A ROUTING ALGORITHM FOR BACKCOUNTRY SKI TOURS

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ABSTRACT: For over a decade skitourenguru.com has been assigning daily avalanche risk scores to thousands of backcountry ski tours in the alpine region. These ratings are based on the "Quantitative Reduction Method" (QRM) and on "Screening the Likelihood of Avalanches on Backcountry Ski tours" (SLABS). Both methods combine information from the avalanche forecast and the terrain to a risk score.

The standard routes made available on Skitourenguru are edited and reviewed by experts in Geographical Information Systems. End users have frequently wished to draw their own routes and have them rated afterwards. However, routes drawn by end users often lack the necessary quality. Therefore we developed a routing algorithm that not only adjusts existing routes but also generates new routes from a given start to a given end point. This algorithm is based on cost optimization (Dijkstra) through a cost surface. The cost surface is dependent on slope angle, curvature, forestation and other criteria such as roads, paths, rivers, bridges, lakes or information about ski routes and tracks. The optimization algorithm is implemented with the GRASS tool r.walk.

For Switzerland, the feature has been available on skitourenguru.com/rating-view since December 2023. Users can either prospectively draw a route on a map or retrospectively upload a GPX file. Subsequently the route is adjusted by the algorithm and the avalanche risk score is calculated based on an avalanche forecast chosen by the user. The feature was immediately embraced by the backcountry skiing community in Switzerland. In the winter of 2023/2024, users rated more than 50.000 routes. Starting from December 2024, this feature will become available for the entire alpine region. Given its playful nature, we are confident that this feature can make a significant contribution to "avalanche education and learning."

In this contribution we present the feature, give an insight to the routing algorithm, explain its purposes, discuss its limits and give an outlook to the future.

KEYWORDS: Backcountry ski touring, Routing algorithm, Avalanche risk, Skitourenguru.

1. INTRODUCTION

Skitourenguru is a selecting and planning tool for backcountry ski tours throughout the Alps. To this end, avalanche risk scores are assigned fully automatically to approximately 10,000 routes. The risk score is split into three categories: *green* (slight avalanche risk), *orange* (elevated avalanche risk) or *red* (high avalanche risk). The risk scores are based on the latest local avalanche forecasts and governmental terrain data. For this purpose Skitourenguru developed three algorithms, presented and discussed in the following papers:

- Algorithm based on the GRM (Graphical Reduction Method): Schmudlach and Köhler (2016),
- Algorithm based on QRM (Quantitative Reduction Method): Schmudlach et al. (2018)
- Algorithm based on SLABS (Screening the Likelihood of Avalanches on Backcountry Ski tours): Degraeuwe et al. (2024).

So far all provided routes were drawn manually by experts in a Geographic Information System (GIS). During the digitization and validation process a well defined protocol was followed.

The web site turned out to be very popular within the backcountry skier community, specially in Switzerland, Austria and Germany. In the height of winter, users click on around 40,000 routes per day. Consequently there was a constant flow of feedback from the users throughout the last decade. By far the most frequently desired feature was to be enabled to "*draw routes themselves and have them rated afterwards*". A poll executed by the Swiss Council of Accident Prevention (bfu) executed in the year 2019 confirmed that finding.

From a technical point of view, a feature that allows the public to draw routes themselves is rather simple. However a route to be rated by the algorithms of Skitourenguru must meet some quality criteria. A poorly drawn route will be assigned a risk score of low informative value.

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Drawing a route of elevated quality by taking into account the avalanche danger, the danger to fall down and ergonomic criteria is not easy. It was therefore clear from the outset that such a feature would have to be accompanied by an algorithm that could adjust the manually drawn route.

Eisenhut (2013) presented in a master thesis an algorithm that was able to draw a route by just providing a start point and an end point. The approach was based on a cost surface and the optimization algorithm ArcGis-PathDistance.

Throughout the next 10 years Eisenhut constantly improved the applied approach. Based on the experience gained, Eisenhut presented an algorithm that could automatically draw a backcountry skiing map for the entire Swiss Alps (Bachmann, 2020). The resulting map was made available to the public by Skitourenguru (2020).

A few years ago Skitourenguru started to migrate the routing algorithm with tools provided by the Open Source GIS “GRASS”. The feature went online in November 2023 under the name “Rating of user-defined Routes” (Skitourenguru, 2023). The provided extent was limited to the Swiss Alps. In the winter 2023/2024 the users let rate approximately 50’000 routes. As the feature attracted a lot of attention, Skitourenguru was given the opportunity to refactor the cost surface with GRASS tools and extend it to the entire Alpine region.

Tbl. 1: Digital Terrain Models

Name	*Extent (Resolution)*
swissALTI3D	Switzerland (2 m)
BEV ALS DTM1	Austria (1 m)
LDBV DGM1/5	Bayern (5 m)
IGN LiDAR HD	France (5 m[1])
Arso Lidar DTM	Slovenia (1 m)
Liguria DTM	Liguria (5 m)
Piemonte DTM5	Piemonte (5 m)
Valle d’Aosta DTM2	Valle d’Aosta (2 m)
Lombardia DTM 5x5	Lombardia (5 m)
Trentino Lidar PAT 2014 DTM	Trentino (0.5 and 2 m)
DGM	Südtirol (2.5 m)
DTM5000	Friuli Venezia Giulia (5 m)
DTM5	Veneto (5 m)

To our knowledge, there are no other publications on the subject. However, we are aware that Skida.com (and may be other platforms) are working on similar approaches.

The present paper describes the current cost surface (chapter 2 and 3.1), the optimization procedure (chapter 2 and 3.2) and the provided feature on Skitourenguru (chapter 4). In chapter 5 the purpose and limits of the feature is discussed and an outlook is given.

Tbl. 2: Surface data

Name	*Extent (Extracted Features, Resolution if raster data)*
swissTLM3D	Switzerland (freeways, roads, tracks, paths, railways, cable cars, bridges, tunnels, galleries, lakes, glaciers, rivers, dams, forests)
OpenStreetMap	Alps (freeways, roads, tracks, paths, railways, cable cars, bridges, tunnels, galleries, lakes, glaciers, rivers, dams, borders, coastlines, ski pistes)
Tree Cover Density	Alps (tree cover density, 10 m)
Vegetation height model NFI	Switzerland (vegetation height, 1 m)
Corine Landcover Backbone	Europe (sealed areas, woody areas, 10 m)
Ski routes	Switzerland (Ski routes provided by Swisstopo and Swiss Alpine Club)
ATHM	Alps (Avalanche Terrain Hazard Map, 10m)
Risk to fall down	Alps (A map about the risk to fall down, 10 m)
Route Collection of Skitourenguru	Alps (A collection of ~10’000 manually drawn ski routes, maintained in cooperation with Skitourenguru)
Track Collection of Skitourenguru	Alps (a private collection of GPS tracks recorded by users during their backcountry skiing activity)

2. DATA

Since the beginning of ski touring, routes have been drawn on topographical maps. As ski touring is independent of any transport infrastructure, the topography of the terrain (slope angle, slope form) is of particular importance. In order to develop a routing algorithms for ski touring Digital Terrain Models (DTM) of high resolution and accuracy are required. Global data like SRTM (United States of America), ALOS (Japan) or EUDEM (European Union) don’t provide the required quality. In our approach we systematically rely on data from governmental

1 The official DTM5 of the IGN doesn’t provide everywhere in the french Alps the required quality. Therefore a DTM is derived from raw lidar data, applying PDAL’s SMRF ground filter.

geo-data providers. The applied DTM's have a resolution of at least 5 m and an absolute accuracy of approximately 1-2 m. The relative accuracy is usually much higher.

Table 1 lists all applied data sources, needed to cover the Alps. All DTM's are re-projected to the common Coordinate Reference System (CRS) with an EPSG code of 3035. Subsequently they are clipped at the borders and merged into one seamless DTM covering the whole Alps and providing a resolution of 5 m.

In addition to the terrain, the natural and artificial earth surface also plays an important role in the suitability of a particular spot for ski touring. Table 2 lists all applied data sources, needed to cover the Alps and the features extracted from them. All surface data are re-projected to the common Coordinate Reference System (CRS) with an EPSG code of 3035. Vector data is rasterized with a resolution of 10 m. Wherever data from two different sources is available, the data with the higher quality is selected. The result are 40 raster input layers, covering the whole Alps and representing each one a particular feature (example: lake yes/no).

3. METHODS

3.1 Cost surface

We cover the Alps with a raster (checkerboard pattern) of 10 m resolution. Each raster cell is assigned a cost value in the range [1..99]. Table 3 defines the meaning of the values.

Tbl. 3: Cost values legend

Color	*Cost*	*Meaning*
Green	1..4	Very low cost values
Yellow	5..14	Low cost values
Orange	15..60	Intermediate cost values
Brown	61..98	High and very high cost values
Black	99	Barrier (its not possible to cross the cell)

Such a raster layer is called *"cost surface"*. A good cost surface represents the preferences of backcountry skiers. The smaller the cost value, the more a cell is suited to be transited with skis.

Figure 2 shows a highly simplified overview on how the input layers (gray) are processed into a cost surface layer (green). Basically there occur four major operations (red rectangles):

- Sum: Initial costs (SurfaceSumCosts) are calculated from slope angle, fold (convex or concave terrain) and forestation. More information about *fold* you find in Schmudlach and Köhler (2016).
- Max: Some alternative costs can override the initial costs. Here are some incomplete examples: A water accumulation algorithm (Grass-r.watershed) is applied to estimate the width of the rivers and streams. The final RiversCost depend on the river width and the river's altitude. Crevassed zones are identified by calculating a topological position index (gdaldem-TPI) from the DTM. Railways, freeways, reservoirs and sealed zones lead to very high costs, respectively to barriers. The transit costs of lakes depend on their elevation.
- Min: Paths, tracks, roads and bridges can lower the costs calculated from the max operation. The procedure also depends on the degree of forestation.
- Mod: So far we have a raw cost surface that will contain also some cells with very high transit costs. Data sets about backcountry skiing can moderate (mod) the final costs. Tracks are usually recorded by a GPS during outdoor activity. Routes are lines drawn manually on maps by backcountry skiers. Depending on the quality level of tracks or routes they can moderate a barrier and make it transitable.

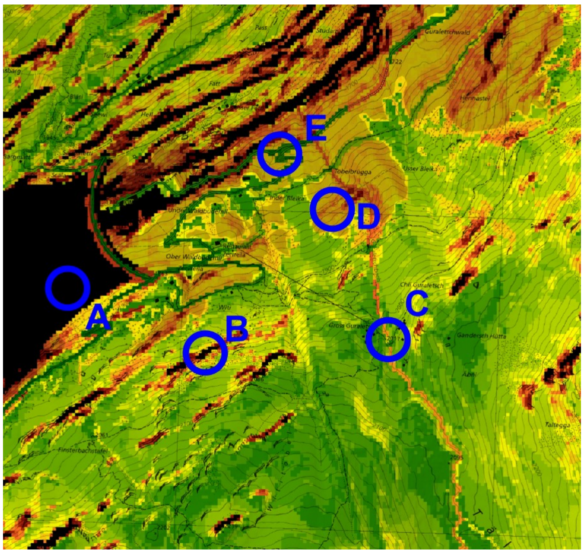

Fig. 1: Cost Surface (legend in table 3)

Figure 1 shows a cost surface of the area around Zervreila (Switzerland). Cost values are represented by the colors defined in table 3. The reservoir of Zervreila (A) is a barrier. B shows a cliff hard to be transited on skis. C represents a bridge over a stream. The forest of D reflects higher cost due to dense forestation. On the other hand the roads on spot E have low cost values.

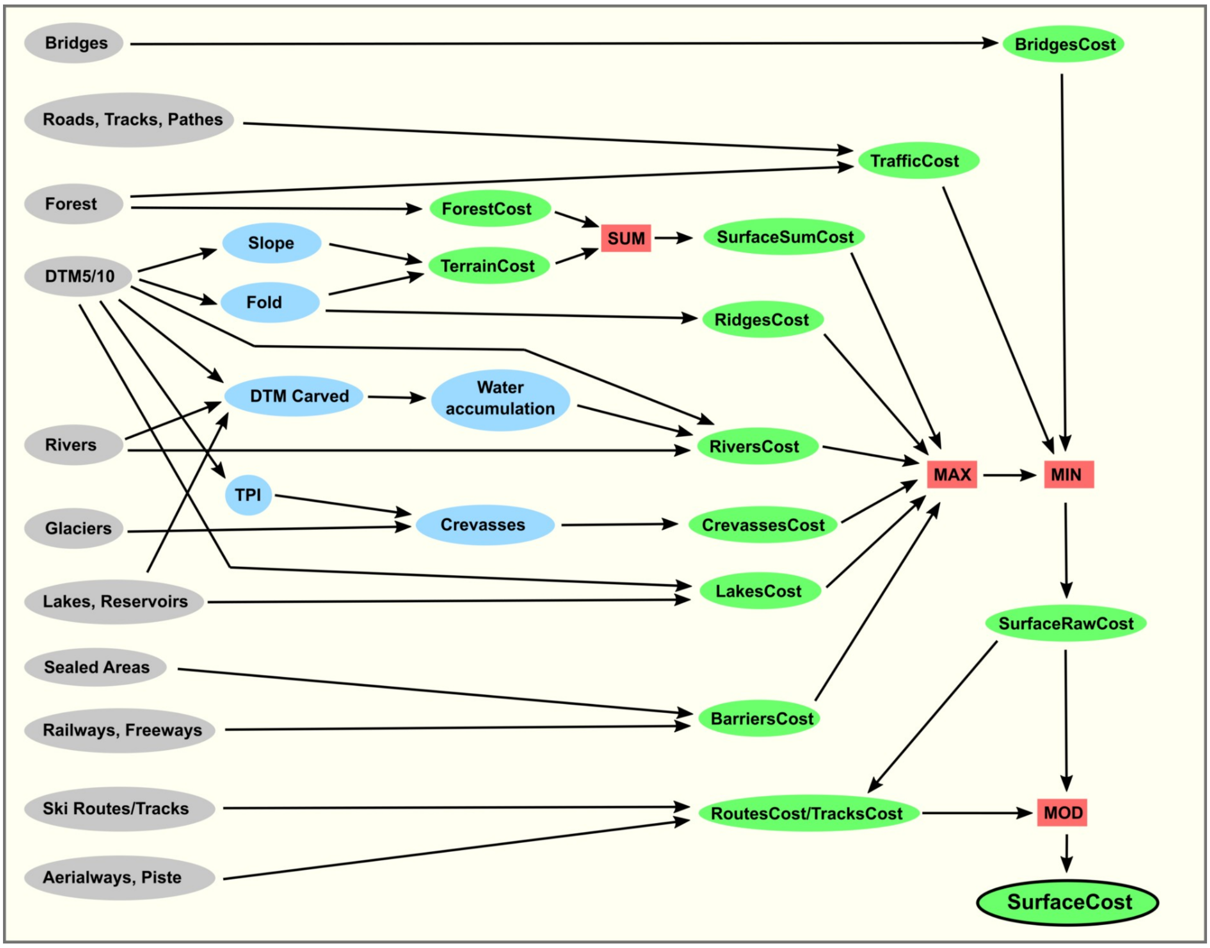

Fig. 2: Simplified raster data flow chart: From input raster layers (gray) to a cost surface (green). Major operations in red rectangles.

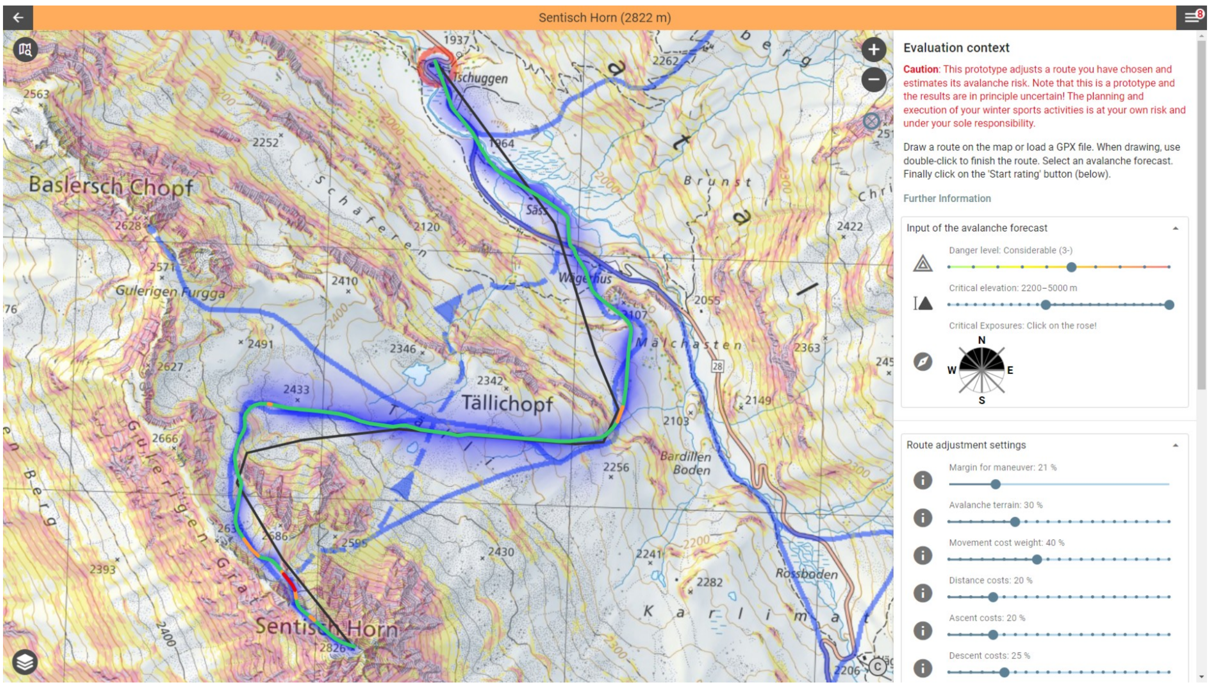

Fig. 3: Screenshot of the feature Routing of user-defined routes (RUDR). Black line: The route drawn by the user, Green/orange/red line: The adjusted route rated with the avalanche forecast entered at the top right. Blue transparency colors: A corridor of alternative solutions. Blue lines: The ski routes of the Swiss Alpine Club (SAC).

3.2 Routing

Calculating the "cheapest path" through a cost surface is just a matter of CPU power. To this end Skitourenguru applies the tool Grass-r.walk. r.walk computes anisotropic cumulative cost of moving between a start and end point on an elevation raster layer (DTM) combined with a raster layer whose cell values represent transit costs. The tool optimizes the sum of movement costs plus transit costs. As transit costs serves the cost surface of chapter 3.1. The movement cost depend on the vertical and horizontal distance covered. A so called *lambda* value defines if more weight is given to the transit costs or to the movement costs. The result of r.walk is a raster layer that represents cumulative costs from the start point to each cell. r.walk is applied twice, once for each direction. The sum of both cumulative cost raster layers makes up for a corridor raster layer, that represent possible alternative solutions. The transparent blue values of figure 3 give an example of such a corridor. The more opaque the blue value, the better the spot to be transited with skis. If the cumulative cost raster layer is given to Grass-r.path, the optimal path can be calculated. As r.walk is based on Dijkstra's algorithm (Dijkstra, 1959), it will always find the optimal path. Before the optimal path can be displayed, it's first simplified and then smoothed (Grass-v.generalize).

4. RESULTS

The resulting application named Rating of user-defined Routes (RUDR) can be tried out on skitourenguru.com/rating-view.

Basically there are three major use-cases:

1. The user draws a route on the map and lets the algorithm adjust it (prospective use-case).
2. The user uploads a GPX file (a track recorded by GPS or a route drawn on a map) and lets the algorithm adjust it (retrospective use-case).
3. The user draws a route by defining only a start point and an end point. The algorithm will then calculate automatically a corridor and an "*optimal route*". This use-case is not the primary focus

In all three use-cases the user can choose a setting called "*Margin for maneuver*", a value in the range of [0..100]. The higher the value, the more the algorithm is free to deviate from the route entered. The smaller the value, the more the algorithm keeps tied to the route entered. If the value 0 is chosen, the algorithm won't adjust the route. The value will be preset automatically depending on the number of points of the route entered. The more points were given, the smaller the initial value and the more the algorithm keeps tied to the route. However the user can always override the preset value.

Route description

Summit	Zervreila (1835 m)
Start	Fanellhorn (3103 m)
Elevation gain	82 m
Route length	5500 m
Ascent time	3h 40'
GPS track	GPX file
Difficulty grade	AD– (automatic)
Avalanche risk	**1.95**

Fig. 4: Route properties identified by Skitourenguru.

There are five other settings (see Fig. 3 at the bottom right):

1. Avalanche terrain: The higher the value, the more the avalanche terrain (Schmudlach and Köhler, 2016) is taken into account in the route adjustment. In a typical dry snow situation the user eventually wants to give more weight to the avalanche terrain, then in a typical spring situation. A strong consideration of the avalanche terrain can be at the expense of accessibility (more difficult terrain).
2. Movement cost weight: The higher the value, the more the movement costs are taken into account compared to the transit costs. The movement costs depend on the vertical and horizontal distance. Transit costs depend on the values of the cost surface. This setting directly impacts *lambda* mentioned in chapter 3.2.
3. Distance costs: The higher the value, the more detours are avoided.
4. Ascent costs: The higher the value, the more ascents are avoided.
5. Descent costs: The higher the value, the more descents are avoided.

Improving the results of the adjustment algorithm by changing the default settings is tricky and needs a deeper understanding of r.walk and some experience.

The user can also define an avalanche forecast by specifying the *danger level*, the *critical elevations* and the *critical aspects* (see Fig. 3 at the top right). Skitourenguru will then calculate an avalanche risk score (green: *slight risk*, orange: *elevated risk*, red: *high risk*) by applying the QRM or SLABS algorithm. The course of the route is also marked with these traffic light colors. Keep in mind, that in no case the current avalanche forecast is automatically read from avalanche warning services. The user has to enter it manually. This restriction has several reasons:

- Skitourenguru wants to encourage users to take a closer look at the avalanche forecast.
- The need to specify an avalanche forecast makes clear, that the user has his share of responsibility.
- By giving the possibility to alter the avalanche forecast, it becomes possible to experiment with virtual (past or future) scenarios.

Skitourenguru also identifies some route properties (see Fig. 4). Not only it finds out the field names of the start and end point, it calculates also a difficulty grade (Reincke and Schmudlach, 2021) and figures out the elevation gain, route length and ascent time. Additionally its also possible to download a GPX file of the route.

Finally Skitourenguru provides a permalink, that can be shared with buddies and called later on. Data keeps private to people who share the permalink.

5. DISCUSSION

The standard features provided by Skitourenguru help people to select and plan a ski tour with low avalanche risk. During the ski tour usually information becomes available that allows to update the risk assessment made during the planning phase. Note that Skitourenguru should only be used as a supplementary source of information for planning a ski tour at the users own responsibility. That applies not only to the standard features of Skitourenguru but also to the RUDR feature.

Avalanche risk assessment systematically suffers from a lack of feedback. Fortunately most outings end without any harms to the participants. That means in the same time absence of feedback. The features of Skitourenguru provide consistent, reproducible feedback, independent from human biases.

The present feature has a great potential for avalanche education and learning. An avalanche course can adopt the following procedure:

1. The course participants draw on a map individually a route from a predefined start point to a predefined end point.
2. The course participants perform a risk assessment by applying a strategic method (like the Graphical Reduction Method, StopOrGo, DavSnowCard or the Avaluator).
3. The course instructor moderates a discussion about the results from the participants: Why do they agree or disagree?
4. Now the participants individually apply RUDR on the web site of Skiturenguru. They experiment with different manually drawn routes and different avalanche forecasts.
5. The course instructor moderates a second discussion, where manual and automatic results are compared.

During the procedure the participants can learn, that humans and machines have both their merits and their limits. In order to get an experienced back-county skier its crucial to develop a critical attitude towards the conclusions from humans and from machines.

The routing service presented in this paper has limits:

- All data introduced in chapter 2 are a virtual representation of the real earth. Although data quality has improved massively in the last two decades, they cannot accurately reflect reality. That specially applies to the forestation and to heavily modulated terrain.
- Assigning costs is a rather subjective process. It requires a good knowledge of the “*cost language*” as introduced in table 3 and a lot of experience.
- The nature of some of the features is dynamic (lakes, streams, rivers, glaciers), however they are treated statically.
- In highly modulated terrain (for example on ridges) and in trackless forests, the algorithm may have difficulties in providing a good indication of accessibility.
- Back-country skiing faces some other dangers not handled by the algorithms: Ice and stone chipping, danger to fall down, loss of orientation, exhaustion, etc.
- The routing service has a focus on the ascent and not on the descent. A focus on the descent with skis would require a customized cost surface.
- The local snow and avalanche conditions are unknown to the algorithm. Therefore a final risk assessment update must be performed at each individual decision point.

All those limits can lead to eventually sub-optimal or even wrong results.

The potential of further developments is enormous:

- Cost assignment currently is based on expert knowledge. Machine learning has a huge potential, if a good target variable about the back-country skier activity is available. See also the Travel Usage Dataset (TUD) described in Skitourenguru (2022). However initial tests suggest that machine learning can reproduce the most important correlations, but struggles to reproduce the exceptions.
- Currently the cost surface and routing is based on 10 m and partly on 5 m. A systematic upgrade to a 5 m resolution is recommended.
- The current snow and avalanche situation could be taken into account when adjusting the route (see Techel et al. 2024).
- With the present cost surface its possible to calculate automatically a back-country skiing map covering the whole Alps. Such a map would represent the routes by corridors (Bachmann, 2020).

CONCLUSIONS

When Eisenhut started to develop a routing algorithm for backcountry ski touring in the year 2012 it was not clear, whether this was more then just a dream. Now, more the just 10 years later we are convinced, that its possible to develop routing algorithms of high quality. This conclusion is due to two reasons: Firstly the virtual representation about the physical earth steadily improve. Secondly the snow blurs out earth properties of very local character. In contrast to summer sports back-county skiing doesn’t require to have knowledge about the physical earth at very large scale. In summary, the algorithm can provide a reasonable performance in classic, open ski touring terrain, but our procedure potentially reaches its limits in steep foot terrain or in forests outside of registered trails.

Humans and machines make mistakes. This also applies to the drawing of ski tours. Two difficult questions arise in this context. Firstly, how do you measure the quality of routes? Just think about real-life disputes whether variant A or B is the better option. Secondly, what criteria can be used to decide whether a specific measure of quality is sufficient? Despite countless discussions about these two issues the answers remain unsatisfactory. However we are confident that this feature will stimulate such discussions, whether in formal avalanche courses or in private contexts. These discussions have enormous potential to improve the decisions of outdoor sports enthusiasts.

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