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Determining transmission line path alternatives using a valley-finding algorithm

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ABSTRACT

Since new (Power) Transmission Lines (TLs) can have a long-term effect on the makeup of a landscape and on the human living space, it should be expected that the route of any new TL will be based on objective criteria that take into account the views of the public. Geographic Information Science (GIScience) provides powerful tools that assist in the determination of feasible locations for new TLs based on objective criteria and georeferenced data by combining methods from Multi-Criteria Decision Analysis (MCDA) and Least Cost Path (LCP) analysis. If such an approach is applied, the LCP analysis usually yields one optimal result. However, stakeholders and decision-makers prefer to compare multiple distinct path alternatives in order to find a solution that will be acceptable to as many stakeholders as possible.

We have developed a method that calculates spatially distinct and Pareto optimal path alternatives based on the same cost surface using an algorithm for determining valleys on a Digital Elevation Model (DEM) to determine local low-cost points, which were then connected to a network graph by geometrical rules. Finally, we selected all non-dominated path alternatives that represented Pareto optimal conditions regarding a specific main objective. We then asked ten expert stakeholders to cross-compare the calculated path alternatives and assess our novel method. The concept of applying linear programming to obtain Pareto optimal path alternatives yielded routings that were mostly preferred over the LCP and had a greater likelihood of being realized than the results obtained by conducting the LCP analysis. The stakeholders determined the method's key concept to be useful and assert it a high potential to support planning, matter-of-fact argumentation, and discussions about TL routing.

1. Introduction

The turn toward renewable energy sources is challenging for numerous reasons. The demand for electricity is increasing across the world due to steady population growth (International Energy Agency, 2019) and the benefits that electricity use fosters, namely economic growth and increased social welfare (Taylor, 2017). However, electricity generation by renewable energy power plants, especially photovoltaics and wind energy, is subject to current weather. This hampers the reliable prediction of electricity supply, when and how much electricity will be transmitted through the grid. The existing grid must be modernized to meet the technical requirements of transmitting renewable energy to a growing population.

Extending the existing grid is challenging. Legal requirements have become more stringent in the years since the grid was first established (Jullier, 2016). Furthermore, citizens often worry about potential health issues caused by the (Power) Transmission Lines (TLs)' magnetic field (Hedtke et al., 2018). This leads to low community acceptance of grid extension projects. Citizens want to be involved in the decision-making process concerning TLs (Lienert, Suetterlin, & Siegrist, 2015), especially regarding the social impacts of the TL path, so that the path is socially accepted and not simply strategically laid out as 'objective' as possible (Haggett & Devine-Wright, 2011). Geographical Information Systems (GIS) are ideal tools to support the whole decision-making process. GIS provide a mathematical, computer-based platform that can analyze social-consideration data and other stakeholder data to determine the best path for new TLs, thus increasing the TL acceptance by as many stakeholders as possible.

An approach that is often used to determine the TL's path combines methods provided by Multi-Criteria Decision Analysis (MCDA) and Geographic Information Science (GIScience) methods. Geographic entities of the same type (as e.g., forests, lakes, settlements, etc.) are first

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grouped into layers. A user then weights these layers according to their suitability for TL construction. The weighting must consider legal restrictions concerning protected areas and hazard zones to obtain a realistic result. For each area, which is represented as a pixel, the weighted average is then calculated using the Weighted Linear Combination (WLC) method. The result is the *cost surface* whereas *costs* represent an abstract friction that must be overcome to construct the TL on the corresponding area (Malczewski & Rinner, 2015). In this regard, costs can represent, for example, resistances derived from given by-laws, monetary costs for laying a cable, or frictions due to the potential visibility of a transmission tower. Each of these *factors* generates costs that prevent the planning institution the more from building a TL the higher these costs are. Finally, the Least Cost Path (LCP) is calculated on the calculated cost surface using Dijkstra's Algorithm (Dijkstra, 1959) from the starting to the ending point.

If we consider the LCP to be the best Tranmission Line Path (TLP) representation that connects two given points—the starting and the ending point—with each other, then the described approach results in one *optimal* solution (among possible others) that is based on a single cost surface (Berry, 2007). A different path alternative can be determined either by (1) searching for a second optimal or (2) sub-optimal solution on the same cost surface, or (3) using a different cost surface. However, all four approaches have a limited effect in practice. First, Berry (2007) indicates that the occurrence of a second LCP on the same cost surface might occur. Complex decision models do not necessarily present distinct alternatives. Second, sub-optimal solutions could be calculated using the k-shortest path algorithm (Medrano & Church, 2011) or by computing and visualizing the Transmission Line Corridors (TLCs) (Schito, Jullier, & Raubal, 2019). However, it remains unclear how much a sub-optimal path must differ from the LCP to be perceived as a realistic solution. Third, empirical data from this research project suggested that conducting the LCP analysis in reverse, from the ending to the starting point, results in a similar TLP. Therefore, altering the cost surface would be the last remaining option. However, there are drawbacks to this option, as determining a new set of weights might be expensive and cumbersome, especially when applying participatory MCDA techniques (Belton & Stewart, 2002). Even if a new set of weights could be determined, Schito, Wissen Hayek, and Raubal (2018) suggested that altering the weights does not necessarily provide a distinct TLP in a natural environment. TLP options that were calculated using different GIScience methods (different weight sets) do not meet stakeholder's expectations.

We developed and statistically evaluated a method that first identifies 'basins' of least costs and then connected them to a network. We used parts of the algorithm developed for identifying topographic valleys on a Digital Elevation Model (DEM) (Straumann, 2010), but we applied it to an aggregated cost surface by using the method described by Moncecchi (2020). Linking the resulting low-cost points to a network and then conducting the same LCP analysis described by Schito et al. (2018) allowed us to determine the different path alternatives that fulfilled specified *objectives*. Similar to the optimization method described by Bachmann et al. (2018), stakeholders could then use linear programming to identify path alternative that best represented their objectives. We evaluated our methods in a case study with ten participants, all TL planning experts familiar with the study area. Participants had in average 9 years of experience with planning or approving TLs (Table 2). They were affiliated to five different organizations, among them three federal offices, Swissgrid, and a private company. We detailed our methodology, study parameters, and results, and then discussed the results and alternatives approaches.

2. Method

2.1. Study area

Per our project partner *Swissgrid*, we focused on the region between the Innertkirchen and Mettlen substations in central Switzerland (Fig. 1). The topography in this region is characterized by pre-alpine mountains where lakes and rivers follow the main valleys down to the flatland and the lake of Lucerne. The grid renewal project in this area aims at replacing the existing 230 kV TL with a 380 kV TL. The crux of the matter is that the existing TL partially passes through an area that is protected by the Constitution and cannot be considered for a future TLP.

2.2. Data preparation

We based our decision model on the criteria that must be considered by law (DETEC, 2001) and identified 58 spatially explicit factors that could legally influence the construction of a TL (Table 1). These factors were grouped into three categories: environmental protection, urban planning, and technical implementability. Each of the 58 factors used in our decision model was assigned one of the *main objectives* Ω_1–Ω_7 listed in Table 1.

We collected the appropriate data sets from open governmental data portals. Point or line features were transformed into areal features by applying a buffer, with a width determined by either legal requirements or expert opinion. Since one objective aims at fostering bundling with existing linear infrastructure, we included a data set that increases the costs for building a new TL if the path is farther than 100 m from an existing TL, highway, or railway line. Furthermore, we used a DEM with a cell size of 100 m to derive the visibility impact of a possible transmission tower (in case of an overhead line) or of a possible forest aisle (in case of an earth cable) for each pixel of the study area. The same DEM has been used to identify areas with a terrain that the expert stakeholders assessed to be unsuitable for constructing a TL, areas over 1300 m above sea level and areas with a slope greater than 55°. Based on our expert participants' advice, we further included a factor that increases the costs for building a TL on south-facing slopes between the azimuths 111.5° and 292.5°, as the visibility of Overhead Lines (OLs) facing south is higher than those facing north.

2.3. Decision model and factor weighting

For the current study, the participants assessed which of the 58 factors i defined in the decision model should accept or decline the construction of a TL. A scenario was defined by the set of *resistances* r_i that complied with legislation. These resistances were then enhanced by defining a *weight* w_i. While resistances represent, based on legal texts, the extent which a factor is suitable for building a TL on the corresponding area, the weights, which were originally derived from the 'Assessment Scheme for Transmission Lines' (SFOE, 2013), represent the relative importance of the factors. We used a Likert 5-point acceptability scale for the resistances and a Likert 3-point priority scale (Vagias, 2006) for the weights. Since the resistances needed to allow both scales to accept or to decline a TL, the weighting was corrected by a function $h_i(r_i, w_i)$ that decreased the value of all resistances below 3, keeps 3 neutral, and increases the value for all resistances above 3. To accomplish this, we applied the empirically determined Eq. 1 on the weight w_i depending on the resistance r_i. We employed the resistances and weights from an intermediate scenario (Table 1). Lastly, we used a linear utility function and the MCDA method WLC (Malczewski & Rinner, 2015) to calculate the *total resistance* t_x for each point at the location x by Eq. 2, which computed the *cost surface*. We selected these approaches based on their superior results and easy comprehension compared to other methods (Schito et al., 2018).

$$h_i(r_i, w_i) = \begin{cases} \sqrt{\frac{1}{w_i}} & \text{if} \quad [1 \le r_i < 3] \\ 1 & \text{if} \quad r_i = 3 \\ \sqrt[7]{w_i} & \text{if} \quad [3 < r_i \le 5] \end{cases} \tag{1}$$

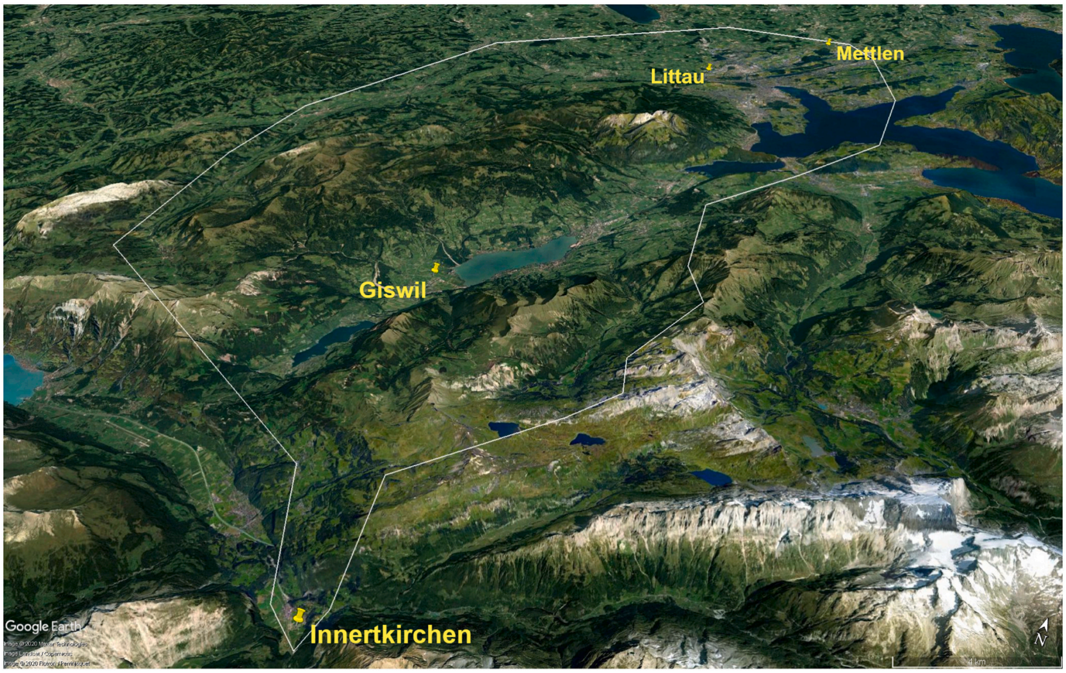

Fig. 1. The study area between Innertkirchen and Mettlen substations, central Switzerland. Image created by using Google Earth.

$$t_x = \sum_{i=1}^{n} r_i \cdot h_i \tag{2}$$

2.4. Network algorithm on low-cost basins

Next, we computed the *aggregated cost surface* in two steps. First, we used Dijkstra's algorithm (Dijkstra, 1959) to determine the aggregated costs for each pixel from the start to the end and back. The resulting *cost distance* maps were then compiled into an aggregated cost surface, which represents how intractable it would be to reach each point when proceeding on a path from the start to the end. This aggregated cost surface *can* be interpreted as relief of low and high resistances, from which we *can* assume that paths passing through low-resistance basins represent low-cost alternatives to the LCP. However, even though these alternatives are inferior to the LCP in terms of total costs when considering the whole path length, they can encompass sections that are Pareto optimal regarding one or more objectives. Thus, building a network of path alternatives that pass through low-resistance points and evaluating these alternatives with regard to the objectives listed in Table 1 allows the user to optimize an array of paths according to stakeholder interests.

We determined the low-cost basins on the aggregated cost surface by applying the method described by Straumann (2010). On these basins, we selected the points with the least resistance, or *local minima*. In the case that the local minimum was assigned to multiple points in the same basin, we selected the mid-point of these points and defined it as basin center. As a result of our empirical findings, we further defined that if two or more local minima were located less than 1500 m apart, we selected the local minimum with the least resistance.

Next, we created an undirected graph by connecting the starting and the ending points with the local minima defined by geometric constraints. Similar to the approach used by Rheinert (1999); Piveteau (2017), we constrained the questionable connection points, as shown in Fig. 2, based on the deflection angle between the azimuth and the ending point and based on a minimum and maximum distance range. To limit unnecessary detours, we aligned our network model on existing TLs and searched for connecting points within a range between 1.5 and 16 km and an opening angle of 130° compared to the target azimuth (Fig. 2). Using these constraints, we determined that a cutoff value of four or fewer connections avoided detours most effectively.

2.5. Selection of non-dominated alternatives and linear optimization

The network graph contained a set of connections (consecutive edges), in which the local low-cost points (vertices) could be connected from the starting to the ending point (see Section 1 of Fig. 3). We then computed for each edge the LCP, length, and degree to which it fulfills the *main objectives* (see Section 2.2). The degree f_Ω to which an objective Ω_i has been fulfilled ranged from 0 to 1 and was calculated by using Eq. 3, with $len(\cdot)$ being a function to determine the length of a path and $A_{\Omega i}$ corresponding to the areas that should not be crossed by the LCP to fulfill Ω_i. We then determined a combined LCP for each connection by assembling the partial LCPs and calculated a score for each connection that was normalized by the partial path lengths to allow comparing the path alternatives in terms of objective fulfillment. A set of combined LCPs, or *path alternatives*, was stored in a database. The resulting data revealed the degree to which each path alternative met the main objectives.

$$f_{\Omega_i} = 1 - \frac{len(LCP \cap A_{\Omega_i})}{len(LCP)} \tag{3}$$

Next, we determined all dominated path alternatives by comparing the calculated scores and deleted them from the database, as they did not adequately fulfill the main objectives. We compared the remaining path alternatives and marked and deleted any notably inferior choices. What remained at this point was a set of non-dominated path alternatives (Sections 2 and 3, Fig. 3), a set of paths from which each represents optimal trade-offs between more than one main objectives. Finally, we used linear programming (Eiselt & Sandblom, 2007) to determine the solution(s) that best fit the stakeholders' interests.

This linear programming approach used the experts' answers to determine weights $w_{\Omega i}$ for each objective fulfillment degree $f_{\Omega i}$ (see Eq. 3). For each path j out of a set of paths $\{1, \ldots, k\}$, the value z_j was calculated by summing the weighted products $w_{\Omega i} \cdot f_{\Omega i}$ for each objective i. The decision variable d_j then selected the path with a maximum z_j, which represents the best fit with regards to the main objectives and stakeholder's preference. We formalized the equation as:

Table 1
Influencing factors f used in the decision model, sorted by category and main objective. For the basic model, each factor was assigned a resistance R_f and a weight W_f, which were multiplied by applying Eq. 2 to a total resistance. A factor resistance R_f marked with a black square (∎) means that it was forbidden to cross the according area.

Category	Influencing factor f	R_f	W_f	Main objective Ω
Environmental protection	Biosphere reserve	4	2	Ω_2: Protect the environment
	Dry grassland: national importance	4	1	
	Dry grassland: cantonal importance	4	1	
	Flood plains: national importance	5	2	
	Flood plains: cantonal importance	4	1	
	Mires: national importance	∎	∎	
	Mires: cantonal importance	∎	∎	
	Bird protection area	4	1	
	Natural reserves	3	1	
	Protection areas according to hunting laws	∎	∎	
	Inventory of protected landscapes	5	2	Ω_3: Protect the landscape
	Mire landscapes	5	3	
	Parks: national importance	5	3	
	Parks: regional importance	5	2	
	UNESCO World Heritage Site	5	3	
	Landscapes worthy of protection	4	2	
	Characteristic objects worthy of protection	4	1	
	Arable land	1	1	
	Vineyards and orchards	1	1	
	Forest	4	2	
Technical feasibility	Natural hazard areas: avalanches	4	2	Ω_6: Decrease risks
	Natural hazard areas: floodings	4	2	
	Natural hazard areas: landslides	4	2	
	Natural hazard areas: rockfalls	4	2	
	Natural hazard areas: sink holes	4	2	
	Groundwater zones: strict	5	3	Ω_4: Ensure implementability
	Groundwater zones: less strict	5	2	
	Inappropriate relief	∎	∎	
	Inappropriate geologic underground	3	2	
	Underground facilities	4	2	
	Punishment when leaving a valley	5	1	
	Lakes	∎	∎	
	Rivers	5	2	
Urban planning	Historic places and areas	4	2	Ω_3: Protect the landscape
	Airports	∎	∎	Ω_6: Decrease risks
	Cable cars	4	1	
	Military sites	4	1	
	Gravel pits	1	1	Ω_4: Ensure implementability
	Special railways	3	1	
	Inappropriate aspect	4	1	
	Areas within a noise threshold of 40 dBA	5	1	Ω_1: Preserve living space
	Residential/work/mixed areas	5	3	
	Industrial areas	3	1	
	Tourism areas	4	2	

Table 1 (*continued*)

Category	Influencing factor f	R_f	W_f	Main objective Ω
	Public core areas	5	2	
	Cultural heritage: high importance	5	2	
	Cultural heritage: low importance	4	1	
	Potential visibility of new transmission line	5	2	
	Wide roads and railways	1	3	Ω_5: Increase bundling
	Existing transmission lines	1	3	
	Public transport areas	3	2	
	Tunnels	3	1	
	Infrastructure plants	1	1	

$$P: Max \quad z_j = \sum_i w_{\Omega_i} \cdot f_{\Omega_{ij}} \quad \forall j \in \{1, \dots, k\}$$
$$i \in \{1, \dots, 7\}$$
$$w_{\Omega_i} \in \{1, \dots, 5\}$$
$$0 \le f_{\Omega_i} \le 1 \tag{4}$$
$$d_j = \begin{cases} 1 & \text{if } z_j \text{ is the maximum value of all } k \text{ path alternatives} \\ 0 & \text{otherwise} \end{cases}$$
$$\sum_j d_j = 1$$

This procedure was conducted for all k path alternatives. The best alternative was moved to the top of a priority ranking list and disregarded it during the next run. This method yielded a priority ranking of all path alternatives based on stakeholders' interests. Our primary concern was to determine whether the described method successfully computed distinct TLPs that outperformed the LCP in terms of how realistic the solutions were. We especially wanted to know whether the priority ranking of the proposed path alternatives matched stakeholders' expectations regarding the implementability of the TL.

2.6. Participants and procedure

Ten TL planning experts, each of them familiar with Swiss legislation and background knowledge of the study area, agreed to voluntarily participate in a two-part study. Following our participants' advice, the study was based on an intermediate scenario with balanced interests between keeping costs as low as possible and protecting the environment and the landscape. We set up a two-part online questionnaire and a web-based service that displayed the layers included in the decision model and the resulting path alternatives.

In the first part of the questionnaire, participants were asked to assess the importance of the seven main objectives (Ω_1–Ω_7, see Table 1 and Table 2) on a 5-point Likert importance scale. These answers were then used as attribute weights in the linear programming model. The model calculated a ranking of all path alternatives based on the interests of the stakeholders. Without knowing the results of the first assessment, the stakeholders then assessed whether or not the k proposed path alternatives and the full LCP could be realized. The planning area, path alternatives, full LCP, and layers were uploaded into a web-based GIS platform as shown in Fig. 4. Participants ranked the alternatives using the same 5-point Likert importance scale.

In the second part of the questionnaire, the participants were provided with the ranked results of their assessments. The participants then assessed on a Likert 5-point agreement scale to what extent they agreed with the suggested ranking and whether the ranking and the path alternatives properly represented their interests. The answers were then statistically evaluated using exploratory data analysis.

3. Results

The results are structured in the same way as we conducted the study. The first questionnaire served to determine the main objectives

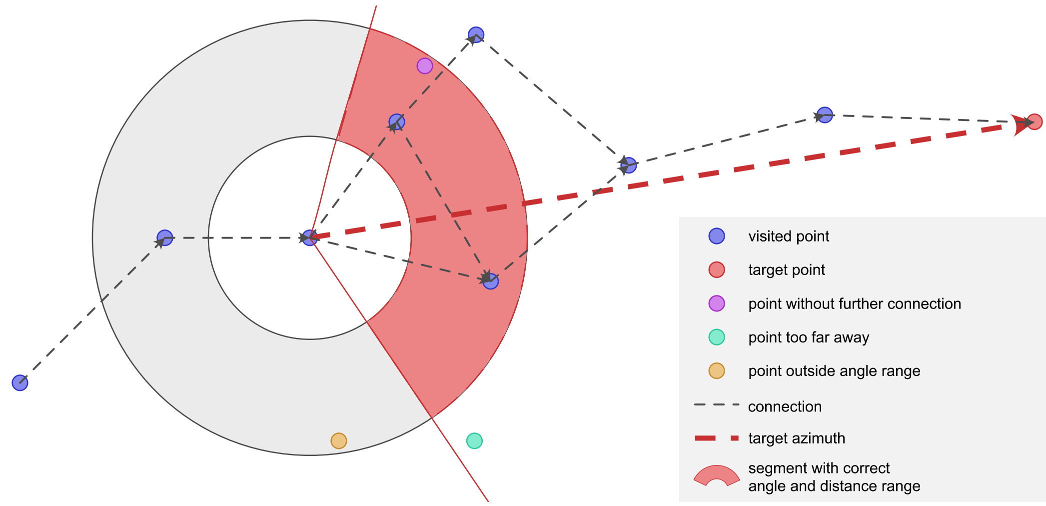

Fig. 2. The geometric decision rules for connecting the nodes with each other: the distance range is defined by a lower and an upper distance and the next potential node must lie within a specific angle with regards to the target azimuth.

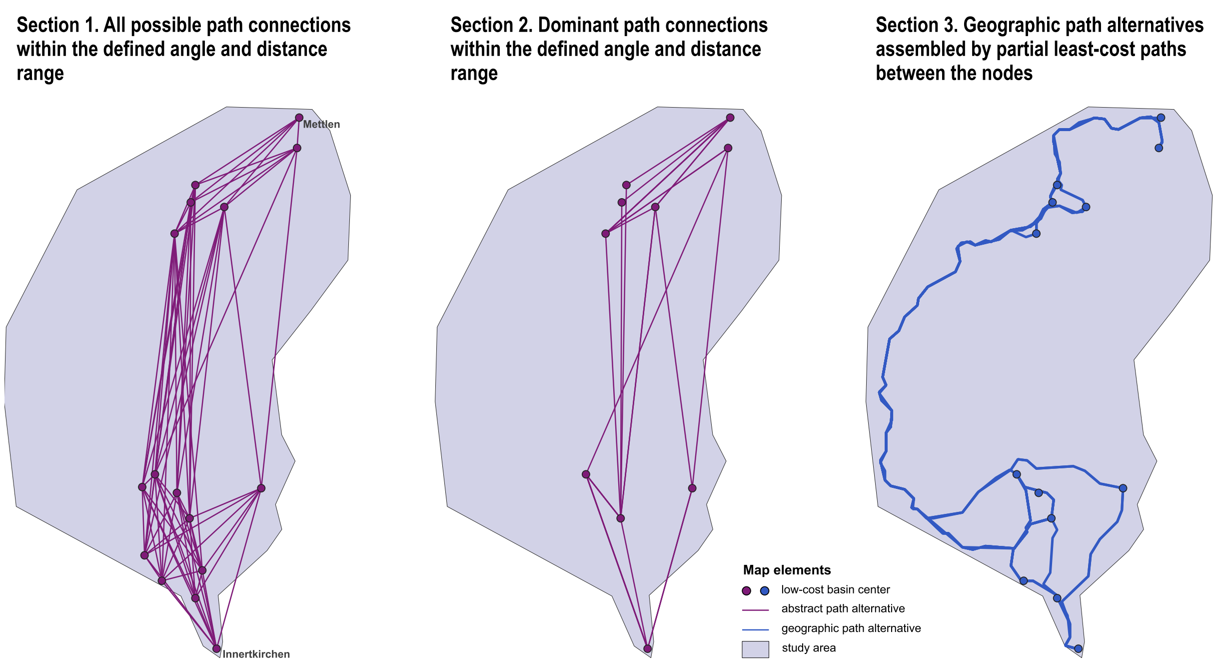

Fig. 3. Stepwise procedure for reducing the number of all possible connections from a random scenario. Section 1: The algorithm searches for connections between low-cost basin center points within an angle and distance range (72 segments assembled to 239 path combinations). Section 2: Eight non-dominated connections were identified while dominated alternatives were deleted. Section 3: Geographic representation of Section 2, as rendered by assembling the partial LCPs into full paths.

that the stakeholders pursue when planning a TL. From these results, we calculated the alleged optimal path alternative ranking. In addition, we asked participants to reveal which features they highlight as being most important for negotiations and used their answers to determine *interest groups* and *mindset groups* by applying a Principal Component analysis (PCA) in combination with k-means clustering.

By filling out the second questionnaire, stakeholders assessed the calculated path alternatives and our novel method in general. We then compared the calculated rankings with the rated rankings using a correlation analysis. Finally, we evaluated the results of the second questionnaire by applying a one-way Analysis of Variance (ANOVA) to investigate if, and if so to what extent, the mindset and years of experience might influence the results.

3.1. Exploratory data analysis of the first part of the study

We began the first part of our evaluation by exploring the answers regarding the main objectives Ω_i (Table 2) and those regarding the features important for negotiation Λ_i (Table 3). Stakeholders assigned the three objectives aimed at protecting the environment, the landscape, and living space Ω_1 to Ω_3 a high importance ($4.3 \leq \mu \leq 4.8$) with a comparably small variance ($.4 \leq \sigma \leq .8$), while factors regarding planning, ensuring implementability, increasing the bundling with existing lines, and decreasing risks Ω_4 to Ω_6 were assigned a moderate importance ($3.7 \leq \mu \leq 3.8$) with ambiguous variance ($.5 \leq \sigma \leq 1.4$). However, decreasing the path length Ω_7 was considered the least important ($\mu = 2.0$) and was as controversial as ensuring the implementability ($1.2 \leq \sigma \leq 1.4$). By knowing participants' interests regarding the main objectives

Table 2

Participants P_i including their affiliation C_P and the years of experience Y_P in planning or approving TLs. The Ω_i show the degree to which participants considered the corresponding main objective to be important. The associated interest group O_P results from clustering the ratings by k-means. Ω_1: preserve living space, Ω_2: protect the environment, Ω_3: protect the landscape, Ω_4: ensure implementability, Ω_5: increase bundling, Ω_6: decrease risks, Ω_7: decrease path length. Ω_7 is non-spatial and is not therefore listed in Table 1.

P_i	C_P	Y_P	Ω_1	Ω_2	Ω_3	Ω_4	Ω_5	Ω_6	Ω_7	O_P
A	C_1	27	5	4	4	4	3	3	1	O_2
B	C_2	3	5	5	4	3	4	4	2	O_4
C	C_3	20	4	5	3	5	4	4	1	O_1
D	C_4	0	5	5	5	1	4	4	1	O_2
E	C_2	9	5	5	5	5	3	4	3	O_1
F	C_5	7	5	4	5	4	4	4	4	O_4
G	C_2	5	2	4	4	5	4	5	5	O_3
H	C_4	6	4	5	5	4	5	3	3	O_1
I	C_2	20	4	4	3	5	4	3	2	O_1
J	C_3	5	5	4	4	5	4	3	2	O_1
μ	–	10.0	4.4	4.5	4.2	4.1	3.9	3.7	2.4	–
σ	–	9.03	0.97	0.53	0.79	1.29	0.57	0.67	1.35	–

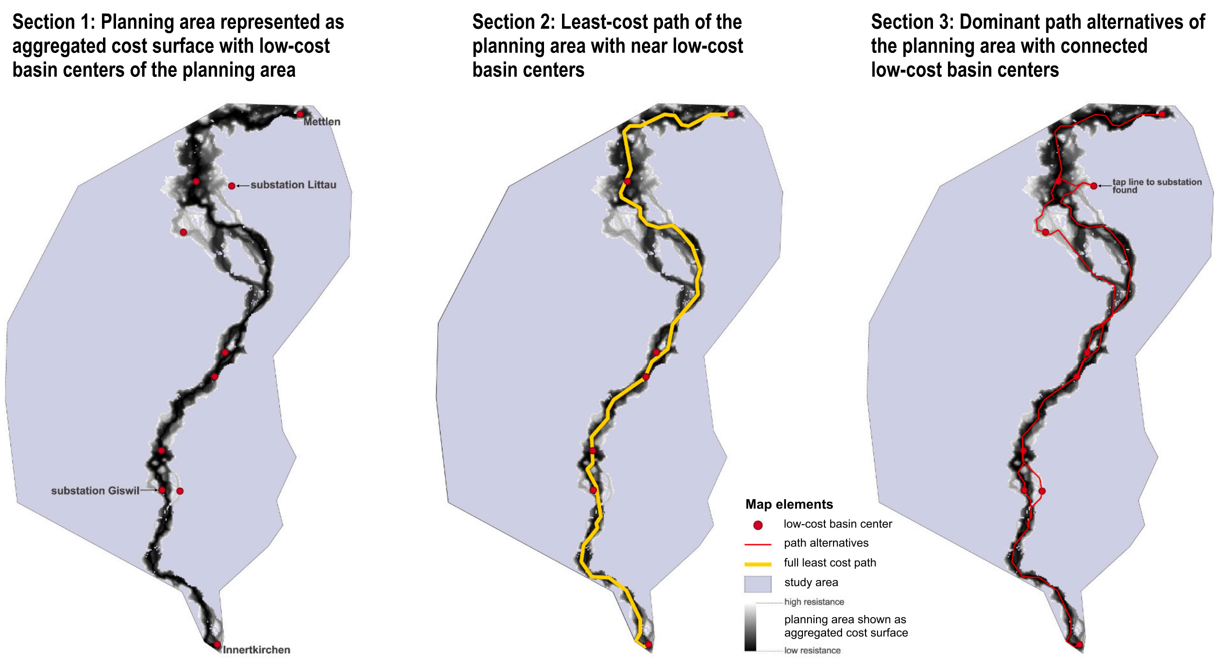

Fig. 4. Maps as provided to the participants in the web-based GIS platform. Section 1: The planning area is represented as a masked accumulated cost surface. Section 2: The full LCP is represented as a yellow line that is routed no farther than 300 m away from five low-cost basin centers. Section 3: The path alternatives are represented as red lines. The tap line to the substation Littau was realistically modeled and used no defined rules. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Participants P_i including their affiliation C_P and the years of experience Y_P in planning or approving TLs. Λ_i shows how participants rated the corresponding feature as being more or less important for a successful negotiation. The associated mindset group L_P results from clustering the ratings by k-means. Λ_1: knowing the legislation, Λ_2: arguing consistently, Λ_3: professional position, Λ_4: affiliation, Λ_5: experience, Λ_6: authority, Λ_7: communication skills, Λ_8: self-awareness, Λ_9: active listening, Λ_{10}: finding compromises, Λ_{11}: remaining objective.

P_i	C_P	Y_P	Λ_1	Λ_2	Λ_3	Λ_4	Λ_5	Λ_6	Λ_7	Λ_8	Λ_9	Λ_{10}	Λ_{11}	L_P
A	C_1	27	5	3	2	2	4	4	4	4	5	5	5	L_4
B	C_2	3	5	2	3	4	3	2	4	2	4	3	3	L_1
C	C_3	20	4	4	3	3	4	5	5	5	5	5	5	L_3
D	C_4	0	5	5	3	2	4	2	4	4	5	4	5	L_4
E	C_2	9	5	4	3	3	4	4	5	5	5	4	5	L_3
F	C_5	7	5	4	3	4	4	4	4	4	4	3	4	L_1
G	C_2	5	5	4	2	4	3	1	5	4	5	1	5	L_2
H	C_4	6	5	3	2	5	5	5	5	5	5	5	5	L_3
I	C_2	20	2	4	3	4	5	3	5	5	5	5	5	L_3
J	C_3	5	4	5	3	4	4	3	5	5	5	3	5	L_3
μ	–	10.0	4.5	3.8	2.7	3.5	4.0	3.3	4.6	4.3	4.8	3.8	4.7	–
σ	–	9.03	0.97	0.92	0.48	0.97	0.67	1.34	0.52	0.95	0.42	1.32	0.67	–

Ω_i, we calculated the ranking order of all path alternatives (Table 6), as detailed in Section 3.3.

Regarding the features important for negotiation Λ_i (Table 3) knowing the legislation Λ_1 and the willingness to compromise Λ_{10} were considered most important ($4.8 \le \mu \le 4.0$ and $.4 \le \sigma \le .8$). In contrast, the professional position Λ_3 and affiliation Λ_4 were considered least important ($2.8 \le \mu \le 3.0$ and $.4 \le \sigma \le .8$). The next section will explain how we used these values to assign each participant to a cluster that should most reliably represent their mindset when aiming to negotiate successfully.

3.2. Principal component analysis and cluster analysis

Table 2 lists the results regarding the main objectives Ωi that the stakeholders considered most important to achieve. In contrast, Table 3 lists the results regarding the features Λ_i that stakeholders considered to be important for negotiating successfully. We conducted a PCA on the results of all Ωi and Λ_i to reduce the dimensionality, aimed at obtaining superordinate interests and features important for negotiations that we could use in further analyses. We then grouped the participants into clusters by applying k-means clustering on the first n Principal Components (PCs) that met Kaiser's criterion. In this way, we obtained *interest groups* and *mindset groups* which aggregate participants with a similar attitude toward main objectives and about features they believe are more or less important for successful negotiation.

The PCA demonstrated that for both, Ωi and Λ_i, four PCs were needed to fulfill Kaiser's criterion (Field, Miles, & Field, 2012), which explained 88.0% and 89.3% of the variance, respectively. From the factor loadings listed in Table 4, we determined $PC1_\Omega$ as 'protect the living space of humans and animals,' $PC2_\Omega$ as 'ensure the TL can be constructed within the human living space,' $PC3_\Omega$ as 'reduce environmental impact,' and $PC4_\Omega$ as 'reduce urban sprawl.' Concerning the mindset groups, we determined $PC1_\Lambda$ as 'factual knowledge vs. communication skills,' $PC2_\Lambda$ as 'find compromises through authority vs. convincing others through tactics,' $PC3_\Lambda$ as 'solution orientation,' and $PC4_\Lambda$ as 'professional background.'

We then set the number of clusters as 4, conducted k-means clustering on the factor loadings, and obtained the interest groups O_P (Table 2) and the mindset groups L_P (Table 3) relating to participants P_i. Section 3.6 describes how we used both group associations for determining, whether or not they have an influence on the attitude toward our novel method.

Table 4
The factor loadings obtained by applying PCA on the main objectives Ω_i and on the features considered important for negotiation Λ_i (Table 3). The four PC explain 88.6% of the variance.

Ω_i	Objectives	PC1	PC2	PC3	PC4
Ω_1	preserve living space	−0.56	−0.11	−0.29	0.21
Ω_2	protect the environment	−0.33	0.37	0.29	−0.42
Ω_3	protect the landscape	−0.19	0.54	−0.35	0.47
Ω_4	ensure implementability	0.43	−0.4	−0.06	0.07
Ω_5	increase bundling	0.1	0.27	0.78	0.37
Ω_6	decrease risk	0.3	0.46	−0.24	−0.56
Ω_7	decrease path length	0.51	0.34	−0.22	0.33

Λ_i	Features	PC1	PC2	PC3	PC4
Λ_1	expertise	0.25	−0.08	−0.38	0.32
Λ_2	argument consistently	−0.24	−0.42	0	−0.4
Λ_3	professional position	0.03	0.08	0.21	−0.73
Λ_4	affiliation	0.01	0.13	0.68	0.33
Λ_5	experience	−0.36	0.35	0.06	−0.03
Λ_6	authority	−0.24	0.5	−0.12	0.1
Λ_7	communication skills	−0.32	−0.17	0.41	0.22
Λ_8	self-awareness	−0.45	−0.05	0.07	0.01
Λ_9	active listening	−0.38	−0.28	−0.2	0.15
Λ_{10}	find compromises	−0.27	0.5	−0.26	−0.11
Λ_{11}	remain objective	−0.41	−0.27	−0.2	0.11

3.3. Evaluation of the Pareto optimal LCPs and the ranking

We started the second part of our evaluation by asking participants, to what extent they agreed with the defined scenario, the proposed planning area, and the calculated full LCP (Fig. 5). In general, stakeholders' acceptance regarding the given scenario was moderate and controversial ($R(Q_1) : \mu = 3.0,\ \sigma = 1.333$). The agreement with the planning area determined by the 3D Decision Support System (3D DSS) was higher ($R(Q_2) : \mu = 3.5,\ \sigma = .972$). Regarding the proposed full LCP, the responses showed that it was regarded as fitting the proposed scenario ($R(Q_5) : \mu = 3.8,\ \sigma = 1.317$) while showing a lower acceptance ($R(Q_3) : \mu = 2.7,\ \sigma = 1.337$) and a medium level of confidence that it could be realized ($R(Q_4) : \mu = 2.9,\ \sigma = 1.287$). The error bars in Fig. 5 indicate if the stakeholders' opinions were controversial.

Next, we asked the experts to rank the resulting path alternatives. For this, we posed the three questions Q_8, Q_9, and Q_{10} in order to evaluate, whether the kind, how the question was posed, influenced the ranking. The box plots in panels A, B, and C (Fig. 6) show the results on the questions Q_8, Q_9, and Q_{10} (Table 7). Rating the path alternatives directly (panel A) yielded the same order as rating them by a subjective ranking (panel C). The ranking changed slightly when the stakeholders had to decide whether or not they were convinced by the path alternative. The negative outliers in panels A and B are based on the fact that one stakeholder disagreed with all alternatives regarding Q_8 and Q_9. However, Q_{10} supported them in distinguishing better and worse path alternatives. A comparison of panels A and B also revealed that forcing stakeholders to decide based on a narrower likelihood scale yielded a similar order, although with higher support or refusal and approximately 30% less variance with regard to the path alternative with the highest or lowest rank.

3.4. Evaluation of the ranking order of the path alternatives

Next, we compared the path alternatives ranking order calculated by our method with the rating order that stakeholders assessed to be best (Table 6). We matched stakeholders' rankings to those determined by our method and calculated Kendall's τ to obtain a correlation measure between the calculated and self-assessed ranking orders. In three cases, the correlation was above 80% from which one achieved a perfect match. The results in Table 6 reveal that stakeholders with a high Kendall's τ assessed the ranking as reasonable ($R(Q_6)$) and one which represented their interests well ($R(Q_7)$). The relationship between the predicted and the assessed ranking order yielded a weak correlation with medium variance ($\mu_\tau = .390,\ \sigma_\tau = .550$). Stakeholders' accordance with the rated ranking order did not vary across the calculated ranking order patterns (Table 6) that our method determined to be optimal for each stakeholder ($F(1,8) = .133,\ p = .725$).

Stakeholders expected an average of 6.5 different ranking orders from our novel method to be considered optimal after asking ten participants. However, our method determined three different ranking orders (Table 6) based on stakeholders' interests. Indeed, the values Ω_i in Tabe 2 show generally low to medium variance. Therefore, we conducted a sensitivity analysis to determine the number of all possible ranking orders under the given scenario. From a total of 2,187 permutations (three possibilities [1,5,9] raised to the power of seven main objectives Ω_i), we obtained 58 distinct possible ranking orders. Thus, we regard the outcome of three proposed sets of ranking orders as a matter of the low variance of Ω_i.

In general, stakeholders perceived the number of proposed alternatives as 'about right' ($R(Q_{12}) : \mu = 3.4,\ \sigma = .966$) while the spatial variance was assessed as being too low ($R(Q_{13}) : \mu = 1.9,\ \sigma = .876$) (Fig. 7, panel A). The question of whether the proposed ranking order was perceived to be appropriate (Q_{14}) or that it represented stakeholders' interests appropriately (Q_{15}) yielded an intermediate result (R

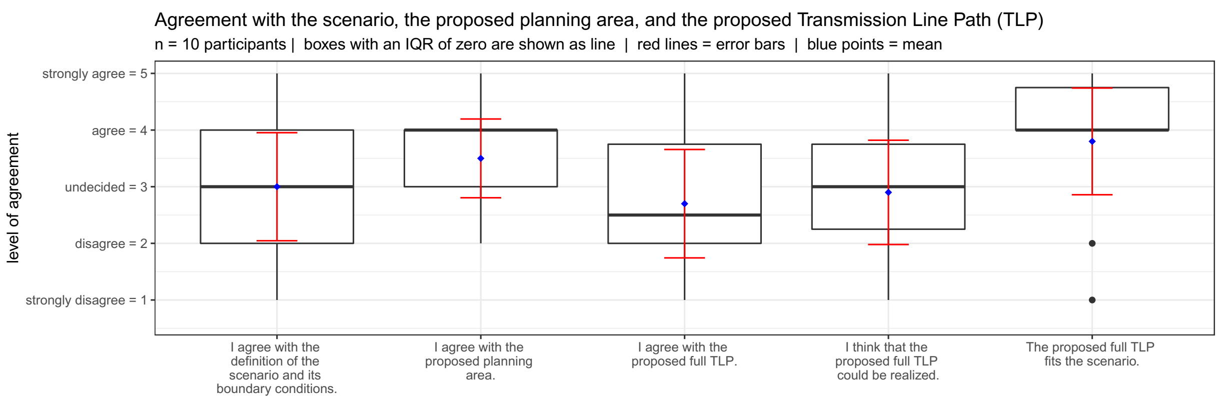

Fig. 5. The box plots show participants' agreement with the scenario, the calculated planning area, and the calculated LCP (yellow line in Section 2, Fig. 4) on a Likert 5-point agreement scale. Boxes with an interquartile range of zero coincide with the mean and are represented as a straight line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$(Q_{14}): \mu = 3.3,\ \sigma = 1.418$ and $R(Q_{15}): \mu = 3.2,\ \sigma = 1.135$) (Fig. 7, panel B).

3.5. How stakeholders assessed the general aspects of our novel method

Stakeholders accepted the key elements of our novel method: a) to connect low-cost points with each other (Q_{16}), b) to use dominance for determining optimal path alternatives (Q_{17}), and c) to rank path alternatives based on objectives (Q_{18}). Those key elements yielded a median of between $4.0 \leq \mu_{1/2} \leq 4.5$, means between $3.67 \leq \mu \leq 4.44$, and standard deviations between $.53 \leq \sigma \leq 1.0$ (Fig. 7, panel C). Regarding the realizability of the calculated TLPs, the results were assessed ambiguously ($R(Q_{19}): \mu = 3.4,\ \sigma = .966$) with a median between 'undecided' and 'agree' (Fig. 7, panel D).

Stakeholders further assert that the applied workflow has the potential to be applied in practice ($R(Q_{20}): \mu = 3.8,\ \sigma = 1.317$) and to simplify discussions ($R(Q_{21}): \mu = 4.5,\ \sigma = .707$) (Fig. 7, panel D). This is consistent with the stakeholders' assertion that the 3D DSS supports matter-of-fact argumentation ($R(Q_{22}): \mu = 4.2,\ \sigma = .919$), which is regarded as an important factor when discussing about the route of a TL (Fig. 7, panel E).

Stakeholders regarded the 3D DSS as being supportive for planning ($R(Q_{23}): \mu = 4.6,\ \sigma = .516$). Furthermore, the stakeholders agreed that the method used by the 3D DSS is transparent ($R(Q_{25}): \mu = 3.7,\ \sigma = .823$). Even though stakeholders slightly agreed that the 3D DSS approach is practice-oriented ($R(Q_{24}): \mu = 3.3,\ \sigma = .823$), it has a good chance of being accepted for real-life applications ($R(Q_{27}): \mu = 3.4,\ \sigma = .843$). The most criticized point was the lack of consideration for the legislation ($R(Q_{26}): \mu = 3.2,\ \sigma = 1.135$), mainly because scattered settlements were not circumvented appropriately (Fig. 7, panel E).

3.6. ANOVA tests for finding relationships between stakeholders' attitudes and their answers

We were particularly interested in investigating whether the following seven independent variables x (Table 5) could explain the responses to Q_{11} to Q_{27}:

- Y_P: years of experience (see Section 3.3)
- C_P affiliation
- τ_P: correlation between the predicted and the assessed ranking order (see Section 3.4)
- O_P: interest group (see Section 3.2)
- L_P: mindset group (see Section 3.2)
- $R(Q_1)$: agreement with the scenario (see Section 3.3)
- $R(Q_2)$: agreement with the planning area (see Section 3.3)

As τ_P was given on a continuous scale at this point, while Y_P, $R(Q_1)$, and $R(Q_2)$ were stored on an ordinal scale, we applied k-means clustering to τ_P and Y_P to obtain four clusters of similar values. Moreover, we simplified the 5-point Likert scales of $R(Q_1)$ and $R(Q_2)$ to a 3-point Likert agreement scale using the levels 'disagree', 'neutral', and 'agree.' After this redefinition, Levene's test identified unequal variances for τ_P ($F(3) = 3.612$, $p = .015$) and L_P ($F(3) = 2.824$, $p = .040$). Therefore, any subsequent results concerning τ_P and L_P must be treated with caution.

For each question, we conducted a one-way ANOVA (Field et al., 2012) by using the listed independent variables as initial regressors. We restricted each model by applying the backward elimination procedure (Howell, 2010) to determine the set of regressors with the lowest Akaike Information Criterion (AIC). We then conducted a one-way ANOVA based on this model and obtained the significance levels for each question (see Table 5).

The results show that the answers regarding the five questions Q_{11}, Q_{15}, Q_{18}, Q_{22}, and Q_{23} varied significantly ($\alpha = .05$) across some independent variables. L_P and $R(Q_2)$ both influence the notion of how many distinct ranking orders should be provided by our novel method (Q_{11}) while $R(Q_2)$ influenced the notion of whether the ranking order adequately represented the stakeholders' interests properly (Q_{15}). This connection seems clear, as a planning area that does not meet stakeholder's expectations cannot properly represent individual interests regarding a ranking order. Stakeholders with a different mindset regarding successful negotiations L_P assess the question of whether the ranking of the path alternatives based on objectives is meaningful (Q_{18}). The notion of whether the 3D DSS supports planning (Q_{22}) is highly ambiguous, as it is influenced by Y_P, C_P, τ_P, O_P, and $R(Q_2)$. Finally, stakeholders with different τ_P, L_P, and $R(Q_1)$ rated the question regarding the 3D DSS's practice-orientedness (Q_{23}) differently. Besides this, the regressors did not have any other influence on stakeholders' answers, which shows that in general, the results have a high level of support across all of the groups.

4. Discussion

4.1. Routing of path alternatives

Our results, as determined by our novel path optimization method, indicated that the full LCP crossed several local low-cost points. We further observed that the spatial variability among the Pareto optimal path alternatives was much higher than with the methods investigated by Schito et al. (2019). From this, we deduced that the consideration of the low-cost basins increased the spatial variability of the proposed TLP while keeping costs low and accordingly, fulfilling at least one of the objectives to a high standard. Since we detected that five low-cost points were located within 300 m of the full LCP (see Section 2, Fig. 4), we

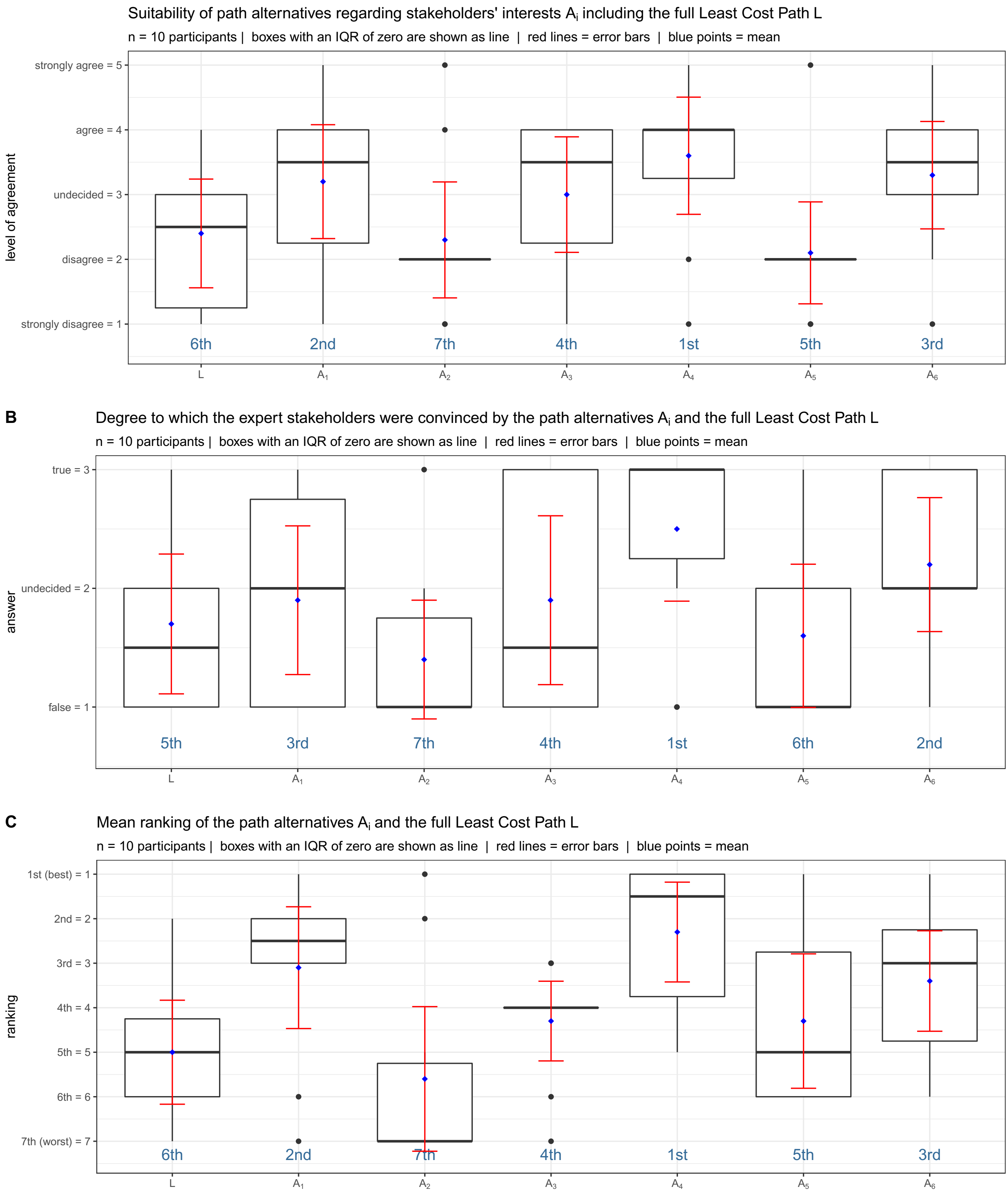

Fig. 6. The answers to the questions Q_8, Q_9, and Q_{10} shown in Table 7, ordered in panel A, B, and C. The box plots show the participants' answers regarding the subjective goodness of the calculated full LCP (yellow line in Section 2, Fig. 4) and with the path alternatives (red lines in Section 3, Fig. 4) by using the Likert scale defined in Table 7. Boxes with an interquartile range of zero coincide with the median and are represented as a straight line. Red lines represent error bars while blue points represent mean values. The ranking is shown on the bottom of each chart. In cases where two different path alternatives obtained the same mean, the alternative with the smaller standard deviation was given the higher ranking. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

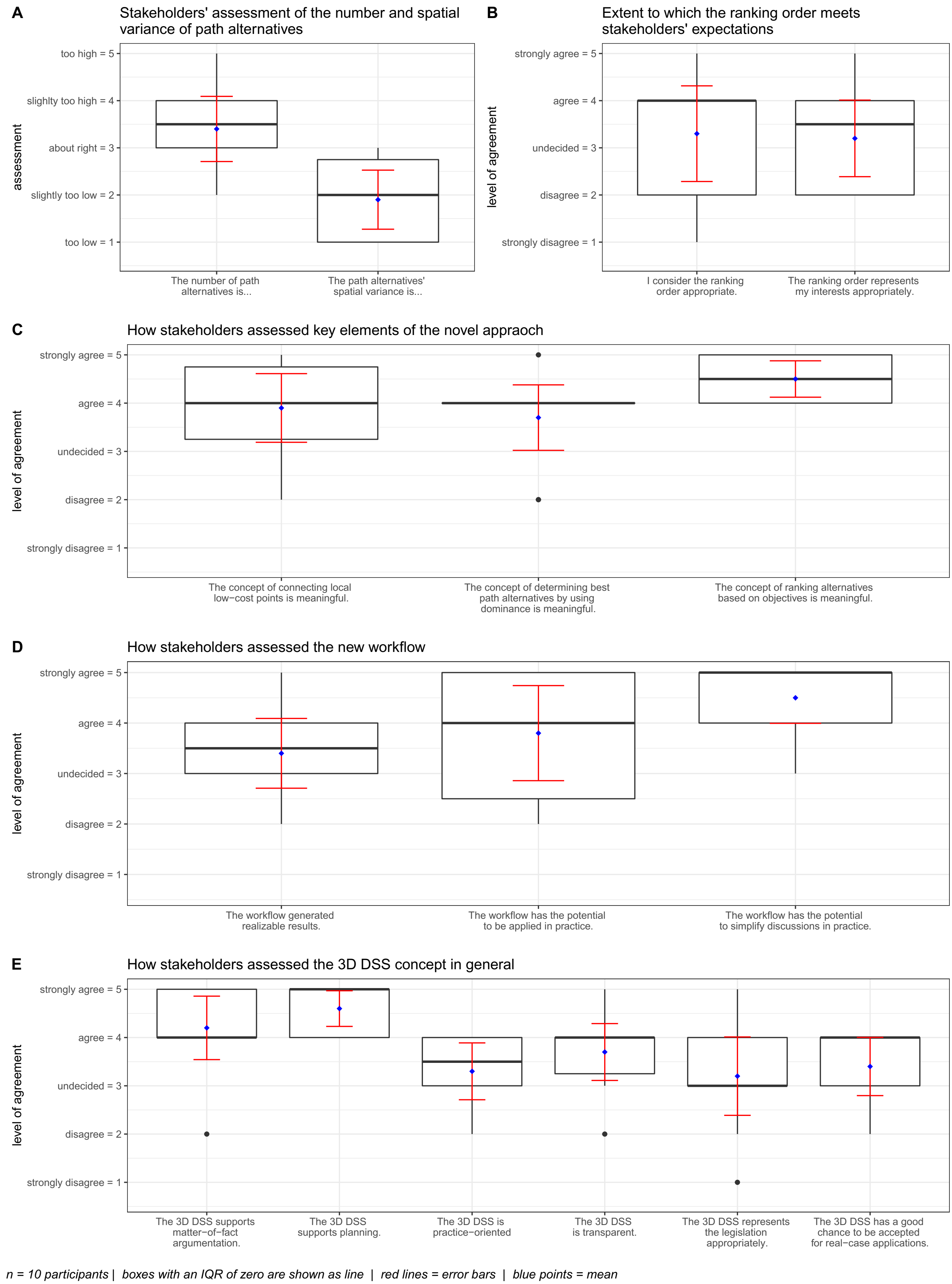

Fig. 7. Results of the general aspects regarding our novel method, split between panels A to E.

Table 5
The resulting significance levels of the one-way ANOVA. x defines the following independent variables depending on participant P's answers: Y_P: years of experience, C_P affiliation, τ_P: correlation between the predicted and the assessed ranking order, O_P: interest group, L_P: mindset group, $R(Q_1)$: agreement with the scenario, $R(Q_2)$: agreement with the planning area. (.): $p < .10$, (*): $p < .05$, (**): $p < .01$, (***): $p < .001$.

x	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}	Q_{17}	Q_{18}
Y_P				.				
C_P								
τ_P								
O_P								
L_P	***							*
$R(Q_1)$								
$R(Q_2)$	**				*			.

x	Q_{19}	Q_{20}	Q_{21}	Q_{22}	Q_{23}	Q_{24}	Q_{25}	Q_{26}	Q_{27}
Y_P				**	.	.		.	
C_P				**		.			
τ_P				*	*				
O_P				*					
L_P					*				
$R(Q_1)$					*				
$R(Q_2)$				*		.		.	

Table 6
The calculated ranking order for each participant P_i results from the answers regarding their interest of Table 2. Participants further assessed the ranking order on their own discretion. A_i describes the path alternatives and L the full LCP. Kendall's τ was used to estimate the correlation between the calculated and the assessed ranking order. $R(Q_i)$ denotes the responses to the questions Q_i, which are listed in Table 7. $R(Q_6)$ refers to what extent the calculated ranking order is reasonable and $R(Q_7)$ refers to the question, to what extent the calculated ranking order correctly represents the stakeholders' interests (Table 7). τ_P and R_i are detailed with the average μ and the standard deviation σ.

P_i	Calculated ranking order	Rated ranking order	τ_P	$R(Q_6)$	$R(Q_7)$
A	$[A_1, A_4, A_3, A_6, L, A_2, A_5]$	$[A_5, A_4, A_6, L, A_2, A_1, A_3]$	−0.238	2	1
B	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	1.000	4	2
C	$[A_1, A_4, A_3, A_6, L, A_2, A_5]$	$[A_4, A_6, A_1, A_3, L, A_5, A_2]$	0.619	4	2
D	$[A_1, A_4, A_3, A_6, L, A_2, A_5]$	$[A_6, A_1, A_4, A_3, L, A_5, A_2]$	0.619	3	3
E	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	$[A_2, A_5, A_1, A_3, A_4, A_6, L]$	−0.333	2	1
F	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	$[A_4, A_1, A_6, A_3, A_5, L, A_2]$	0.905	3	1
G	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	$[A_4, A_6, A_1, A_3, A_5, L, A_2]$	0.810	4	3
H	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	$[A_1, L, A_3, A_4, A_6, A_5, A_2]$	0.429	5	1
I	$[A_4, A_1, A_6, A_3, L, A_5, A_2]$	$[A_5, A_2, L, A_4, A_6, A_5, A_2]$	−0.524	4	2
J	$[A_4, A_1, A_6, A_3, L, A_2, A_5]$	$[A_4, A_1, A_3, A_6, A_5, 2, L]$	0.619	3	3
μ	–	–	0.390	3.4	1.9
σ	–	–	0.550	0.967	0.876

deduced that these low-cost points significantly influence the TLP's routing due to the low costs in their surroundings. We substantiated this finding with three additional low-cost points that attract the path to pass through an alternative corridor (Section 3, Fig. 4). Since these low-cost points yielded distinct Pareto optimal solutions, we can assume that our novel method reliably generates different routing options that stakeholders can use for negotiations regarding path alternatives.

However, stakeholders expected a higher spatial variability regarding the path alternatives and a higher variability in the optimal ranking orders. This former desire coincides with the modest level of consent regarding the given scenario and the proposed planning area. We agree with the stakeholders that making decisions during a real project requires comparing different alternatives with a high spatial variability. However, the 3D DSS meets this requirement by setting the scenarios differently. A comparison between Fig. 3 and Fig. 4 (see Section 3) does indeed show a high spatial variability between the defined scenarios–mainly because different factors could not be crossed. However, the question as to what extent a specific factor should be considered worthy of protection, or even if it should be completely be forbidden to cross, is highly controversial in practice, even though it has the greatest effect on the spatial variability of the alternative paths. Another reason is given by the fact that the 3D DSS determined three optimal path alternative rankings out of 58 possible rankings. We conclude from the low number of determined rankings that the interests were either biased due to the legislation, the affiliation, or according to

Table 7
The questions posed in the questionnaire and their corresponding code Q_i.

Q_i	Question	Likert scale type
1	I agree with the definition of the scenario and its boundary conditions.	5-point agreement.
2	I agree with the proposed planning area.	5-point agreement.
3	I agree with the proposed full TLP.	5-point agreement.
4	I think that the proposed full TLP could be realized.	5-point agreement.
5	The proposed full TLP fits the scenario.	5-point agreement.
6	I find the calculated ranking to be reasonable.	5-point agreement
7	The calculated ranking suitably represents my interests.	5-point agreement
8	The path alternative suits my interest.	5-point agreement
9	The path alternative convinced me.	3-point likelihood
10	I would rank the path alternatives in the following order	7-point ranking
11	Assume that ten participants define their interests. How many different ranking orders do you expect to be determined to be optimal?	range [1;10]
12	The number of path alternatives is [too low – too high].	5-point quantity
13	The spatial variance of the path alternatives is [too low – too high]	5-point quantity
14	I consider the ranking order appropriate.	5-point agreement
15	The ranking order represents my interests appropriately.	5-point agreement
16	The concept of connecting local low-cost points is meaningful.	5-point agreement
17	The concept of determining the best path alternatives by using dominance is meaningful.	5-point agreement
18	The concept of ranking alternatives based on objectives is meaningful.	5-point agreement
19	The workflow generated realizable results.	5-point agreement
20	The workflow has the potential to be applied in practice.	5-point agreement
21	The workflow has the potential to simplify discussions in practice.	5-point agreement
22	The 3D DSS supports matter-of-fact argumentation.	5-point agreement
23	The 3D DSS supports planning.	5-point agreement
24	The 3D DSS is practice-oriented.	5-point agreement
25	The 3D DSS is transparent.	5-point agreement
26	The 3D DSS represents the legislation appropriately.	5-point agreement
27	The 3D DSS has a good chance of being accepted for real-life applications.	5-point agreement

the mandate, or that some of the 58 ranking orders do not make sense in reality (e.g., by weighting the main objective 'protect the living space' as low, which neglects urban planning legislation). As a possibility for obtaining a higher variability, interests could be ranked instead of applying the direct rating method (Eisenführ, Weber, & Langer, 2010).

4.2. *A method suitable for obtaining realizable paths?*

Our results show a significant improvement regarding the realizability of the obtained TLPs. From this, we deduce that our approach to calculating Pareto optimal path alternatives by combining partially optimal LCPs with regard to different objectives exceeds the degree of realism as the classical LCP analysis would have been applied. Moreover, the stakeholders endorsed the key elements of our novel approach and they assessed that it has a high chance of simplifying discussions, supporting matter-of-fact argumentation, and facilitating planning. Our novel method finds spatially distinct, low-cost path alternatives within the planning area that would have been detected by eye on the aggregated cost surface (Section 2.4), but not by any other automated approach with that distinctiveness. Even though a k-shortest path algorithm (Medrano & Church, 2011) would certainly have found feasible path alternatives, our novel method determines Pareto optimal low-cost solutions that can clearly be distinguished from each other. Stakeholders particularly endorsed the key concept of finding Pareto optimal path alternatives–perhaps because it supports matter-of-fact argumentation. Compared to the study conducted by Medrano & Church, 2011, which took four days of computing time, our method took less than one hour (also by using an Intel Core i7 processor) to determine all dominated and non-dominated path alternatives.

4.3. *A method for connecting substations?*

In the real grid expansion project in Innertkirchen-Mettlen, the substations of Giswil and Littau must be connected to the new TL, either directly or by a tap line. We used our novel method to evaluate whether or not it could be applied in finding feasible routes while considering how to connect these substations. While setting up the scenario, we were extremely surprised to find that under certain conditions, our novel method considered both direct connections (mainly Giswil) and tap lines (mainly Littau) to be Pareto optimal. In both cases, but more surprising in the case of Littau because of the specific geographic conditions, we could even model the direction in which the TL is connected with the substation today.

However, stakeholders reserved most of their criticism for the path alternatives with the connection to the substation in Littau. It is clear that the connection did not correspond to a tap line running out from a main line. This, in turn, yielded the TL in the current case to pass too close to the settled area near Lucerne. In contrast, stakeholders preferred the alternatives that connected the substation in Giswil by a direct connection. From this, we give our novel method a high potential for fostering connections to constraint points. However, we see an even higher potential depending on whether the mechanism for identifying tap lines can be improved. One idea for improving this mechanism could make use of our novel method by calculating the partial LCP from the constraint points to near the low-cost points. If the determined partial LCP coalesces with another partial LCP at a junction point, both the LCP sections could be merged and used in further analyses.

4.4. *How the method could further enhance spatial variability*

We realize that we conducted our study and obtained our findings based on just one single scenario in one particular study area. However, we also aimed to support our assertions by statistical power, which in consideration of the limited number of TL planning experts led us to the decision to define one intermediate scenario with balanced interests. The responses of the stakeholders to our decision was mixed. Sometimes, the stakeholders felt too constrained with the given scenario or they did not perceive the legislative provision regarding protected areas as being equally important. A method that might have mitigated this circumstance but ended up complicating the statistical evaluation was to let

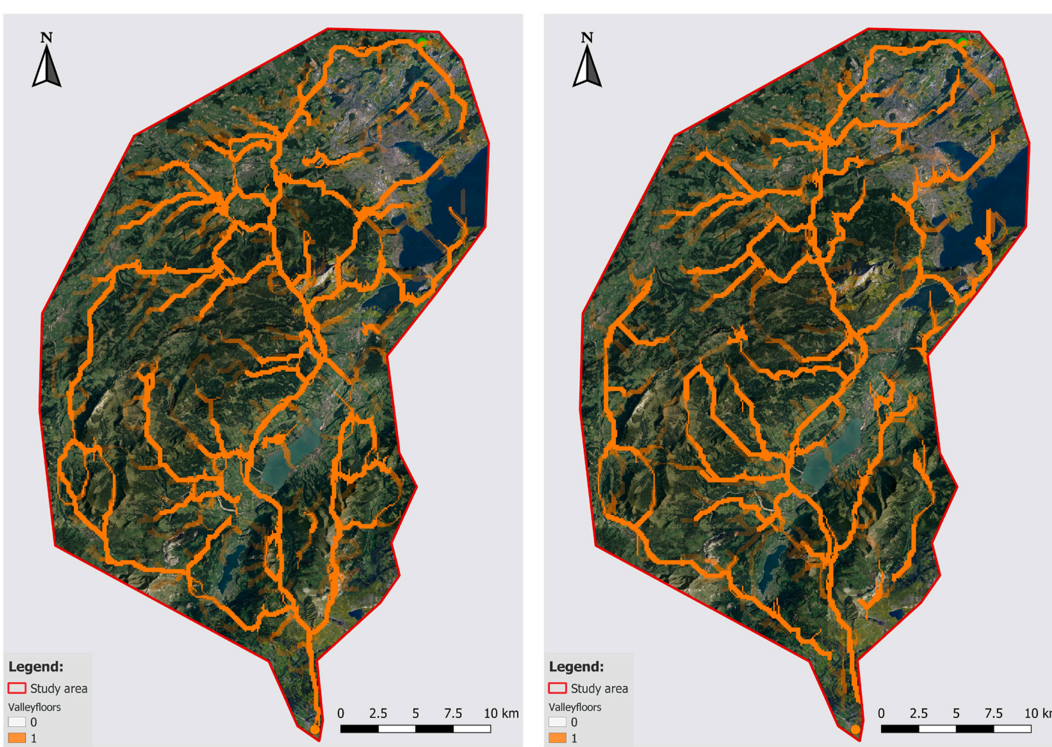

Fig. 8. Partial low-cost corridors between Innertkirchen and Mettlen applied on an aggregated cost surface that is based on two fictional scenarios. Even though the ramification is typical for a flow model, it could be used to identify possible corridors for a new TL. © D. Moncecchi, 2020, base map © Swissimage.

stakeholders decide for themselves which planning area most complied with the given scenario. In this way, the solution space could have been limited to the planning area proposed by the stakeholders. Nevertheless, we are confident that our results are significant because of statistical evidence and the fact that the presented method can be applied to other projects in which MCDA and LCP analysis are used for determining the optimal path of linear infrastructure.

For example, our method could be applied to the case study described by Moncecchi (2020), in which Straumann's valley-finding algorithm 2010 was applied on an aggregated cost surface to determine the least-cost corridors most feasible for constructing a TLP (Fig. 8). Fig. 8 shows some continuous corridors while others are interrupted. By determining the ending point of each line segment, our method could be used to build an extended path segment network (see Section 2.4) and, on this basis, to calculate the non-dominated Pareto optimal path alternatives (see Section 2.5). In this way, we expect that the spatial variability could be enlarged. However, it should also be evaluated just how distinct the path alternatives are when the dominated alternatives are excluded.

5. Conclusions

We developed a method that calculates distinct path alternatives for a new TL based on the same cost surface which takes Pareto optimal solutions into account. In order to do this, we applied parts of a valley-finding algorithm on an aggregated cost surface to identify local low-cost points in central Switzerland. We then connected these low-cost points and two substations with the starting and the ending point by applying an algorithm that built a network based on geometrical rules. Based on a predefined decision model and on a particular scenario, we calculated the corresponding LCP for each segment in this network and assembled connected segments to path alternatives. For each path alternative, our method calculated the extent to which seven specific objectives had been fulfilled. We then cross-compared all path alternatives and excluded those which were dominated by other alternatives. This procedure yielded six path alternatives that represented Pareto optimal solutions, plus the full LCP as a compromise, regarding the given decision model.

We then conducted a study with ten stakeholders and began by using linear programming to calculate the path alternative ranking orders that should best represent their interests. In this regard, our results showed, on average, a moderate correlation between the ranking order calculated by our method and those which participants considered to be best. By applying a PCA with subsequent k-means clustering, we categorized stakeholders into four different interest and mindset groups. Next, we applied a one-way ANOVA to investigate how the correlation, both group associations and four other factors, affected the likelihood that the stakeholders would either accept or reject key elements of our novel method. We deduced from these results that stakeholders who disagreed with the proposed planning area are more likely to disagree with the suggested path alternatives ranking order. Obviously, different notions about successful negotiation strategies influence the attitude toward discussing about subjective ranking preferences. The results from the ANOVA showed that almost none of the other answers varied across any of the groups. This is surprising, as we expected a clearer bias between stakeholders with different interests, mindsets, or experience.

Even if the stakeholders' opinions regarding the chosen scenario were ambiguous, five of the seven path alternatives obtained better results than the full LCP, which was calculated by applying a classical LCP analysis based on a spatial MCDA decision model. Furthermore, stakeholders endorsed the key elements of our novel method and assessed it as having a high chance of supporting discussions and negotiations regarding the routing of a new TL.

Future research could apply our novel method to similar problems in which path alternatives for linear infrastructure should be identified, and for investigating methods into how it could be improved algorithmically or regarding its practical use for negotiations. As our novel method did not appropriately consider the mandatory minimum distance to scattered settlements, researchers working on similar projects could elaborate on these methods or could refine the linear programming approach in order to comply with the legislation. Since stakeholders assessed that one substation was well-connected while another further away from the main route of the proposed TL was not, future research could also investigate methods for modeling tap lines or for enhancing the spatial variance of the proposed path alternatives without forfeiting realism. In conclusion, our novel method provides planners and stakeholders with a tool for identifying Pareto optimal path alternatives that can be used for discussing and negotiating the routing of a new TL. While the classical LCP analysis lacks reliability, our novel approach makes use of an algorithm built for finding valleys–an approach that aims at keeping social costs low and protecting areas worthy of being protected from new TLs.

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