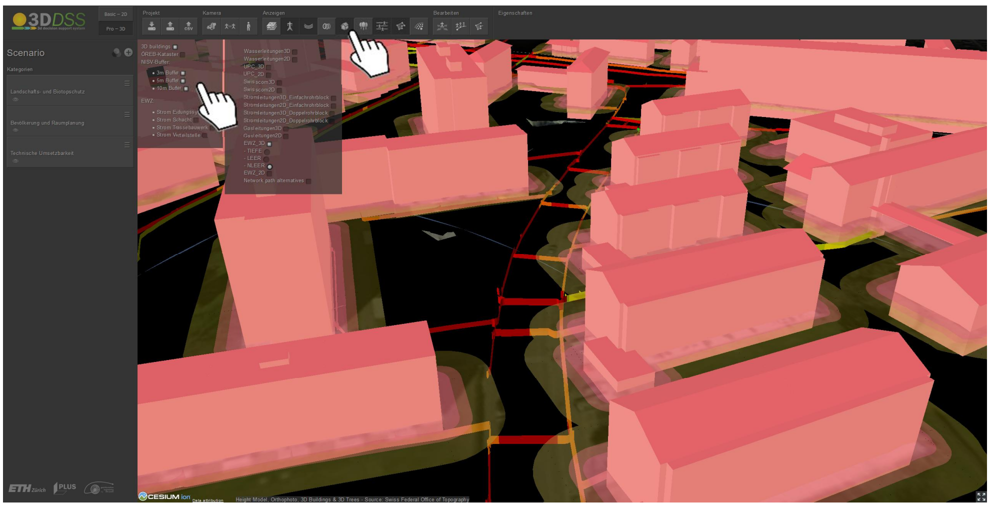


Figure 40: Information layer NISV-Buffer: Buffer of different distances around the buildings.

3.3 Augmented reality solution

After a first year spent in investigating the technology, we then planned the development of the first prototype and set up a case study for demonstration.

One of the major challenges of this task was the lack of existing products or use cases to be used as reference and to learn from as emerged during the investigation of the state of the art of the technology. Also with respect to expertise, competences and existing use cases, the major risks and open questions with respect to the plan of this project were the data transfer to mobile devices and the required data processing for making data compatible with ARkit. Thus, our work aimed at developing a prototype that uses a technology at an early stage for which open questions were addressed during the development phase ("learning by doing").

Prototype design and development

Based on the concept of the architecture shown in Figure 41, we worked on the following components:

- Development of the user interface design
- Creation of the API for transferring the position of the TTs, including their 3D models
- Investigation and attempt to transfer the position of the TTs, 3D including their models and data related to the DTM/DSM
- Different challenges
- Definition of the case study
- Testing on field

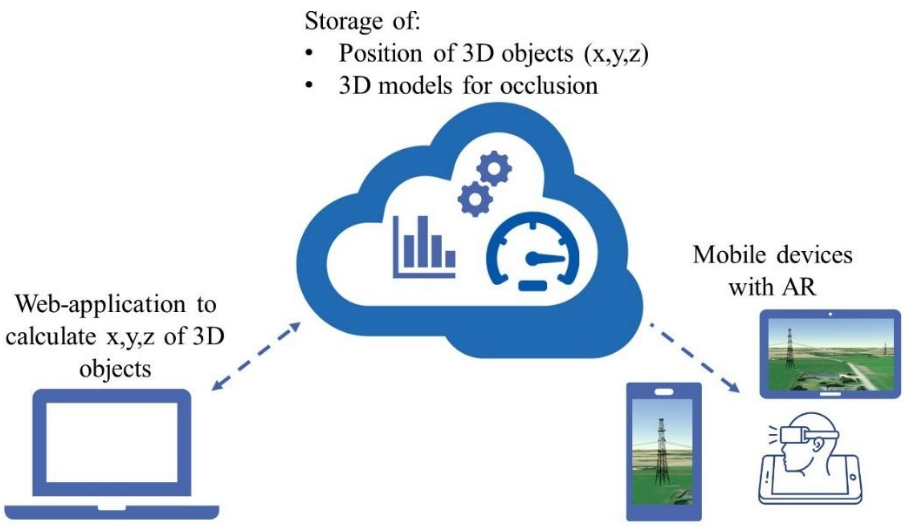


Figure 41: conceptualization of the architecture of the system

Development of the frontend design

The initial concept of the user interface of the solution for mobile devices was to allow users to visualize TTs, locate the position of the device on a small map, add a function to change the opacity of 3D objects, and to add a project description. Figure 42 and Figure 43 show the initial mockup of the user interface of the smartphones.

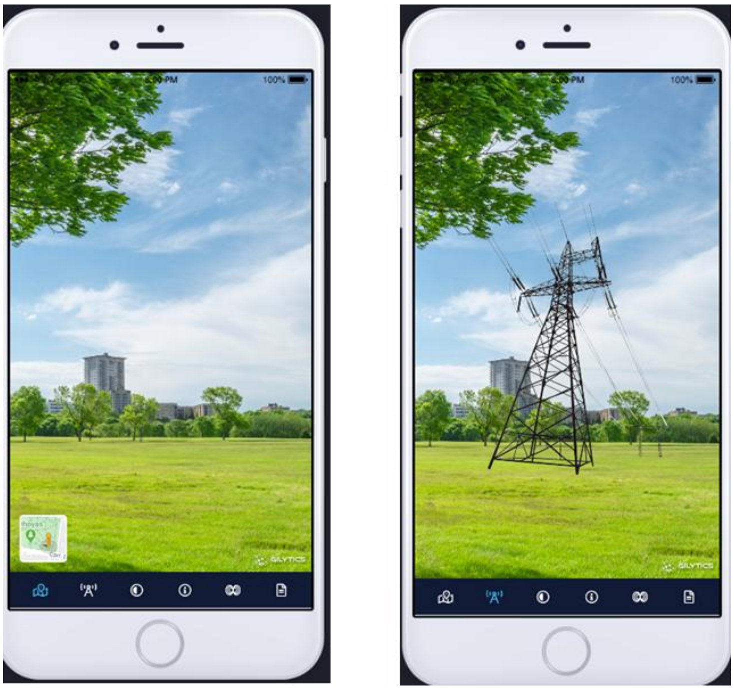


Figure 42: Wireframe of the user interface for smartphones.

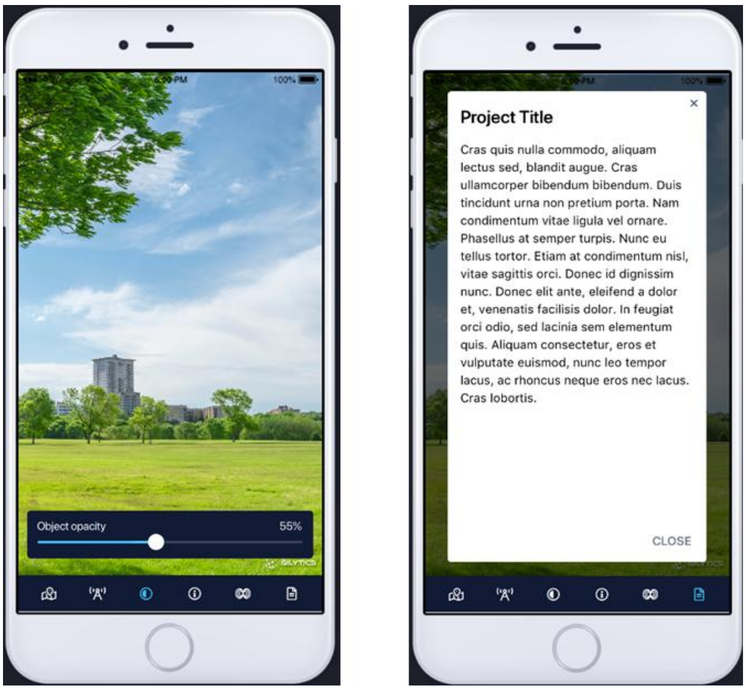


Figure 43: Wireframe of the user interface for smartphones.

Figure 44: Wireframe of the user interface for tablets.

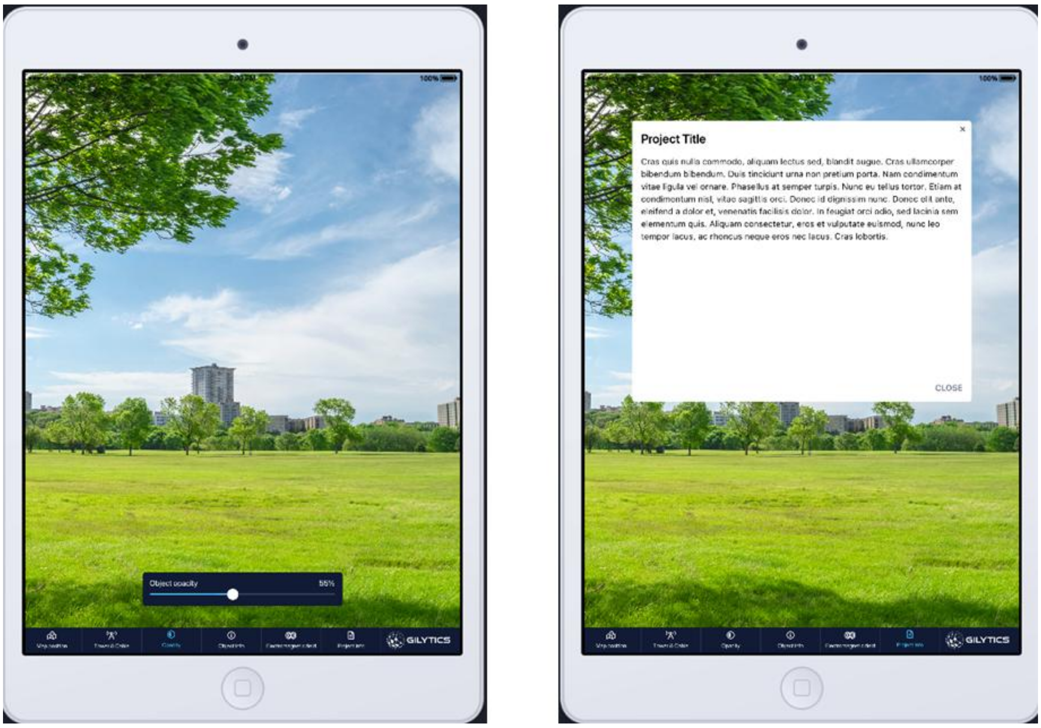


Figure 45: : Wireframe of the user interface for tablets.

Transfer of data through API

This part of the project was one of the most challenging due to the lack of existing products and technologies. Nonetheless, we have attempted with the available time to develop the API and the system to transfer data from a cloud server to mobile devices.

The transfer of the position of the pylons and the DTM in the form of a text file has been accomplished whereas as the transfer of data of the 3D TTs has not been achieved due to issues related to the data format requested by ARkit. As explained before, the compatible formats are Collada, object and FBX. The most suitable format is FBX, whereas the generation of 3D objects from Collada or the object format cannot be easily done with the libraries for data transformation. This task has been accomplished manually and requires the integration of 3D objects integrated into the AR application itself. Nonetheless, due to technical limitations and constraints and because of their size, the transfer of large data sets like the DTM/DSM is, in any case, challenging. One of the major challenges regarded the transfer and the representation of the terrain data including the buildings and vegetation on top of it. The AR kit framework has a limited number of data that can process a handle for the rendering. The AR kit framework tries to represent the reality of the DTM by using polygons. Such polygons are an approximation of the reality and the higher the resolution, the higher the number of polygons in a given region. For this reason, the preprocessing is aimed at finding a compromise between the resolution of the initial raster and the number of polygons necessary to describe the reality. This yields a distortion of the reality depending on the complexity of the topography and the objects on top of it. For instance, for a flat terrain, few polygons are necessary to render a piece of land or how it will look in the future. On the contrary, in case of a hilly or mountainous terrain, more polygons are necessary, and therefore, the representation seems more realistic. The same rationale can be applied for 3D objects, such as the TTs: elements such as texture or small details may require additional polygons, which are not necessary in order to show the impact or the “big picture” of a 3D object.

Different challenges

Here below additional challenges that we have found during the development are summarized:

Tracking quality:

- During the development, the tracking quality on iOS has turned out to be a bigger issue than anticipated—especially in terms of a broader distribution.
- Current developments on the core framework (ARKit by Apple) promise to improve that, but will not be released before fall/winter 2020. Further testing will be needed to approve iOS as a platform for wide adoption.
- Instead, the Android platform has proven to be more stable in terms of tracking. In the current version, there is a graphical issue with the camera image being too underexposed on certain devices. But this is already fixed in a future release of the core engine used to develop the app.

Occlusion with terrain data:

- At the particular location Zurich Hönggerberg, the official elevation data was not accurate enough to be effectively used as occlusion geometry since the difference between the actual situation and the data sets is too big. In some areas, the elevation difference is up to 30 meters and more. (Figure 49)
- The DSM (Digital Surface Model) has not proven to be better suited than the DTM for that purpose. Further testing has shown that the DSM shows even more issues than the difference between the real situation and the elevation data itself. The biggest issue being that, due to hardware limitations on current generation mobile devices, the geometry resolution (poly count) of the DSM 3D model

had to be reduced. To display all the details like foliage, buildings and so forth the number of polygons necessary would go into the millions (Figure 46, Figure 47, Figure 48).

- Generally speaking, the DTM is better suited but lacks some information like buildings, forests and other important features. To work around this, the data sets would need to be corrected and combined by hand, which cannot be determined as a feasible option in terms of cost and time effort. The combination of DTM data and separate 3D building data is an option and has been done in the past, but only if the terrain has not changed too much since the date of recording.
- Alternative options exist that allow to deal with occlusion in AR applications. However, each of those has their own advantages and disadvantages. The most promising solution would be hardware and software improvements on the underlying AR frameworks ARKit (Apple) and ARCore (Google). Apple has made some progress in that matter by adding LiDAR sensors to their newest generation iPads, which can be used to gather occlusion data in real-time, but as of today, only at close distance (few meters).

Figure 46: Issue related to with DSM.

Figure 47: Issue related to with DSM

Figure 48: Issue related to with DSM.

Figure 49: Issue with the elevation.

Case study

In order to test the developed solution, we selected the area close to the campus of ETH Zurich Hönggerberg for a use case. The search area is characterized by a hilly terrain, some forests, some farms, and the buildings of ETH Zurich. The position of the TTs, as shown in Figure 50, was determined by applying reasonable distances between the TTs themselves in the range of 300 m to 415 m. This means that a more accurate analysis of the position of the TTs may results in a different mutual distance. This situation allowed us to test major factors and aspects of the developed AR solution, such as the occlusion effect due to the terrain and buildings.

Testing on field

The testing of the developed application on field as given the results that can be seen in the video available on the following link: https://youtu.be/vMRWEFU0lRs. An additional small test has been done with virtual reality using HoloLens in order to compare the results: https://youtu.be/vlAMZU5dZWY. The results show a big difference in terms of accuracy, data representation, and stability of the image. Nonetheless, HoloLens can be very useful for information days which typically take place indoor in halls.

Figure 50: position of the pylons in red circles

4 Evaluation of the enhanced 3D DSS from a practice perspective

4.1 Assessment of the advanced functionality of the 3D DSS

Twenty-two workshop participants completed the online questionnaire for assessing the advanced functionalities of the 3D DSS. The majority (46%) were TL planners, nearly one-third (27%) do assessments of TL plannings, and the remaining participants are advisors in the SÜL process (9%), GIS-specialists (9%), or focus in their work on the communication with stakeholders (9%; Figure 51). 55% of the participants use GIS in their work, but only 32% often work with 3D visualizations.

Overall, they rated the usability of the 3D DSS and the suitability of the 3D visualizations positively. They find it comprehensible (86%) and transparent concerning the weighting of goals (77%). However, one-third is undecided or find the weighting of goals to be rather non-transparent. As the transparency of the weighting of goals, and in turn the criteria assigned to the goals, is a crucial step for modeling the resistance map and the alternative corridors, further effort is required to enhance this aspect.

Concerning the visualization of the scenario results in the 2D mode, 82% find the presentation rather to very clear. They assess the level of detail of the TL in the 3D mode of the 3D DSS predominantly as very to rather appropriate. However, together nearly one-third are undecided (23%) or of the opinion that the level of detail is not appropriate (4%). In addition, the visualization of existing underground lines in the case study «City of Zurich» was rated as rather to very helpful (73%), whereas 23% are undecided and 4% find it rather not helpful. It seems that the type and manner of the visualization in the 2D and the 2D mode of the 3D DSS prototype is generally suitable. In order to understand the further requirements regarding the level of detail of visualizing the TL above and below ground, as well as the existing underground infrastructure in the 3D mode, additional exchanges with different practitioners are necessary. Thereby the main purpose of the 3D DSS should not be forgotten. For a building information model (BIM) that supports the construction planning a different level of detail is required than for a tool supporting early phases of studying alternative corridors for TLs.

The overall satisfaction with the functionality was rated quite high with 32% being very satisfied, 50% being rather satisfied, and 18% who are neutral or undecided. The majority (91%) has the impression that the 3D DSS cloud be rather to very supporting for the planning of TLs. In which way the 3D DSS could be implemented in practice, and where there might be resistances and aspects for further enhancement of the 3D DSS is further specified in the following section 4.2.

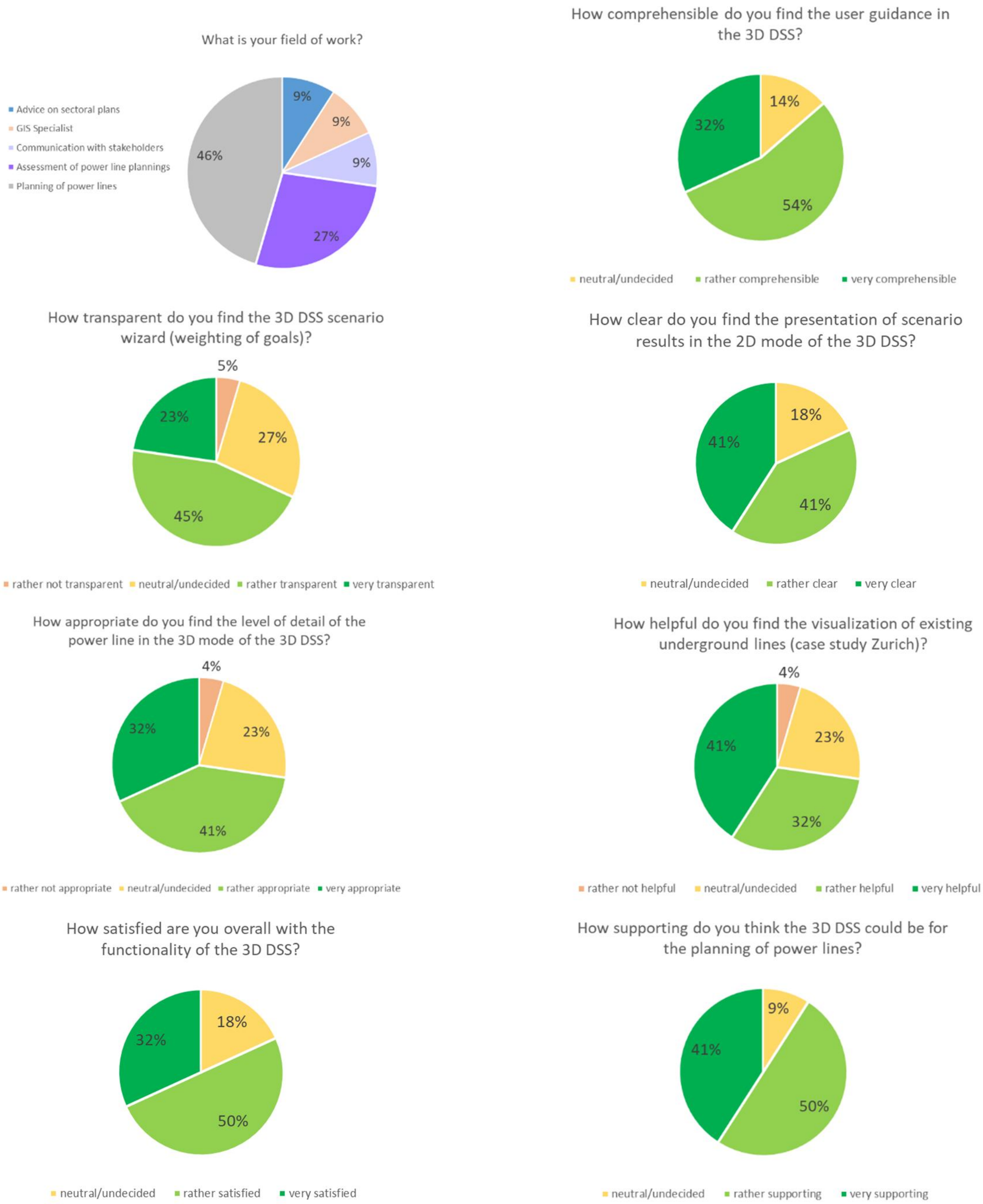


Figure 51: Results of the Questionnaire – Collecting Feedback of Stakeholders from Practice.

4.2 Assessment of the suitability of the 3D DSS for implementation in practice

In this section, the results of the group discussion in the workshop with stakeholders from practice are summarized focusing on the four questions:

(1) In which processes could the 3D DSS be used from a practical point of view?

(2) Where and why is there resistance to its use?

(3) What are the practical benefits of the 3D DSS?

(4) How could the 3D DSS be further developed to better meet practical requirements?

With regard to the processes in which the 3D DSS could be used from a practical point of view, the results of the discussion show that the tool is essentially considered useful for three different areas of application:

1. Planning tool for TL planners

2. Tool for comparing alternative corridors in the SÜL process

3. Tool for communication with different stakeholder groups

For the planning of TLs, the 3D DSS is seen as a tool to promote creative planning and generate initial ideas. It could also automate the generation of the corridor alternatives "overhead line everywhere" and "underground cable everywhere". In addition, there is seen to be potential for using the 3D DSS for strategic planning of the TL network, as it offers modeling of corridors at regional level.

The use of the 3D DSS for planning the path of TLs is controversially discussed, since a very high level of detail is required here, which the 3D DSS does not offer. On the other hand, the tool could make sense in the context of a feasibility study.

Within the context of pre-projects of the SÜL-process, the 3D DSS is regarded as a tool to support the comparison of alternative corridor solutions. It is of interest here that the 3D DSS may also generate alternatives that would not have been created with conventional planning methods. The advantage here is the visualization of the alternatives, which clearly shows the weighing of different factors. In this way, the 3D DSS can provide a basis for discussion among representatives of various authorities, institutions (such as water and electricity companies) and associations (such as environmental associations) as well as other stakeholders to refine the alternatives in very early phases of the study of alternatives. The speed of the calculation of alternative corridors including a cost calculation as well as an aggregation of areas that involve high spatial costs is seen as an advantage of the tool.

The visualization of the modeling results with the 3D DSS is seen as a valuable basis for the discussion of alternative corridors with different stakeholder groups such as the population and government offices. It can help to have an objective discussion. By means of the 3D visualization of the TLs, it can illustrate the changes in the landscape context and also show, for example, where there is still room for ECs. However, the 3D visualization is also viewed critically, as those affected by a planned TL may feel the pylons are even more dominant than they actually are. In this context, the fact that pylons can also be moved by a few meters in 3D DSS is seen as a valuable feature. The tool can help those involved to understand which criteria and weightings led to the alternative corridors, which could increase acceptance. It is important, however, that the 3D DSS and, in particular, the 3D visualization are only used in a supportive manner and that it becomes clear that it is people who decide on the path of new TLs and not the tool.

Where and why there might be resistance against the use of the 3D DSS was answered with characteristics of the tool regarding its legitimacy, validity and credibility, relevance and costs. According to Cash et al. (2003), "legitimacy" refers to the fact that values and beliefs of different stakeholders are incorporated into the tool and conflicting interests are dealt with impartially and fairly, while "validity and credibility" is related to the adequacy of information. "Relevance" is related to the role of the tool for stakeholders in the planning process (Cash et al. 2003).

In terms of legitimacy, it is essential that the 3D DSS is not biased and that no weightings or restrictions in favour of one objective (e.g. nature conservation) dominate the other objectives. Possibilities for the user to control such settings are important, as otherwise, the feeling of being overridden by the machine could arise and thus the results of the modeling are likely to be less accepted. Another weak point is seen in the fact that emotions and fears or the local conditions on site cannot be represented in the algorithm and thus the actual trade-off of interests cannot be carried out by the 3D DSS. The complexity of the weighing of interests is very high and probably cannot be fully represented in the 3D DSS. There is a danger that too much trust is placed in the 3D DSS that "the right thing" comes out of it. Furthermore, the variety of weighting settings makes it possible to create many alternatives, each of which represents the best solution for different stakeholders. Hence, one difficulty is to agree on a common weighting with the stakeholders.

According to the results of the discussion, it is important for the validity and credibility of the 3D DSS that the basic data are accurate, that the settings of the parameters are validated and that legislation is taken into account. Overall, the tool must be "very good", as certain settings can influence the modeling results and in turn decisions that are made. In this context, the transparency of the tool and of the algorithms used also play a role. In particular, it is difficult to map the various technologies in the 3D DSS. It was also argued that in Germany the approval authority could not accept the 3D DSS as a planning basis.

The discussion about the relevance or role of the 3D DSS shows that it must be clear that it is used to support decision-making but not to make decisions. It is important to integrate the tool into the processes of "classical planning" and to use it especially for communication with stakeholders. Potential is seen in particular in the use of the 3D DSS with people who grow up with digital media. But also in situations where physical meetings are not possible, such as currently due to the COVID-19 pandemic, the 3D DSS can help to ensure that, for example, the advisory group process of the SÜL could be continued online.

One point that could also limit the use of the 3D DSS is the cost. However, as the 3D DSS is still under development, it is difficult to quantify the costs today.

The practical benefits of the 3D DSS were seen in the fact that ideas could be generated, planners could be given assistance, the trade-off of interests in the advisory group within the scope of the sectoral plan procedure and communication with other stakeholders could be supported, and finally planning processes could be accelerated. In particular, the rapid generation of ideas and potentially surprising suggestions can promote creative planning. With regard to the weighing up of interests, however, it should be borne in mind that existing TLs, such as that of Innertkirchen–Mettlen, were developed on the basis of ten criteria. Even today, the path of the TL is still judged to be not so bad. The question was therefore raised as to whether there is a limit to the sum of the criteria included in the modeling. It was emphasised that the benefit of the 3D DSS is to support communication, in particular by visualizing spatial resistances and providing better justification of solutions. It can also be shown that underground cabling is also visible in the landscape. A significant benefit of the 3D DSS was further seen in a gain in time, which is mainly due to the option that conflicts could be identified and resolved more quickly.

Suggestions for the further development of the 3D DSS, so that it can better meet the requirements of practice, concern on the one hand the data basis, but also plausibility and validity and user-friendliness. It was stressed that the database must be complete and it was recommended that data maintenance and updating should be simplified or automated. In addition, it was requested to check the plausibility of the models and to improve the algorithms with regard to the cost function and for calculating the earth cable lines, e.g. by taking into account different construction methods (micro-tunneling, drilling etc.). Additionally, it should be possible to justify why one alternative is better than the other, allowing a user to define, which circumstances trigger the choice of the transmission technology. With regard to user-friendliness, it was stated that the fewer "clicks" required, e.g. for setting the parameters, the better. It was wished "something like Excel to SAP". Finally, it was seen as a weak point of the 3D DSS that it is still too academic. In order to be used well in practice, the 3D DSS needs to become more generally understandable.

5 Conclusions and Outlook

The aim was to enhance the existing 3D DSS by developing an algorithm for modeling ECs and combined corridors of OL and EC sections, which is integrated into the user interface for visualization of the results. Further, the visualization functionality was expanded by 3D visualization of modeled ECs and existing underground infrastructure as well as further relevant information required by the project partners from practice. In addition, an AR solution was developed for visualizing virtual TLs at locations in the real world. The results were developed for case studies at different grid levels and evaluated in workshops with stakeholders from practice.

With regard to the modeling techniques, various approaches were developed and tested by carrying out several user studies that enhance semi-automated planning of TLs. First, the existing approach for modeling OLs was improved and adapted in a way that it considers special planning rules for ECs. Second, a unique approach was developed that identifies optimal CLs that consist of both OL and EC sections. As this novel method considers the planning logics followed by the SÜL procedure, several experts acknowledged it in a user study due to its reliability for correctly determining critical areas for OLs. Third, we investigated a novel method for generating path alternatives with a high spatial variability by using the same set of weights. The resulting approach uses linear programming and an algorithm for determining valleys in order to identify Pareto optimal solutions, which was appreciated by several experts in a user study. Fourth, we developed an approach that models ECs under streets and sidewalks by using an algorithm that applies linear programming on a network graph. Also this approach obtained positive feedback by the experts as it determines the optimal alternative based on objectives. Finally, we included an improved version of an existing algorithm into the 3D DSS that enhances the optimal placement of TTs.

In general, we shifted the notion of how costs are understood and defined by stakeholders from an abstract, attribute-centered view towards a hands-on procedure that focuses on objectives. Elicitation methods that allow to trade-off criteria or objectives against each other were well received by experts despite a higher expenditure of time compared to the direct rating method. Now, the extended decision model takes better into account legal distinctions between inventories under protection as well as criteria that must be considered in particular when planning ECs.

From a practice perspective, further transparency of the weighting of goals and criteria in the 3D DSS is required. This still seems to be too complex to be easily comprehensible. When implementing the 3D DSS, it needs to be explained in simple words how the cost calculation works.

Overall, the stakeholders from practice assessed the enhancements of the 3D DSS user interface with the advanced functionalities and 3D visualization of underground cables very positively. However, the level of detail for visualizing modelled ECs and existing underground infrastructure in the 3D mode of the 3D DSS needs further adaptations for specific applications. These user requirements should be further investigated. Furthermore, additional events that trigger the choice of a specific transmission technology should be defined. A data set required to improve the quality of the modeled TL should contain the information, whether a building or a places is considered to be an OMEN or an OKA, which does, however, not exist yet.

Yet, the 3D DSS does not take qualitative information on the landscape context such as landscape aesthetics sufficiently into account. Through the decision model, the landscape is divided into individual aspects. In order to provide also qualitative information on the landscape, the cantonal landscape strategies comprising maps of the cantonal landscape types and goals for their further development could be integrated as further information layer. Alternatively, the aesthetic value of the landscape coluld be estimated by a computational approach, as those proposed, for example, by Tenerelli et al. (2017). Ideally the maps of the landscape types should be available as web feature service (WFS) or web map service (WMS) of the cantonal GIS. Furthermore, the qualitative information needs to be prepared in a format useful for the analysis of alternative TL scenarios with the 3D DSS.

The development and enhancement of the 3D DSS based on different case studies has proved to be an effective way to specify the requirements of the potential users and to get helpful inputs and feedback from practice on the modeling algorithm and the visualization of the results and further information. This approach should be maintained for further adaptation of the 3D DSS to the users' needs. The results of the 3D DSS – EC project can be used by research institutes (e.g., ETH Zurich) to investigate open research questions in the domains of Geographic Information Science, Spatial Planning, or Energy Engineering. Companies devoted to spatial planning (e.g., EBP, Basler & Hofmann, or smaller start-ups), energy planning (e.g., Bouygues, AFRY, or SCS), or software production (e.g., Gilytics, Adaptricity, or Esri) as well as Federal and Cantonal offices or TSOs/DSOs might use an open source version of the 3D DSS in order to enrich their product portfolio or to enhance the quality of what the 3D DSS is aimed at: supporting planning, analysis, and communication of new TLs.

6 National and international cooperation

This research was funded by the SFOE and by the grid operators Swissgrid, Elia Power Systems, and ewz, from which we further received helpful support concerning legal and technical issues. This helped us to profoundly investigate this topic by means of state-of-the-art knowledge form practice. Furthermore, we regularly shared our research findings on the events hold by the Swiss Competence Center for Energy Research on the Future Swiss Electrical Infrastructure (SCCER–FURIES).

Within the scope of this research and in addition to the SFOE, we further collaborated with the federal offices ARE, FOCP, and FOEN, which supported us regarding legal and technical issues. Moreover, we received support regarding technical issues from the Swiss Federal Institute of Aquatic Science and Technology (Eawag) and from the High Voltage Testing an Engineering Commission (FKH).

On an international level, we manly collaborated with our project partner Elia Power Systems (Belgium), but shared our findings also at the scientific dialogues hold by the German Federal Network Agency. Furthermore, we were invited twice to present the state of the art of our research together with representatives of our project partner Swissgrid at the largest conference for grid extension projects in the German speaking area, the “Forum Netzausbau,” hold by the Tagungsgesellschaft mbH Energie. Finally, we presented the 3D DSS on an international level within the scope of the “good practice in grid development webinar” series hold by the Renewables Grid Initiative (RGI) and the European Network of Transmission System Operators for Electricity (ENTSO-E).

7 Communication

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10 Appendix

10.1 Workshops with Project Partners - Programs

10.1.1 Program «Workshop ewz»

3D DSS zur Unterstützung der Planung von elektrischen Versorgungsleitungen: Integration von Erdkabeln - Workshop mit ewz

Termin: Donnerstag, 10. Januar 2019, 13.00 – 17.00 Uhr

Ort: ewz, Pfingstweidstrasse 85, 8005 Zürich, Raum WHA 412

Ablauf des Workshops

13:00 – 13:10: Begrüssung und Programm

13:10 – 13:30: Präsentation «3D-DSS Erdkabel»

13:30 – 14:00: Case Study und Datengrundlage ewz (Diskussion, 30')
• Welches Untersuchungsgebiet soll aufbereitet werden? (Stadt Zürich → Gibt es Gebiete, die besonders genau angeschaut werden sollen?)
• Wer soll mit dem 3D-DSS arbeiten?
• Für welche Planungssituationen soll das 3D-DSS eingesetzt werden? Ziele? (z.B.: Räume für zukünftige Leitungskorridore und Umspannwerke/Umwandlungsstationen identifizieren. Visualisierung sämtlicher Gewerke im Untergrund.)
• Wie soll in den Planungssituationen die Zusammenarbeit aussehen? Wer verwendet das 3D-DSS zu welchem Zweck?

14:00 – 15:00: Datenmodell und AR/VR (Diskussion, 60')
• Wie sollen bestehende Leitungen zusammengefasst und visualisiert werden? Welcher Detailgrad ist sinnvoll? Welche Erwartungen bestehen?
• AR auf mobilen Geräten: Wie wird der erste Prototyp aufgebaut?
• Welche Datensätze sollen zusammengefasst werden?
• Mit welcher Genauigkeit sollen die zusammengefassten Datensätze generalisiert werden?
• Wie sollen die Kategorien für die Tiefen für die Generalisierung festgelegt werden?
• Welche Breite soll für die Korridore angenommen werden?

15:00 – 15:20: PAUSE (20')

15:20 – 16:00: Entscheidungsmodell (Diskussion, 40')
• Welche Kategorien und Faktoren werden berücksichtigt? Bleiben die Faktoren über das Projekt gleich? Welche Ziele werden von den einzelnen Faktoren verfolgt?

• Auf welcher gesetzlichen Grundlage basieren sie? Welche Faktoren werden wie stark gewichtet? Gibt es hier gesetzliche Vorgaben?
• Wie wird entschieden, an welchen Orten die Übergangsbauwerke erstellt werden?

16:00 – 16:30: MCDA-Methode (Diskussion, 30')

• Wie müssen die unterschiedlichen Bauweisen für die Ermittlung des optimalen Pfads berücksichtigt werden?
• Wie soll das Modell zur Gewichtung der Faktoren aussehen? → Diskussion von Alternativen.
• Mit welcher Methode soll der Raumwiderstand für Erdkabel berechnet werden? → Diskussion von Alternativen.

16:30 – 16:55: Kostenmodell und Metriken zur Analyse (Diskussion, 25')

• Wie berechnen sich die Kosten für Erdkabel? Welche Parameter beeinflussen die Kosten?
• Mit welcher Metrik sollen unterschiedliche Varianten miteinander verglichen werden? → Diskussion von Alternativen.
• Wie sollen die Metriken dargestellt werden?

16:55 – 17:00: Zusammenfassung, nächste Schritte und Abschluss des Workshops (alle, 5')

10.1.2 Program «Workshop Swissgrid»

Termin: Mittwoch, 23. Januar 2019, 08.00 – 12.00 Uhr

Ort: Swissgrid, Bleichemattstr. 31, 5000 Aarau, Raum A03 (14P)

Ablauf des Workshops

08:00 – 08:10: Begrüssung und Programm (Stefano und Ulrike, 10')

08:10 – 08:30: Präsentation «3D-DSS Erdkabel» (Joram, 20')

08:30 – 09:00: Case Study und Datengrundlage Swissgrid (Diskussion, 30')

- Wie soll der Untersuchungsperimeter zwischen Innertkirchen und Mettlen festgelegt werden?
- Welche Korridorbreite soll angenommen werden?
- Für welche Planungssituationen soll das 3D-DSS eingesetzt werden? Ziele? Erwartungen?
- Wie soll in den Planungssituationen die Zusammenarbeit aussehen? Wer verwendet das 3D-DSS zu welchem Zweck?

09:00 – 09:50: Datenmodell und AR/VR (Diskussion, 50')

- Wie sollen bestehende Leitungen zusammengefasst und visualisiert werden? Welcher Detailgrad ist sinnvoll? Welche Erwartungen bestehen?
- AR auf mobilen Geräten: Wie wird der erste Prototyp aufgebaut?
- Welche Datensätze sollen zusammengefasst werden?
- Mit welcher Genauigkeit sollen die zusammengefassten Datensätze generalisiert werden?
- Wie sollen die Kategorien für die Tiefen für die Generalisierung festgelegt werden?
- Welche Breite soll für die Korridore angenommen werden?

09:50 – 10:10: PAUSE (20')

10:10 – 11:00: Entscheidungsmodell (Diskussion, 50')

- Welche Kategorien und Faktoren werden berücksichtigt? Welche Anpassungen am Entscheidungsmodell sind nötig? Bleiben die Faktoren über das Projekt gleich?
- Welche Ziele werden von den einzelnen Faktoren verfolgt?
- Auf welcher gesetzlichen Grundlage basieren sie? Welche Faktoren werden wie stark gewichtet? Gibt es hier gesetzliche Vorgaben?
- Wie werden Orte mit erhöhtem Konfliktpotential identifiziert?
- Wie wird entschieden, an welchen Orten die Übergangsbauwerke erstellt werden?
- Wie müssen die unterschiedlichen Bauweisen für die Ermittlung des optimalen Pfads berücksichtigt werden?

11:00 – 11:30: MCDA-Methode (Diskussion, 30')

- Wie soll das Modell zur Gewichtung der Faktoren aussehen? → Diskussion von Alternativen.
- Mit welcher Methode soll der Raumwiderstand für Erdkabel berechnet werden? → Diskussion von Alternativen.
- Soll Direct Rating oder der Analytical Hierarchy Process angewandt werden?

11:30 – 11:55: Kostenmodell und Metriken zur Analyse (Diskussion, 25')

- Wie berechnen sich die Kosten für Erdkabel? Welche Parameter beeinflussen die Kosten?
- Mit welcher Metrik sollen unterschiedliche Varianten miteinander verglichen werden? → Diskussion von Alternativen.
- Wie sollen die Metriken dargestellt werden?

11:55 – 12:00: Zusammenfassung, nächste Schritte und Abschluss des Workshops (alle, 5')

10.1.3 Program «Workshop Elia»

Date: Thursday, 24. January 2019

Place: Elia, Boulevard de l'Empereur, 20 - 1000 Brussels - Room EMP 1.08 (25P)

Proceeding of the Workshops

09:00 – 09:10: Welcome and program (Stefano, 10')

09:10 – 09:30: Presentation «3D-DSS Earth Cables» (Stefano, 20')

09:30 – 10:00: Case study and data base (Discussion, 30')

- How should the case study perimeter be determined?
- Which corridor width should be assumed?
- For which planning situations should the 3D-DSS be used? Goals? Expectations?
- What should the cooperation look like in the planning situations? Who uses the 3D-DSS for what purpose?

10:00 – 10:50: Data model and AR/VR (Discussion, 50')

- How should existing lines be combined and visualized? Which level of detail makes sense? What are the expectations?
- AR on mobile devices: How is the first prototype set up?
- Which data sets should be combined?
- With what accuracy should the summarized data sets be generalized?
- How should the depth categories for generalization be defined?
- What width should be assumed for the corridors?

10:50 – 11:10: PAUSE (20‘)

11:10 – 12:00: Decision model (Discussion, 50‘)

- Which categories and factors are considered? Which adjustments to the decision model are necessary? Do the factors remain the same throughout the project?
- Which goals are pursued by the individual factors?
- On what legal basis are they based? Which factors are weighted to what extent? Are there any legal requirements?
- How are locations with increased conflict potential identified?
- How is it decided at which locations the transition buildings (Übertragungsbauwerk) will be constructed?
- How do the different construction methods have to be taken into account to determine the optimal path?

12:00 – 12:30: MCDA method (Discussion, 30‘)

- What should the model for weighting the factors look like? Discussion of alternatives.
- Which method should be used to calculate the space resistance for underground cables? → Discussion of alternatives.
- - Should *Direct Rating* or the *Analytical Hierarchy Process* be used?

12:30 – 12:55: Model of the costs and metrics for analysis (Discussion, 25‘)

- How are the costs for underground cables calculated? Which parameters influence the costs?
- Which metric should be used to compare different alternative solutions? → Discussion of alternatives.
- - How should the metrics be presented?

12:55 – 13:00: Summary, next steps and conclusion of the workshop (all, 5‘)

10.1.4 Program «Workshop mit Begleitgruppe»

Als ein Resultat des Workshops mit Swissgrid wurde ein weiterer Workshop organisiert, der aufzeigen soll, welche Ansprüche die Begleitgruppe an das 3D DSS hat.

Workshop 3D DSS: "Planungssitzung zur Bestimmung eines geeigneten Korridorverlaufs"

Termin: Montag, 4. Februar 2019, 14.00 – 17.00 Uhr

Ort: BFE Bern, Sitzungszimmer _UVEK-Sizi_1.00.082-B

Agenda

1. Begrüssung und Einleitung (Swissgrid)
2. Ablauf Begleitgruppensitzung heute und mögliche Answendung 3D DSS im Sachplanverfahren (Alle)

Pause

3. Weitere Anwendungsmöglichkeiten 3D DSS (Alle)

10.2 Summarized results of workshops with project partners

10.2.1 Case study and data base

How should the case study perimeter be determined? Which corridor width should be assumed? For which planning situations should the 3D-DSS be used? Goals? Expectations? What should the cooperation look like in the planning situations? Who uses the 3D-DSS for what purpose?

ewz	**Perimeter:** • Oerlikon - Hoenggerberg, Leimbach (Border of the city of Zurich) • Special focus: Waldegg - Sihlfeld **Planning focus:** • The supply to the city of Zurich is in revision. With the future substation (Unterwerk) Waldegg new pipe blocks for earth cables are required (left of the Limmat, Sihlfeld, Altstetten). As in future, there will be only three supply points, redundant cables need to be established in order to ensure grid stability in the city of Zurich. For example, new cables are required between Waldegg and Sihlfeld and maybe Frohalp. • Parts of the pipe blocks (90%) are already available for Waldegg. The 3D DSS could be used to prove whether the path is optimal. Particularly because not all existing pipe blocks fulfill the NISV. • Does it make senses to use or alter existing pipe blocks? Where is the NISV violated? Where are new pipe blocks required? • If new pipe blocks need to be built, how deep does the pipe block need to be and how do the cables need to be arranged (Tiefe und Bauweise)? **Requirements:** • The 3D DSS shall provide rough paths (ideas/scenarios); the engineer does the detailed planning.
Swissgrid	**Perimeter:** • Innertkirchen – Mettlen (including Entlebuch, Glaubenberg, Oberwalden, Melchtal) • Substations Littau and Giswil need to be in the perimeter. The earth cables need to go to these substations. **Planning focus:** • Purpose of the 3D DSS is to support the advisory board of the sectoral plan procedure and, when the corridor is defined, to inform and participate the local public for finding a suitable path. In the latter phase, the 3D DSS shall be used in the dialogue with the local council and also with individual stakeholders directly affected by the power line. Hence, the major purpose of the 3D DSS is to support communication. • After the planning area is defined, the search for an area for the corridor takes place. The advisory board wants to know the reasons for the corridor selection as well as the amount of earth cables in the right and left side of

	the valley. It is discussed in which parts earth cables make sense in the whole planning area. Different suitable areas for power lines are discussed and how they can be connected. This means, a selection of alternative corridors needs to be discussed. • The advisory board just looks at the area in which cables are required respectively not required. The transition buildings are of minor relevance. • The advisory board has the role of weighting and negotiating different interests. • There may be too many alternatives for the advisory board to compare. The 3D DSS could have an added value if it helps to focus on the most important alternatives ("In der Diskussion die Varianten auf den Punkt bringen."). The most interesting alternatives to discuss are the ones that have major differences in the path. • Swissgrid uses 3D DSS and elaborates 2-3 alternative corridors. Then the advisory board assesses these alternatives. They are also going to the field to evaluate the alternatives also from a landscape perspective. The discussion of alternatives in the advisory board meeting serves for thinking through the impacts. The 3D DSS can support this process but it cannot replace it. • The large number of possible solutions is created by the question where overhead lines and where earth cables are required. The 3D DSS cannot help in reducing these alternatives. However, it might assist the evaluation of the alternatives. Therefore, it needs to follow the assessment scheme (Bewertungsschema). **Requirements:** • The model needs to take into account all relevant factors because it should support a decision, which is according to the law. Therefore, public interests cannot go into the analysis. It is not the primary goal to enhance acceptance of the local public but court-proof decisions. During the SÜL the public acceptance is only a minor part. A negotiation of different stakeholder's interests has to take place with the public being one of the stakeholders. • The environmental resistances for power lines (environment and spatial development) are more important than technical aspects and costs. In order to find alternative corridors, the costs should not have too much weight. They should rather be used for evaluation. • The tool shall be operated predominantly by the service company (Gilytics). The tool is currently too complicated to be operated by Swissgrid. However, the tool should be designed so that Swissgrid could operate it himself in order to demonstrate something. • The tool should be as simple as possible.

	• The tool shall support Swissgrid in their planning process. It should help to design initial corridor alternatives. • The tool should provide alternative corridors in a form that supports the advisory board in thinking through the individual alternatives, their discussion and comparison with other alternatives. • When implementing the 3D DSS, the missing data (e.g. qualitative information on landscape aesthetics) must not be neglected! – The landscape context is not taken into account. The problem is that the tool separates the landscape into single aspects. • The results of the 3D DSS shall not overrule the arguments of the advisory board. • The tool might need a bi-directional access so that an upload of own solutions is possible. The tool should then provide the according weighting of the factors. • The tool needs to follow the assessment scheme of the advisory board. If criteria are not integrated in the 3D DSS it needs to be made explicit where the tool cannot provide a basis for the discussion. • The tool shall allow to superimpose alternative corridors. • The tool shall not be used in the advisory board to calculate new corridors. • The tool shall show the corridors for overhead lines / for earth cables / for the combination of both. • The tool shall help in assessing, which combinations do make sense. • For the advisory board the tool needs to show the layers that led to a shown alternative. It needs to be made plausible why the tool came to a certain alternative. → Functioning of the tool needs to be clear for the members of the advisory board. However, the documentations are too scientific. The system needs to be communicated with simple words and it needs to be easily understandable why the tool comes to a certain solution. It needs to be possible for the advisory board to explain in an evaluation process that the tool came to this solution because of certain parameters, which were defined in certain ways. • The advisory board does not want to play with the tool. • Default values of the resistances shall be set in the tool. ETH / Swissgrid need to define these values according to legal requirements. • A workshop shall be organized with the advisory board (BAFU, BFE, ARE, maybe Elcom) in order to demonstrate the tool and for the advisory board to understand the effects of different weightings.

Elia	**Perimeter:** • Vlanders and Wallonie • Case 1: Point 1: Poederlee (Substation), Point 2: Heerentals (Substation). New industry and they ask for more capacity. Elia needs to bring 150kV to Heerentals and then from Heerentals to Poederlee. • Case 2: Denoult (Substation) going to Ravels (Substation). Between these two cities an earth cable is required (70 kV). **Planning focus:** • 380 KV is overhead lines; no overhead lines below 150 kV; 70 kV and 36 kV are always earth cables. • Elia has a lot of projects on underground cables (30 projects; currently 17 new earth cable projects), therefore they need the 3D DSS. • Community relation managers and engineers will use the 3D DSS. • Elia receives a project from developers. The developers decided already that there is an underground cable between two sub stations. Engineers look at a map to find several alternatives. Then a community relation manager goes on site and looks which alternative is best to construct and talks with the local communities. For them it is very good to have arguments why an alternative is best (transparent arguments). • A road is a public area and Elia can construct cables there with a low permit procedure. When they go to the private land, they need to discuss and exercise the environmental impact assessment. Then it is the Vlamish government to approve the path. When it is only 10% on private land, the permit on private land is no problem. • Communication: Elia analyzes how many communities are affected. Then they find out the community majors and have several meetings with them. When the majors are positive, 90% of the permit is okay. For national roads, the Vlamish administration is looking after the roads. In this case, Elia takes the plan and asks for an official letter. • When a new substation in the green field near housing is required, Elia organizes an evening (17 – 20h) for the population, communicating the planning procedure with brochures and answering questions. • If the people are against a power line/earth cable, they need to argue, why they are against the lines. The government decides what to do with this information. • For Elia it is interesting if they can put the cable into the road. It is then the task of the engineer to make the detail planning. • Elia has the problem that they do not have a tool that draws all the alternatives together to support a good argumentation for or against a certain path.

	Requirements: • The tool needs to be very simple! • Elia is interested in the path, not the corridor. • For a cable going from A to B, Elia is interested in the indicators of how many km in living/agriculture/natural environment/how many houses and people are affected.

10.2.2Data model and AR/VR

How should existing lines be combined and visualized? Which level of detail makes sense? What are the expectations? AR on mobile devices: How is the first prototype set up? Which data sets should be combined? With what accuracy should the summarized data sets be generalized? How should the depth categories for generalization be defined? What width should be assumed for the corridors?

ewz	**Data:** • Data of underground objects available from administrations in standardized format (INTERLIS) • Information on pipe blocks, how many cables are already there, and depth of the available empty pipe blocks. • There is no data set for OMEN. In actual projects, the radiation is calculated with real world parameters taken from the site. For example, if there is a bedroom the distance for a higher radiation protection is required. **Visualization:** • Seeing what is below ground in an interactive way. • Show 2-3 scenarios for comparison. • Show buildings (TLM 3D was desired). • Show conflict buffer around building (NISV; e.g. 10m, 5m,…). • Width of the path: 1.25m • Streets are the corridors because in most cases the pipe blocks are built under the streets, as they are public ground. • Elements underground should be visualized as lines and boxes. • Cables have the information of the middle line and their width but no diameter. This needs to be calculated. • Pipe block as box and the cables (lines) that are in the box. • Pipe block (single): 60cm height x 62,5 cm width (double: 1.25 width) • Access points is available as 3D model (= box). Either 2 or 5 access points because the segments need to be either 3 or 6 equally long sections. In general, access points need to be located in the sidewalk. Private ground

	is also possible (forecourt or garden) because the city is allowed to build up to a distance to 5 m from the building. • Possible underground areas for building new pipe blocks and cables might be visualized as Voxel models. 4-5 layers of depth. At the top with finer cells and at the bottom with larger cells. **AR:** • Does not matter if VR on Laptop or AR. Laptop needs to be possible. • Cables will be displayed as line on the ground in the initial prototype. Then the required level of detail will be further discussed with the user.
Swissgrid	**Data:** • Data for underground infrastructure will be provided by Swisstopo. • Geological Atlas provides information on soil layers up to 15 m depth. Generally, there is 1-2 m of topsoil, and then Molasse follows. • Data of cantonal underground infrastructure is not available Swiss-wide. Very heterogeneous and partly incomplete data sets. • Include layer on landscape concepts (Kantonale Landschaftskonzepte) as info-layer for assessing the alternative corridors. **Visualization:** • For the sectoral plan procedure only 2D visualizations are required. • Corridor width needs to be displayed with varying width (no line with equal width). Provide the mean of the corridor values for defining the width. In the end, the advisory board defines the corridor width. When the corridor width is too narrow, there is no scope left for defining the path. • Individual values of resistances should be interactively shown in the visualization because users want to know why the resistance is high at specific locations. • Data of the overhead power line design program PLS CADD (http://www.powline.com/products/pls_cadd.html) should be importable into the 3D DSS for comparison of designs. • Show overhead power lines, transition buildings, magnetic field of the earth cables (1 microtesla (μT)), access points (Muffenschächte), pipe blocks (Rohrblöcke) and single cables (Phasen) in order to show threshold values (Anlagengrenzwerte). • Level of detail does not need to be very high for earth cables. For overhead lines a higher level of detail is more important. • Show earth cable and the electromagnetic field in form of lines on the left and the right side, which is a no-building or clearance zone (Freihaltezone) also for trees. The electromagnetic field can easily be calculated if it is linear. If two cables run in parallel or cross each other it becomes difficult.

	Crossings should not be regarded in the 3D DSS prototype. The visualization should not be seen as a prove that the magnetic field is according to the law but just as a visualization. **AR:** • AR does not have first priority. • Might be useful in the common inspection of a possible path at the local site (but not for the sectoral plan process). • Might be interesting for landowners. • Maybe interesting for maintenance. • Should not be offered for public download. • For optimizing a planned path by moving a pylon etc. interactively. • The added value is that the visualization is closer to reality. • A scenario could be that people download an app, stand at their window and look at the overhead power line. • Might be interesting for public planning with project opponents. • During inspection of the plan by all interest groups (aufgelegte Variante) • AR maybe helpful for individual questions during the discussion of the corridor. E.g., how does the overhead line look like on very steep slopes, e.g., at Innertkirchen.
Elia	**Data:** • Gilytics has the data for Vlanders and Wallonie for overhead lines. Data on underground infrastructure is missing. • No common data basis for Vlanders available; for each region Elia has to ask what the underground data are. They get this information mostly in form of paper maps. Everyone who has underground cables has to provide the information. Making the data available is associated with costs. • The online-platform of Vlanders (http://www.geopunt.be) provides many layers that are important for Elia. Download of LiDAR data is also possible. • For Wallonia the data layers are provided for free. • The zoning plan is very important. The blue zones are for Elia (Gebieden voor gemeenschapsvoorzieningen en openbare nutsvoorzieningen) to build substations. • Gewestplan (Vector data), all Natura 2000, GRB (roads and natural roads) • Elia has a GIS database. If ETH/Gilytics need data, Elia can extract them. • Existing cables: Elia-Website = network of Elia available for download. Elia > Publicities > Maps > grid of 2017 (PDF)

	• Gilytics suggests to include CAD data because they provide further detailed information. Conversion into shape files is possible. – But CAD data are not used for visualization purposes. • Gilytics suggests to use Sentinel 2 satellite data for the visualization in collaboration with ESA. **Visualization:** • Two tasks for visualization: (1) Before permit = map okay with some statistical data. (2) When permit is obtained and communication with public = professional visualization required. – In the first task, engineering should be supported, where they have to look at all the databases. Afterwards, when a compromise is found, then the public communication starts. The first task is more important. • Current visualization tool: alternative paths are shown as overlay = „human elements" (electromagnetic fields; buffer of noise; ... schools, sport centers,...) are also visualized. • Maximum length for each section of a cable: 700m • Every 700m they put a conjunction (3m width x 10m length) and they have access to this. Earth cables are put into the road at the side and this needs a space of approx. 1m. • The grid of substations is already available. • Heat map of the quality: For underground cables: 100 m buffer (50m on both sides of the cable for these indicator maps). Base heat map on how many km public roads, private roads, natural area crossed; how many population is affected. • Electromagnetic field: Visualization is not required. Only if this is demanded. People get information in written form. When they have questions and need a visualization, Elia does it but only according to these requests. – For overhead lines the electromagnetic field should be calculated with the formula of Elia (123-321) and the result should be shown in 2D. Important information on the electromagnetic field: 200 Microtesla are the limit. 10 Microtesla = a house becomes uninhabitable. 0.4 Microtesla is admissible everywhere. • Natura 2000 areas: With 1km - 5km of earth cables in a protected zone an environmental impact assessment is necessary, below 1km it is no problem. • Substations cannot be set directly on the border between Vlanders and Wallonie. They need to be on either side. • Substations vary in size according to the type (150 kV; 70 kV; 38 kV). 3D models are available. Their visualization should not be too abstract. The standard building is an industrial building with a sort of cover (they put something around). When a politician asks for another building, Elia tries

	to find a compromise. Size of the building needs to be the same, external part can be designed, e.g. with bricks. Green roofs are not possible for Elia. • For the population it is good to see the bird's eye view and to see where they live and where the cable comes through. • The street view is not necessary, because once the cable is built you do not see it any more. • Zoom into the area. The environment needs to be visualized (like in Google Earth). In Google Earth you have not always the recent images. It is important to see the most recent state of the environment. **AR:** • AR/VR is a priority for Elia. • AR is important for overhead lines and new substations, not for earth cables. Elia should decide which options can be made public for AR. One problem is that smart phones are not exact in displaying the correct height if you are in a building. In Belgium the error when watching from the ground is 2-3m. For the intended visualization purpose this was not seen as problematic. • For overhead lines the electromagnetic field should be taken into account. Elia should provide the formula for calculation (new approach 123 – 321) in order to ensure that the right formula is used.

10.2.3 Decision model

Which categories and factors are considered? Which adjustments to the decision model are necessary? Do the factors remain the same throughout the project? Which goals are pursued by the individual factors? On what legal basis are they based? Which factors are weighted to what extent? Are there any legal requirements? How are locations with high potential conflict identified? How is it decided at which locations the transition buildings (Übergangsbauwerk) will be constructed? How do the different construction methods have to be taken into account to determine the optimal path?

ewz	**Factors:** • Do not go under the minimum radius (40cm; guidelines 30x cable radius) • Minimum bend radius: 1.6-2m; 2.5m • Tramways can be crossed. • Building cables below tramways is only possible in theory. • Constructing cables underneath buildings is possible as long as the NISV is not violated. But for the model: Do not go under buildings. • The further away from other infrastructures the better. For example, if an earth cable is over a water pipeline and the latter needs to be revised, the pipe block needs also to be put out of operation.

	• If all earth cables run in one pipe block this is not good because if this pipe block needs to be put out of operation all these paths are targeted. • Crossing waterways is difficult. • Crossing trees is difficult. Costs per tree = approx. 20’000.- for cutting roots • Schools and hospitals are sensible buildings and should be avoided when new paths are planned. • When the street pavement is new, for 5 years no construction in the street is approved. However, this is no strong argument because building time of an earth cable is about 20 years. • NISV: The closer to a building, the higher is the resistance for a cable. Minimum distance to a building is available but the design of a pipe block matters as well. → Approximation based on the building: User defines degree of punishment based on how close the cable comes to a building. Choose the pipe block type after a path is found. • Standard pipe blocks (Normrohrblock): Calculation with 430 and 600 Ampere. Radiation is about 9.5m. With two parallel cables, the radiation field is bigger than 2 x 9.5m due to interactions. → ewz provides calculations for such cases. • OMEN: Take sum of distances to the building because then the calculation of NISV is avoided. • The closer to district heating pipes the worse for cables. • The less turns the better. • The shorter the cable, the better (Costs for pipe block with cable: 600.- CHF /m cable + 1000.- CHF /m for laying the cables + 10% costs for planning) • The cable should not be longer than 1000m • Factor of symmetry of segments (1 = all with same length) **Indicators for evaluation:** • Indicators related to elements that are increasing the costs: – Length of cable segments – Depth of pipe blocks – Amount of access points / Amount of segments – Amount of crossings – Amount of curves/bending (how straight the path is) – Expected traction (erwartete Zugkraft) – Amount of conflicts with defined buffers around buildings – Strength of the conflict (e.g. with other infrastructure) • Violation of OMEN

	• Quality of the path: – Relation of cable length and regularity of the segmentation of sections – Amount of curves (better: few small curves than one big curve) – Amount of parallel running infrastructure • Percent of areas with certain land use the cable runs through.
Swissgrid	**Factors:** • One cable length = 1 km • The less system transitions, the better (Möglichst wenig Systemübergänge). • Good: with a cable into the substation. • 3 alternative construction methods: pipe block, flushing, tunnel (Rohrblock, Spülung, Tunnel); Effect on the soil is assessed by BAFU • Resistance per meter cable / power line • Area required for transition building (Übergangsbauwerk). Placing the transition buildings needs enough area. • Costs per cable (Einheitspreis) • Costs per type of transition building, defined per line (Einheitspreis) • NISV-distances to building and to forests • Close to a forest is good because this disguises the power line but not in the forest. • Costs for forest cutting (Einheitspreis) • Costs for 1km earth cable: 10-20 Mio CHF; 1 km power line: 2 Mio CHF • Do not construct earth cables in the streets but along the streets. • Do not construct earth cables directly along highways due to the existing infrastructure for ground water protection located in the service lane. • Forest needs to be cleared. Therefore, the resistance value is high for constructing earth cables. However, low construction costs. But maintenance costs. • Crossing of gas pipe lines is difficult. Distances need to be ensured. • Norms (NISV, national protected areas) • Catalog of the sectoral plan (SÜL-Katalog): no new paths that cut others; concentration of infrastructure → these are of high importance from a legal view • The function “traversing” (Überspannen) should be included.

	Indicators for evaluation: • Calculating costs is very difficult because it needs to include also approximations for restoration and compensation. It is not realistic that the 3D DSS provides the numbers on that.
Elia	**Factors:** • How many people live at the public roads? The less people the better is the earth cable scenario. • Natura 2000 areas (all elements of nature): In these areas earth cables are not possible. • The earth cables should not overlap with buildings for housing due to the magnetic field. Industrial buildings are not a problem. Electromagnetic field: 3m buffer is suitable to simulate the magnetic field of 150 kV cables. In case of two cables, the buffer needs to be doubled. • Under the roads are only the water and wastewater pipes, and other underground infrastructure is on the site. • National roads are used for overhead lines; at highways, 30m earth cables are allowed at the side. Overhead lines along highways is not possible. Earth cables are allowed in community roads. Earth cables are laid into the road requiring space of approx. 1m width. • Rivers/Canals/Railways: Cable can go underneath. Cross national road: Drilling is possible. Earth cables cannot be built on bridges. • Earth cables of 30 km length are no problem. Maximum length for each section of a cable: 700m. Every 700m there is an access point (3m width x 10m length). • A dense grid of substations is already available. They have approx. 20 – 30 km distance. Substations types are specific for each kV type (150 kV, 70 kV, 36 kV). The noise of substations must be in the legal limits. Near a natural environment the limits are lower than near industrial areas. Substations cannot be built in areas with risk of high-rise waters. • When earth cables cross a garden, then a 3m zone for the cable is required, which is bought from the land owner. For 2 cables, a zone of 6m width is required. • Regarding costs it is better to build in „green land", but concerning the permission it is better to avoid private land. • The raster to be used for the decision model needs to be very fine grained. Resolution: 2-5 m, because the fine distances in the land use need to be taken into account. • All layers and buffer distances shall be assigned based on the law or expertise of the engineers.

	Indicators for evaluation: • Amount of communities at the path • Kilometers of public / private roads used • Amount of people living at the public roads / people affected • Amount and area of Natura 2000 areas crossed • Amount of private land at the path crossed • Costs: Earth cable = 4x cost of overhead line; 2 Earth cables = 6x cost of overhead line; Earth cable = 1 Mio per km; 2 cables = 1.5 Mio per km (depending on the cable type; greatest costs are the cable costs); Costs of an open construction and drilling is today the same.

10.2.4 MCDA method

What should the model for weighting the factors look like? Discussion of alternatives. Which method should be used to calculate the space resistance for underground cables? Should *Direct Rating* or the *Analytical Hierarchy Process* be used? Model of the costs and metrics for analysis. How are the costs for underground cables calculated? Which parameters influence the costs? Which metric should be used to compare different alternative solutions? How should the metrics be presented?

ewz	**Weighting and Resistances:** • Resistance of the depth: minimum depth is 50 cm (by law); maximum depth is 10m (below earth cables make no sense) • 4-5 depth layers shall be defined for analyzing whether infrastructure is in these layers. • Summarize the resistances.
Swissgrid	**Weighting and Resistances:** • Alternative “Buffers” around factors (as decided 4 years ago) is good. Alternative “Sharp edged” needs to be available as well. • Simple Additive Weighting. This calculation is easy and transparent and the protection objectives are met in most cases. • Definition of terms. Categories and Factors are not used in practice (Kriterien = Faktoren, Kriteriengruppen, Pfeiler = Kategorie). Make a Cross-Reference-Table because the 3D DSS is used in different countries and the terms should work for all users. • Resistances shall be set according to the law. Weighting shall be done by the user/stakeholder. Additionally, a weighting of major goals shall be possible. The user chooses the major objective and the tool sets the weightings accordingly. If the objective gets a high value (e.g. 3), the tool gives the according factors also a high value. A differentiation in primary and secondary factors shall be possible (tool gives different values to these factors). For factors belonging to different goals, the weighting needs to be

	treated in a special way, because the factors are not necessarily very important (e.g. dividing the weighting value in half; use a scale from 0-10 to set weightings). • It is important that the rulers of setting the resistances cannot be misused in order to tweak the results in the desired direction. Therefore, only weightings should be variable. The weighting should be set according to the overarching objectives. • Only the major objectives shall be integrated in order to keep the 3D DSS as simple as possible. • Intangible values such as landscape aesthetics need to be weighted as well so that they can be contrasted with the costs. In this way the costs for the protection of an area are demonstrated. • The advisory board suggests that Swissgrid (together with ETH) shall define the default values for resistances. • A workshop with the advisory board shall be organized by Swissgrid for demonstrating the tool and for the advisory board to understand the effects of different weighting scenarios.
Elia	**Weighting and Resistances:** • The MCDA method should be the same as in Austria or Switzerland because in Belgium the general approach is the same. Hence, simple additive weighting is okay. • The weighting needs to allow a bigger value in city areas with higher population. • Different weights need to be applied for Wallonia/Vlanders. Parameters are different and the common point of conjunction on the border needs to be found. Substation can only be on either side of the border, not on the border.

10.3 Final Workshop and Evaluation

10.3.1 Program – Workshop 3D DSS – Freileitung oder Erdkabel?

Geografische Informationssysteme (GIS) ermöglichen die Berechnung und Visualisierung von Stromleitungskorridoren in 3D. Bestehende Ansätze beschränken sich jedoch auf Freileitungen. Ziel des Projekts 3D DSS ist es daher, einen integrativen Ansatz zu entwickeln, der Freileitungen und Erdkabel unter Berücksichtigung geologischer, infrastruktureller, ökologischer sowie sozioökonomischer Aspekte in einer 3D-Web-GIS-Plattform kombiniert.

Die Resultate aus mehreren Erdkabelstudien würden wir gerne vorstellen und mit Ihnen Erfahrungen austauschen.

Zeit	17.11.2020, 13:30 – 16:00
Ort	Online
Teilnehmerfeld	Leitungsplanung und –bau; Prüfung, Beurteilung, Bewilligung von Leitungsplanungen; Kommunikation mit Interessenvertretern; Begleitung SÜL
Ziel	**Weiterentwickelte Ansätze des 3D DSS präsentieren und aus Praxissicht diskutieren und bewerten**

Programm

13:30 – 13:35	Begrüssung und Programm (5' Martin Raubal/ Philippe Bieri)
13:35 – 14:25	Hybride-Planung Erdkabel-Freileitung Höchstspannung (10' Joram Schito; 8' Ulrike Wissen)
	Erdkabel-Planung im Verteilnetz in städtischem Gebiet (10' Joram Schito; 7' Ulrike Wissen)
	Erdkabel-Planung auf Mittelspannungsebene; AR-Lösung (15' Stefano Grassi/ Philippe Bieri)
	Fragen werden im Chat gesammelt
14:25 – 14:45	Diskussion: Feedback zu den verschiedenen Ansätzen (20'; Moderation Philippe Bieri)
14:45 – 14:50	Befragung zur Nutzerfreundlichkeit der Bedienung und zum Nutzern für die Praxis (5', Zoom Poll)
14:50 – 15:00	**Pause (10')**
15:00 – 15:05	Einführung in die Gruppenarbeit (5', Moderation Philippe Bieri)
15:05 – 15:30	Gruppenarbeit (in max. 4 Breakout rooms mit je einem Moderator):
	In welchen Prozessen könnte das 3D DSS aus Sicht der Praxis eingesetzt werden? Wo und warum gibt es Widerstände gegen den Einsatz? Welchen Nutzen hat das 3D DSS für die Praxis? Wie könnte das 3D DSS weiterentwickelt werden, damit es die Anforderungen der Praxis besser erfüllt? (25')
15:30 – 15:40	**Pause (20')**
15:40 – 15:55	Plenumsdiskussion: Anwendbarkeit und Nutzen des 3D DSS für die Praxis (15', Philippe Bieri)
15:55 – 16:00	Abschluss des Workshops (5' Martin Raubal/ Philippe Bieri)

10.3.2Questionnaire – Collecting Feedback of Stakeholders from Practice

Fragen zur Qualität der erweiterten Funktionalität der 3D DSS-Benutzerschnittstelle

1) Wie **nachvollziehbar** finden Sie die Benutzerführung im 3D DSS?

☐	☐	☐	☐	☐
gar nicht nachvollziehbar	eher nicht nachvollziehbar	neutral/ unentschlossen	eher nachvollziehbar	sehr nachvollziehbar

2) Wie **transparent** finden Sie den Szenario-Wizard des 3D DSS (Gewichtung von Zielen)?

☐	☐	☐	☐	☐
gar nicht transparent	eher nicht transparent	neutral/ unentschlossen	eher transparent	sehr transparent

3) Wie **klar** finden Sie die Darstellung der Szenario-Resultate im 2D-Modus des 3D DSS?

☐	☐	☐	☐	☐
gar nicht klar	eher nicht klar	neutral/ unentschlossen	eher klar	sehr klar

4) Wie **angemessen** finden Sie den Detailgrad der Leitungen im 3D-Modus des 3D DSS?

☐	☐	☐	☐	☐
gar nicht angemessen	eher nicht angemessen	neutral/ unentschlossen	eher angemessen	sehr angemessen

5) Wie **hilfreich** finden Sie die Visualisierung von bestehenden Leitungen im Untergrund (Beispiel Zürich)?

☐	☐	☐	☐	☐
gar nicht hilfreich	eher nicht hilfreich	neutral/ unentschlossen	eher hilfreich	sehr hilfreich

6) Wie **zufrieden** sind Sie insgesamt mit der Funktionalität der 3D DSS-Benutzerschnittstelle?

☐	☐	☐	☐	☐
sehr unzufrieden	eher unzufrieden	neutral/ unentschlossen	eher zufrieden	sehr zufrieden

7) Wie **unterstützend**, denken Sie, könnte das 3D DSS **für den Planungsprozess** von Leitungen sein?

☐	☐	☐	☐	☐
gar nicht unterstützend	eher nicht unterstützend	neutral/ unentschlossen	eher unterstützend	sehr gut unterstützend

8) Was ist Ihr Tätigkeitsbereich?

- ☐ Planung von Leitungen
- ☐ Prüfung / Beurteilung von Leitungsplanungen
- ☐ Bewilligung von Leitungsplanungen
- ☐ Kommunikation mit Interessenvertretern
- ☐ Begleitung von Sachplänen
- ☐ GIS-Spezialist

9) Verwenden Sie GIS-Modellierungen bei Ihrer Arbeit?

☐ Nein ☐ Ja

10) Haben Sie öfters mit 3D-Visualisierungen zu tun?

☐ Nein ☐ Ja

10.3.3Documentation of the group discussion

In welchen Prozessen könnte das 3D DSS aus Sicht der Praxis eingesetzt werden?

(1) Planungstool für Leitungsplaner

- Erste Idee
- Planung unterstützen
- Prozess für die Planer und weniger in der Entscheidphase. Im Verfahren würde es zu aufwendig, das Tool selber anzuwenden.
- Förderung der Kreativplanung
- Automatisierung von Verkabelungsvarianten/Freiluftleitungen
- Eher als GIS für Planer nutzen (intern).
- Modellierung einer ganzen Region -> strategische Planung des Netzes
- Projektierung
- Während dem Bauprojekt in der Kombination mit anderen Tools
- Trassenfindung im Bauprojekt mit einer höheren Auflösung
- Bauprojekt ist schon ziemlich im Detail – dann macht vielleicht die Software keinen Sinn mehr.
- Eher Einsatz in der Machbarkeitsstudie

(2) Tool zum Variantenvergleich im SÜL-Prozess

- Im SÜL-Prozess
- SÜL – Vorprojekt
- Sachplanverfahren/Raumordnung --- Kommen doch neue Varianten in Frage, die mithilfe der herkömmlichen Planungsmethoden nicht hervorgekommen wären.
- Im Verfahren würde es zu aufwendig, das Tool selber anzuwenden.
- Behörden benötigen eine Variante, die sie beurteilen. Sie möchten nicht die Varianten selbst erstellen.
- Variantenvergleich
- In einem frühen Stadium einer Variantenstudie. Vorteile liegen in der Visualisierung. Klare Darstellung der Abwägung verschiedener Faktoren. Eine Zone wird verschont, dafür wird eine andere evtl. verletzt.
- Diskussionsbasis zur Verfeinerung von Varianten
- Prozess gut für die Erarbeitung von Varianten. Ergebnisse gut für die Kommunikation. Augmented Reality: eher spielerischer Charakter. Option für die Zukunft, um der Bevölkerung nahezubringen, dass es ein durchdachtes und überlegtes Projekt ist.
- Planungsgeschwindigkeit zur Variantenberechnung: Kostenberechnung, Raumbelastungspunkte technisch voraggregieren.
- Abwägung zwischen Erdkabel und Freileitung und auch Kombination davon
- In Absprache mit anderen Interessenvertretern/Institutionen (z.B. Wasser, Elektrizitätswerke)
- Absprachen mit anderen Stakeholdern wie Umweltverbänden

(3) Tool zur Kommunikation mit verschiedenen Interessengruppen

- Kommunikation / Diskussion in Planungsgruppen
- Kommunikation mit Gemeinden/Info-Veranstaltungen/Stakeholder Engagement
- Diskussionsgrundlage für verschiedene Interessengruppen (Bevölkerung, Ämter, etc.) → hilft in der Sachlichkeit der Diskussionen
- Visualisierung kann bei der Kommunikation helfen. Könnte aber auch hinderlich sein (Mast noch dominanter). – Für Planungsphase
- Zur Veranschaulichung von verschiedenen Werkleitungen. Zeigen, wo es noch Platz im Untergrund hat.
- Kommunikation und Dialog mit der Bevölkerung, um Varianten vorzustellen, zu diskutieren.

- In Gesprächen mit der Öffentlichkeit für das Bauprojekt zu kommunizieren (z.B. Mastverschiebung um einige Meter)
- Menschen und Gruppen entscheiden; nicht Programme. Dadurch Akzeptanz erhöhen. Unterstützung der Planung; nicht Ersatz. 3D-Visualisierung unterstützt Diskussionen und Entscheidungsfindung.
- Faktor Mensch: Leute können verstehen, was hinter den Varianten stecht (Kriterien). Als Unterstützung im Prozess.
- Prozess gut für die Erarbeitung von Varianten. Ergebnisse gut für die Kommunikation. Augmented Reality: eher spielerischer Charakter. Option für die Zukunft, um der Bevölkerung nahezubringen, dass es ein durchdachtes und überlegtes Projekt ist.

Wo und warum gibt es Widerstände gegen den Einsatz des 3D DSS?

(1) Legitimität des Tools
- Es darf nicht befangen sein
- Wenn es offene Fragen nicht beantwortet
- Zu starke Abstützung auf das Tool könnte Fragen aufwerfen, z.B. ist das Tool wirklich objektiv oder werden gewisse Parameter zu stark berücksichtigt?
- Wenn zu viel Gewicht auf Naturschutz gelegt wird, dann hat die Bevölkerung Mühe mit der Akzeptanz (z.B. Leitung Reussthal)
- Es sollte keine No-Go Zone geben (z.B. Naturschutz, NISV etc.)
- Maschinelle Entscheidungen ohne Eingriffsmöglichkeiten von realen Leuten haben vermutlich eine geringe Akzeptanz. Man fühlt sich übersteuert.
- Für eigentliche Interessenabwägung, Emotionen, Ängste gibt es keine Algorithmen.
- Eindruck vor Ort muss trotzdem gewonnen werden.
- Interessenabwägung wird im 2025 anders. → Leitung im BLN wird möglich. → Komplexität der Interessenabwägung im Tool abzubilden ist gross.
- Gefahr, dass man zu sehr darauf vertraut, dass das Richtige herauskommt.
- Je mehr Optionen, je mehr Faktoren, die gewichtet werden können nach eigenen Vorstellungen, das vervielfältigt die «Wahrheit». Grosse Schwierigkeit, sich auf die Gewichtungen zu einigen. Leute müssen diskutieren.

(2) Validität und Glaubwürdigkeit des Tools
- Genauigkeit der Grundlagendaten
- Validierung der Einstellung der Parameter
- Gesetzgebung muss berücksichtigt werden
- Stelle mit der Waldschneise aus der Präsentation ist nicht sinnvoll (Wald wird nicht in offener Grabenweise gebaut)
- Tool muss sehr gut sein. Trigger für Erdkabel oder Freileitung – da ist Verbesserungspotenzial da. Kann Entscheid enorm beeinflussen.
- Gewichtungen: Wenn sich diese ändern, wenn sie für verschiedene Regionen angepasst werden müssen. Wer macht das? Welche Auswirkungen hat das?
- Blackbox (Transparenz)
- Schwierige Abbildung der verschiedenen Technologien innerhalb des Tools
- Genehmigungsbehörde könnte das Tool nicht als Grundlage akzeptieren (zumindest in Deutschland)

(3) Relevanz des Tools
- Vorschläge sind keine Entscheide
- Wichtig: Tool zur Entscheidungsunterstützung, aber nicht zur Entscheidung.

- Klassische Planung -> Integration des Tools in die Prozesse
- Kommunikation mit den Stakeholdern
- Für die Generation, die ganz anders mit digitalen Medien aufwachsen, ist es vielleicht die Zukunft. Aber die Algorithmen müssen sehr gut sein.
- Wenn physisches Treffen nicht möglich ist: virtuell weiterarbeiten. Grosses Potenzial.

(4) Kosten des Tools
- Aufwand vom Standpunkt der Firma (Schwierig zu quantifizieren)

Welchen Nutzen hat das 3D DSS für die Praxis?

(1) Ideen generieren
- Überraschende Vorschläge
- Rasche Ideengenerierung + kreative Planung
- Impulse können zur Beschleunigung genutzt werden

(2) Planer unterstützen
- Hilfestellung für den Planer (Umweltplaner oder technischer Planer)
- Faktenbasierte Planung (blendet etwas die subjektive Einschätzung der einzelnen Planer ab)

(3) Interessenabwägung unterstützen
- Die Visualisierung, die Unterstützung der Planungsprozesse, die Variantenfindung
- Bildet eine seriöse Basis für die Bearbeitung des Sachplanverfahrens im Rahmen der Begleitgruppe
- Interessenabwägung
- Aber: Bestehende Leitung von Innertkirchen–Mettlen ist gar nicht so schlecht. Wurde mit 10 Kriterien gemacht. Nun zieht man sehr viel mehr Kriterien ein. Entscheid ist aber möglicherweise nicht besser. Müsste man sich anschauen, wo liegt die Grenze für die Summe der Kriterien, die angeschaut wird.

(4) Kommunikation unterstützen
- Nutzen liegt bei der Kommunikation
- Dialogförderung
- Visualisierung für Kommunikation nutzbar
- Raumwiderstände lassen sich gut visualisieren und kommunizieren
- Entscheid kann mit dem Tool noch besser kommuniziert werden. Z.B. Siwssgrid → Lösungsweg besser begründen.
- Zeigen, dass auch Erdkabel sichtbar sind

(5) Planungsprozess beschleunigen
- Zeitgewinn
- Konflikte schneller erkennen und schlichten

Wie könnte das 3D DSS weiterentwickelt werden, damit es die Anforderungen der Praxis besser erfüllt?

(1) Datenbanklösung
- Datenpflegen zu vereinfachen/automatisieren
- Vollständige/aktualisierte Datenbank

(2) Plausibilität und Validität prüfen

- Plausibilität überprüfen
- Gegen welche Gesetze wurde verstossen?
- Kostenfunktion optimieren
- Für Kabelleitungen müssen die verschiedenen Bauverfahren berücksichtigt werden (Mikrotunneling, Bohrung etc.)
- Begründen, warum V1 besser ist als V2

(3) Nutzerfreundlichkeit verbessern
- Je weniger Klicks desto besser (Einstellung der Parameter)
- Es ist noch zu akademisch, muss allgemein verständlicher werden.

10.4 Data model considered in the 3D DSS

Table 3: Data model including categories, criteria, and main objectives.

Category	Criterion	Main objective
Environmental protection	biosphere reserves	Protect the environment
	dry meadows: national importance	
	dry meadows: cantonal importance	
	flood plains: national importance	
	flood plains: cantonal importance	
	mire biotopes: national importance	
	mire biotopes: cantonal importance	
	bird reserves	
	nature reserves	
	protection areas according to hunting laws	
	BLN	Protect the landscape
	mire landscapes	
	parks: national importance	
	parks: regional importance	
	UNESCO World Heritage Sites	
	landscapes worthy of protection	
	characteristic objects	
	arable land	
	stocked areas	
	forests	
Technical feasibility	natural hazard zones: avalanches	Decrease risks
	natural hazard zones: floodings	
	natural hazard zones: landslides	
	natural hazard zones: rockfalls	
	natural hazard zones: sink holes	
	S1: strict	Ensure implementability
	S2: less strict	
	inappropriate relief	
	inappropriate geologic underground	
	underground facilities	
	punishment when leaving a valley (valleyness)	
	surface waters: lakes	
	surface waters: rivers	
Urban planning	historic places and areas	Protect the landscape
	airports	Decrease risks
	cableways	
	military sites	
	gravel pits	Ensure implementability
	special railways	
	inappropriate aspect	
	areas within a noise threshold of 40 dBA	Preserve living space
	residential/work/mixed zones	
	industrial zones	
	tourism zones and recreational areas	
	public core zones	
	cultural heritage: high importance	
	cultural heritage: low importance	
	potential visibility of a new transmission line	
	wide roads and railways	Increase bundling
	existing transmission lines	
	public transport zones	
	tunnels	
	infrastructure facilities	

10.5 Description of the used data sets

Airport This entity contains larger airports and smaller airfields for sports, civil, or military aviation. OLs should not be constructed next to airports as they are obstacles to open air traffic.

Arable land This entity contains zones that are used for agricultural purposes. The data set does not differ with regard to different agricultural uses but evaluates all types of use equally. The European data set CORINE Land Cover 2012 was used as a source for determining arable land zones. Stocked areas, as vineyards and orchards, were listed in a separate layer, as they are subject to stricter rules regarding building regulations.

Area within a noise threshold of 40 dBA Since the noise immission limit of a transmission line to an inhabited building (OMEN) is 40 dBA, the program 'HVLNoise 1.0' (Heutschi and Eggenschwiler 2010) was used to calculate how large the distance would have to be for an OL to not exceed 40 dBA. The calculation was carried out for a 'Barrel' and a 'Danube'-shaped electricity pylon (Figure 52) during rain. Since, for compliance with the ONIR, a distance of 100 m to buildings was always assumed and as the 40 dBA isoline is below this distance for both pylon types, the noise immission factor was calculated, though deactivated in the current decision model.

Biosphere reserve Biosphere reserves are model regions in which sustainable development is to be realized. In addition to nature conservation aspects, sustainable economic and social development is also sought. Biosphere reserves are proposed by governments and recognized by UNESCO in accordance with their requirements. They are subject to restrictions on use, since interventions in the biosphere must always be sustainable.

Bird reserve Bird reserves are listed separately due to species protection programs in cooperation with the European Union. Bird reserves include Ramsar areas, waterfowl reserves, and migratory bird reserves.

Cableway Aerial cableways have been extracted from the swissTLM3D data set and must be taken into account, in particular when planning OLs.

Characteristic object Characteristic objects for a specific landscape encompass churches, chapels, monasteries, castles, palaces, ruins, high chimneys, tree rows, towers, and walls. All objects were extracted from the Inventory of the Historic Traffic Routes of Switzerland (IVS) and swissTLM3D data set.

Cultural heritage object Cultural heritage objects represent cultural property objects of high historical and cultural value. They consist of objects from the Federal Inventory of Heritage Sites (ISOS) and Inventory of Objects under Protection of Cultural Property (KGS) inventory. As these objects are of high historical and cultural value, the Federation is obliged to protect the objects from the ISOS inventory according to Art. 5 NCHA and those of the KGS inventory according to Art. 1 of the 'Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict.' As all cultural heritage objects were represented as point features, they had to be buffered in order to obtain an area that could be considered to be protected. Since KGS A objects were assigned a higher cultural value than KGS B objects, KGS A objects and objects from the ISOS inventory were buffered with a larger radius (100m) than KGS B objects (50 m).

Dry meadow Dry meadows are species-rich habitats that are characterized by agricultural use. As 95% of the dry meadows in Switzerland have disappeared since 1900, the Federal Council has included dry meadows and those of national importance in an inventory in accordance with Art. 18a NCHA.

Existing transmission line OLs and, in particular, TTs are perceived as elements that dissect the landscape. The Swiss Confederation is therefore pursuing the goal of slowing down landscape fragmentation by means of linear infrastructures. New TLs should therefore, if possible, be bundled with existing lines in order to avoid urban sprawl. This data set takes up this issue by penalizing areas that are outside a certain distance from existing TLs with costs. Thus, the user defines the costs in case the bundling with existing TLs is ought to be deliberately avoided.

Flood plain In order to protect valuable floodplains and endangered amphibians, the Federal Council has put two inventories into force: The ‘Federal Inventory of Floodplains of National Importance’ and the ‘Inventory of Amphibian Spawning Areas of National Importance.’ Both are protected under Art. 18a NCHA and encompass inventories of national importance. By contrast, wetlands worthy of protection are defined as areas that are habitats considered worthy of protection under Art. 18 NCHA, although not included in a national inventory. These include mire biotopes of regional importance, wetlands belonging to the National Ecological Network (REN), watercourse sections with high species diversity (hotspot zones), and spawning grounds of protected species.

Forest Forests play a central role in promoting biodiversity. Forests were collected from different sources and are not further differentiated. Pro-Natura forests, which are subject to private law, were also integrated into the same data set.

Geotope Geotopes are geologically valuable parts of the landscape. They contain important witnesses of the Earth’s history and provide insight into the development of the landscape and climate. For this reason they are important for the public, landscape, and nature conservation as well as for research and education. Examples are natural monuments, rock formations, fossil-rich quarries, moraine landscapes, caves, springs, or waterfalls. Although geotopes are not explicitly mentioned in the federal legislation, they are protected—depending on their form—by the Civil Code (ZGB), the SPA, and the NCHA as well as by cantonal protection ordinances.

Gravel pit Gravel pits were combined in a separate entity as they are industrial sites that change over time due to gravel mining. As landscapes with gravel pits are already affected by opencast mining, spanning a gravel pit might concentrate the burden to that location without affecting undisturbed landscapes located further away. Furthermore, the construction of an EC through a gravel pit may save resources and decrease the construction costs.

Historic site Historic sites include archaeologically valuable areas as well as preserved buildings of historical value. These include, for example, excavation sites, churches, chapels, castle ruins, castles, historic factory sites, and stone circles.

Inappropriate aspect Zones with an aspect of 111.5° to 292.5° azimuth deviation from the North Pole could lead to higher power losses when transmitting electricity through an EC due to increased ground heating. For this reason, all areas within this aspect range (WNW to ESE) were combined into one layer.

Inappropriate geologic underground Areas with an inappropriate geologic underground for the construction of high-voltage power lines were derived from the soil cover of the swissTLM3D data set (loose rock, glacier, rock), from the soil classes (loose rock, sand, gravel, clay, organic and soft deposits) and from the geothermal map of the Canton of Lucerne. All loose or unstable subsoil materials were defined inappropriate even though they do not always make the construction of a high-voltage power line technically impossible, but at least more difficult.

Inappropriate relief A pixel on the DEM has been defined inappropriate for constructing a TL if it reached a slope of at least 55° or an altitude of at least 1400m ASL. Although construction is not impossible, it does involve considerable additional costs. Therefore, the choice of the slope for an unsuitable relief should take these considerations into account. The slope of 55° was determined in an expert survey, while a preliminary study concluded that 84% of all TTs in Switzerland (the average elevation plus one standard deviation) are located below 1400m ASL.

Industrial zone Industrial zones according to the zone plan.

Infrastructure facility Infrastructure facilities are crucial for offering important services to the public. In this entity, we included infrastructure facilities as wastewater treatment plants, workshops, waste incineration plants, recycling plants, water treatment plants, power stations, wind turbines, transformer stations, dams, and radio antennas.

Inventory of heritage sites The Federal Inventory of Heritage Sites, in German called 'Bundesinventar der schützenswerten Ortsbilder der Schweiz von nationaler Bedeutung' (ISOS), describes an inventory that contains objects that are characteristic and highly valuable for the view of a place. The inventory encompasses objects of national importance that are subject to special protection by the Federation according to Art. 5 NCHA. A buffer of 300m was used around objects of high protection value, while a buffer of 50m was chosen for objects of low protection value. These buffer radii were determined in a preliminary study.

Inventory of nationally protected landscapes The inventory of nationally protected landscapes, in German called 'Bundeslandschaftsinventar' (BLN), describes an inventory of landscapes worthy of protection of national importance. It contains the most precious landscapes and natural monuments of Switzerland which are, by virtue of their silence, privacy, and beauty, particularly attractive. The Federation is obligated, according to the NCHA, to conserve and sustain them for a long term.

Inventory of objects under protection of cultural property The inventory of objects under protection of cultural property in the event of armed conflicts, in German called 'Kulturgüterschutz' (KGS), encompasses collections of objects, facilities, and archaeological sites that are considered to be important cultural assets and thus, worthy of being protected according to Art. 1 of the 'Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict.' Even though the Hague Convention protects valuable cultural assets in the event of an armed conflict and not from the perspective of monument conservation, the objects included in the KGS inventory were considered worthy of being protected due to their high cultural value. KGS objects are categorized into A and B objects, whereby KGS A objects are of higher cultural value than KGS B objects and thus, enjoy protection also during armed conflicts. They can be of local, regional or supra-regional to national importance, whereby KGS A objects might be of national importance. Due to their higher cultural value, KGS A objects were buffered with a larger radius (100 m) than KGS B objects (50 m). The Federal Act on the Protection of Cultural Property in the Event of Armed Conflicts, Catastrophes, or Emergencies (KGSG) regulates the measures for the protection of the KGS objects in the event of armed conflicts, catastrophes, or emergencies.

Inventory of the historic traffic routes in Switzerland The inventory of the historic traffic routes in Switzerland, in German called 'Inventar der historischen Verkehrswege der Schweiz' (IVS), contains relics of transport routes that are of historical value. These may be still visible paved roads from Roman times or covered or built over traffic routes that are present but not visible any more. Also companions, such as historically significant fountains, way crosses, or marking stones are counted to the inventory. Depending on their significance, buffers of different sizes were defined around the original objects, whereby traffic routes were considered more significant than their companions. The Federation is obligated, according to Art. 5 NCHA, to conserve and sustain them for a long term.

Landscape worthy of protection Landscapes with high protection value include geotopes, Alpine protection areas according to the Alpine protection convention, landscapes of regional importance, cantonal protection zones for habitats and landscapes, and an inventory of natural objects of regional importance. These landscape elements are protected by the NCHA and might be inventoried as individual objects or as areas.

Military site Since military sites are subject to high mechanical stress, it must be checked in advance whether the operation and maintenance of an OL or EC is not subject to excessive risks. For this reason, military sites were listed as a separate entity.

Mire biotope Mire biotopes include fens and raised bogs. Mire biotopes are protected by the Federal Constitution (Art. 78 para. 5 BV). No installations may be built in them, nor may any changes to the soil be made. Excluded are facilities that serve the protection or the previous agricultural use of the mires.

Mire landscape Mire landscapes are characterized by the presence of bogs, whereby the part being free of them is “in close ecological, visual, cultural, or historical relation” to the bogs (Art. 23b NCHA). Mire landscapes, like mire biotopes, are protected by the Federal Constitution (Art. 78 para. 5 BV). In contrast to Art. 78 para. 5 BV, however, the NCHA and the Ordinance on Fen Protection differentiate between mire biotopes and mire landscapes. Art. 23d para. 1 NCHA permits the design and use of mire landscapes, as long as this does not contradict the preservation of the typical features of mire landscapes. Art. 23d NCHA puts Art. 78 para. 5 BV into concrete terms with regard to the buildings and installations, which are generally permissible in mire landscapes. It must then be examined whether the projection is compatible with the specific protection objectives of the mire landscape. However, OLs—even those of national interest (Art. 5 para. 2 subpara. d of the Ordinance on Mire Landscape Protection)—are generally not compatible with the protection objectives, with the consequence that they are not permitted to be built in mire landscapes.

Natural hazard zone Natural hazard zones are defined on a cantonal level and include zones that are endangered by floods, avalanches, debris flows, or landslides. Only zones with a high probability of a moderately severe natural event, occurring within 30 years, were selected for modeling. In general, the less frequently an event occurs, the greater its severity. A time horizon of more than 30 years for the occurrence of a severe natural event affecting a larger area was not taken into account, as these events occur very rarely and possible damages can be repaired. It should be noted that earthquakes are not among the natural hazards described by the Confederation. Although the probability of an earthquake at a certain point is not evenly distributed over whole Switzerland, the risk of earthquakes is neglected because they have only a negligible impact on TLs due to the estimated maximum magnitude per possible entry period.

Nature reserve Nature reserves include, in particular, municipally and cantonally designated and Pro-Natura nature reserves. Areas belonging to the Emerald Network of Areas of Special Conservation Interest (in German called ‘Smaragdgebiete’), which have a high diversity on species, were also included despite their lack of legal status, although these are largely protected by cantonal nature reserves in the study area.

Park Parks of national importance are guided by the principle of sustainable development in order to fulfill an ecological, economic, and social purpose. They protect the natural habitats of many animal and plant species, which fosters biodiversity and preserves beautiful landscapes and their cultural assets. Parks of national importance include national parks, regional nature parks, and nature discovery parks. The Confederation is obliged to protect these areas under the NCHA.

Potential visibility of a new transmission line The visibility of a potential new OL was calculated by applying the method according to Grassi et al. (2014). It was calculated for each pixel cell within the study area, from how many other pixels a TT of 80m height would be seen. For these pixels, the disturbing effect was then calculated based on the inverse distance. Based on the study conducted by Nohl (1993), it was assumed that an OL which is located 2 km away has no disturbing effect any longer. However, not only OLs but also ECs may be visible in the landscape. Since the construction of an EC through a forest would entail a reforestation of low-growing trees (if at all), an aisle would be visible in the forest. For these cells, it was determined from how many other cells this aisle would be visible.

Protection area according to hunting laws These wildlife protection areas include wildlife protection zones, game resting areas, and hunting ban areas. The protection of wild mammals is governed by the Federal Hunting Act (JSG).

Public core zone This data set includes publicly accessible zones. Regarding the ONIR, the data set does not distinguish between OMEN, such as schools or hospitals, and OKA, such as squares, churches, concert or theater halls, and viewing terraces. Sports and leisure zones are listed separately and are not included in this data set.

Public transport zone Public transport zones include OKA, which are mainly accessible by motorized individual transport. These include parking areas, rest areas, driving areas, traffic areas, and traffic zones.

Punishment when leaving a valley Overcoming a mountain crest does not only affect the landscape if a new OL should be constructed but is also technically complex and expensive. For this reason, staying in a valley can be rewarded, while overcoming a mountain crest is punished. For this purpose, the algorithm of Straumann (2010) was applied to the DEM, which identifies the valleys based on the (relative) valley floor.

Residential/work/mixed zone Residential/work/mixed zones according to the zone plan. Regarding the regulations of the ONIR, zones aimed for living and working, including mixed zones, are characterized by OMEN.

S1 groundwater zone Core zone for protecting groundwater areas with an absolute construction ban. S1 groundwater zones are regulated by the WPO.

S2 groundwater zone Inner protection zone for protecting groundwater areas from contamination of drinking water with pathogenic microorganisms. Constructions in S2 groundwater zones are restricted in order to prevent "the groundwater being polluted by excavations and underground works near to groundwater wells or recharge installations" (Art. 123.a WPO). S2 groundwater zones are regulated by the WPO.

Special railway Special railways may complicate the construction of an EC. Entities included in this data set are ski lifts and conveyor belts.

Stocked area Stocked areas consist of vineyards or orchards and were extracted from the CORINE Land Cover 2012 data set.

Tourism zone or recreational area Tourism zones are areas that are devoted to tourism. By contrast, local recreational areas describe areas where people spend their leisure time, which include city parks, cemeteries, sports facilities, race tracks, and other places for short-term stays (OKA).

Tunnel This entity includes existing tunnels known to the public and listed in the swissTLM3D data set or in the cantonal structure plans for a planned construction.

Underground facility Although not all underground infrastructure facilities are publicly accessible or shown in maps, the known underground facilities were selected from the swissTLM3D data set (ventilation shafts, underground buildings, and water basins) and from the obstacle file of the Canton of Berne. Such installations should be bypassed when planning an EC.

UNESCO World Heritage Site The Convention Concerning the Protection of the World Cultural and Natural Heritage (World Heritage Convention, SR 0.451.41) aims at preserving cultural and natural properties of outstanding universal value as part of the World Heritage of all mankind. The three natural properties included in the World Heritage List must be protected and preserved. Although a UNESCO World Heritage Site is located close to the study area, it is not affected, and therefore, not included in the decision model.

Water body Surface water bodies, such as rivers or lakes, represent natural barriers to the construction of a TL. They are not impassable, as the laying of underwater cables is an alternative. However, constructing underwater cables is challenging, and entails additional planning costs, since, among other things, conversion stages and construction measures are necessary to realize such a project. Therefore, the choice of the resistance value for crossing a lake should take these considerations into account.

Wide road or railway Roads, highways, and railroad lines cut the landscape through their linear form and foster urban sprawl. The Swiss Confederation is therefore pursuing the goal of avoiding urban sprawl. New TLs should therefore, if possible, be bundled with existing roads of at least 8m width (freeways, highways, and wide main roads). The used data set takes up this issue by penalizing areas which are located outside a certain distance from existing roads of at least 8m width with costs. The user thus defines the costs for the case that the bundling with wide roads is deliberately omitted.

10.6 Legal terms and sources

BV Federal Consitution of the Swiss Confederation, in German called 'Bundesverfassung' (BV), SR 101.

EleG Federal Act on High- and Low-Voltage Systems, in German called 'Bundesgesetz betreffend die elektrischen Schwach- und Starkstromanlagen' (EleG), SR 734.0.

EPA Federal Act on the Protection of the Environment (EPA), in German called 'Umweltschutzgesetz' (USG), SR 814.01.

Federal Act on the Conversion and Expansion of the Electricity Grid Federal Act on the Conversion and Expansion of the Electricity Grid, in German called 'Bundesgesetz über den Um- und Ausbau der Stromnetze' (StromVG), BBl 2017 7909, is based on the EleG.

GSchV Water Protection Ordinance, in German called 'Gewässerschutzverordnung' (GSchV), SR 814.201.

Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict The Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict, SR 0.520.3, came into force in Switzerland in 1962 and refers to the convention of the UNESCO concluded in 1956.

JSG Hunting Act (JSG), in German called 'Jagdgesetz' (JSG), SR 922.

Judgement 1C_398/2010 from 5 April 2011 The Judgement 1C_398/2010 from 5 April 2011 (BGE 137 II 266) implies that in the case of the planned TL in Riniken interests among stakeholders were evaluated insufficiently and unbalanced. Therefore, the Federal Court judged in favor of an alternative that proposed a partial earth cabling through Riniken.

KGSG Federal Act on the Protection of Cultural Property in the Event of Armed Conflicts, Catastrophes, or Emergencies (KGSG), in German called 'Bundesgesetz über den Schutz der Kulturgüter bei bewaffneten Konflikten, bei Katastrophen und in Notlagen' (KGSG), SR 520.3. The KGSG is based on the Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict, SR 0.520.3.

LeV Ordinance on Electrical Lines, in German called 'Leitungsverordnung' (LeV), SR 734.31.

NAO Noise Abatement Ordinance (NAO), in German called 'Lärmschutzverordnung' (LSV), SR 814.41.

NCHA Federal Act on the Protection of Nature and Cultural Heritage (NCHA), in German called 'Natur- und Heimatschutzgesetz' (NHG), SR 451.

OKA Locations for short-term stay, in German called 'Orte für den kurzfristigen Aufenthalt' (OKA), encompass all locations in which people stay for a short time and which are not classified as OMEN.

OMEN Locations with sensitive usage, in German called 'Orte mit empfindlicher Nutzung' (OMEN), encompass according to Art. 3 para. 3 ONIR playgrounds and rooms in which people stay periodically for longer time.

Ordinance on Fen Protection Ordinance on Fen Protection, in German called 'Verordnung über den Schutz der Flachmoore von nationaler Bedeutung, SR 451.33.

Ordinance on Mire Landscape Protection Ordinance on Mire Landscape Protection, in German called 'Moorlandschaftsverordnung, SR 451.35.

PGV The Planning Approval Procedure, in German called 'Plangenehmigungsverfahren' (PGV), describes the procedure that must be applied to set a legally binding TLP that encompasses the transmission technology, the voltage level, and the exact positions including the pylon types of all TTs'. The PGV is regulated in the Regulation on the Planning Approval Procedure for Electrical Systems (VPeA) (Swiss Federal Council, 1994c), which is based on the Federal Act on the Electricity Supply (StromVG).

RPV Ordinance on Spatial Planning, in German called 'Raumplanungsverordnung' (RPV), SR 700.1.

SPA Spatial Planning Act (SPA), in German called 'Raumplanungsgesetz' (RPG), SR 700.

SPV The Sectoral Planning Process, in German called 'Sachplanverfahren' (SPV), describes the process that must be applied to enact an adaption of the SÜL, in which a legally binding and technically feasible TLC is proposed. The proposal must further include details regarding the voltage level, the transmission technology, and a possible route for a TLP. The SPV is regulated in the Regulation on the Planning Approval Procedure for Electrical Systems (VPeA) (Swiss Federal Council, 1994c), which is based on the Federal Act on the Electricity Supply (StromVG).

StromVG Federal Act on the Electricity Supply, in German called 'Bundesgesetz über die Stromversorgung' (StromVG), SR 734.7.

SÜL The Sectoral Plan for Transmission Lines, in German called 'Sachplan Übertragungsleitungen' (SÜL), is an authoritative plan governed by the ARE that encompasses sectors reserved for TLs.'

VBLN Ordinance on the Federal Inventory on Landscapes and Natural Monuments, in German called 'Verordnung über das Bundesinventar der Landschaften und Naturdenkmäler' (VBLN), SR 451.11.

VEMV Ordinance on Electromagnetic Compatibility, in German called 'Verordnung über die elektromagnetische Verträglichkeit' (VEMV), SR 734.5.

VPeA Ordinance on the Planning Approval Procedure for Electrical Systems, in German called 'Verordnung über das Plangenehmigungsverfahren für elektrische Anlagen' (VPeA), SR 734.25.

ZGB Civil Code, in German called 'Zivilgesetzbuch' (ZGB), SR 210.

10.7 Transmission tower types

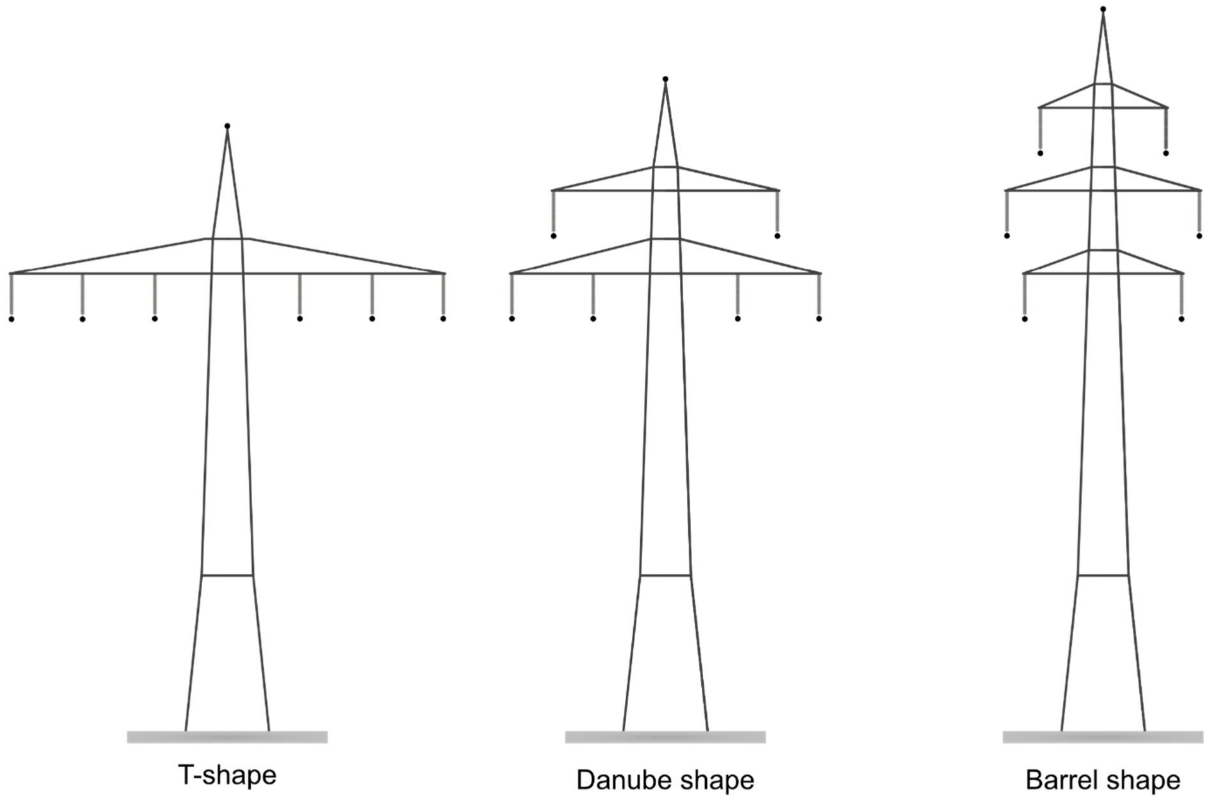

Figure 52: Transmission tower types: T-shape, Danube shape, and Barrel shape.