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Network analysis for search areas in WiSAR operations

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Abstract

Purpose – A search and rescue incident is ultimately all about the location of the missing person; hence, geotechnical tools are critical in providing assistance to search planners. One critical role of Geographic Information Systems (GISs) is to define the boundaries that define the search area. The literature mostly focuses on ring- and area-based methods but lacks a linear/network approach. The purpose of this paper is to present a novel network approach that will benefit search planners by saving time, requires less data layers and provides better results.
Design/methodology/approach – The paper compares two existing models (Ring Model, Travel Time Cost Surface Model (TTCSM)) against a new network model (Travel Time Network Model) by using a case study from a mountainous area in Austria. Newest data from the International Search and Rescue Incident Database are used for all three models. Advantages and disadvantages of each model are evaluated.
Findings – Network analyses offer a fruitful alternative to the Ring Model and the TTCSM for estimating search areas, especially for regions with comprehensive trail/road networks. Furthermore, only few basic data are needed for quick calculation.
Practical implications – The paper supports GIS network analyses for wildland search and rescue operations to raise the survival chances of missing persons due to optimizing search area estimation.
Originality/value – The paper demonstrates the value of the novel network approach, which requires fewer GIS layers and less time to generate a solution. Furthermore, the paper provides a comparison between all three potential models.

Keywords GIS, Network analysis, WiSAR

Paper type Research paper

1. Introduction

In the European Alps, particularly in tourist areas, many hiking trails allow unlimited access to the mountains, almost regardless of visitors' hiking skills. In Austria, about 400 people annually are reported missing in the mountains and have to be taken back to safety (OEBRD – Austrian Mountain Rescue Organization, 2013). If the location of a missing person is unknown, an extensive search operation is necessary first. In the preparation and planning process of these operations, Geographic Information Systems (GISs) are increasingly used to assist the management and analysis of spatial data, providing support to the search and rescue (SAR) team. Critical in this process is the estimation of the search area size, affecting the time necessary to cover the area during the search. A more accurately search area results in more efficient SAR operations with increasing chance of survival for the person missing. Therefore, different geospatial methods were developed – mostly

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focusing on area-based approaches. The aim of this paper is twofold: first, to present a network-based GIS approach using roads and trails, in this paper defined as Travel Time Network Model (T2Net). Second, to compare strengths and weaknesses to create a probability of area (POA) map with the two most common methods, Ring Model and Travel Time Cost Surface Model (TTCSM). The metric used to compare the three models is the preparation time factor, required data, analytical techniques involved and the probability density (Pden).

2. SAR in mountainous areas – related work

SAR operations are emergency situations where trained experts help a person in distress. An operation includes two stages, which can significantly differ due to the situation and which are not necessarily carried out simultaneously. First, the person has to be located. In the rescuing phase, the person has to be brought back to safety and provided with medical care (Cooper, 2005).

Operations in largely unpopulated areas with minimal access to infrastructure are referred to as wilderness or wildland search and rescue (WiSAR), including missions in mountainous areas. If access to shelter or medical care is missing, WiSAR operations can also occur in urban areas, e.g. after natural disasters (Durkee and Glynn-Linaris, 2012). SAR teams in Austria are based on rescue and relief organizations (firefighters, mountain rescue and Red Cross), in the mountains WiSAR operations are carried out by specialized mountain rescue teams and alpine police units (SARUV Austria, 2016). According to the 2013 annual report of the Austrian Mountain Rescue Organization, over 7,000 operations took place (five-year average 6,745 operations), with approximately 400 searches annually (OEBRD – Austrian Mountain Rescue Organization, 2013). Despite this high number, no database for these operations is available.

Four steps characterize SAR procedures: locate – access – stabilize – transport. From a geo-analytical perspective, each step is representing a separate spatial problem (Wysokinski *et al.*, 2014). The locate and access phases are critically important regarding time and space (Winter and Yin, 2010) – a limited number of task forces must find a person as soon as possible within a correspondingly large area, since the chance to survive drops with increasing time (Doherty *et al.*, 2014). An analytical measurement for finding a person is the probability of success (POS), which is calculated based on the POA and the probability of detection (POD) (Koopman, 1999):

$$\mathrm{POS} = \mathrm{POA} \times \mathrm{POD}$$

To increase POS, different methods are feasible, e.g. to increase POD by using a higher number of emergency teams and/or better sensors and tactics to increase the POD for each team, or to reduce the search area by improving the estimation of the POA (Cooper *et al.*, 2003). Due to limitations in work force and difficulties to influence the POD, Doherty *et al.* (2014) suggested to optimize the search area. Another metric is the Pden, which is calculated as the probability per search size (Sava *et al.*, 2016).

3. GIS for SAR – underlying considerations

3.1 Potentials of GIS

To analyze spatial problems and manage large amounts of data, both before and during SAR operations, GIS offers numerous possibilities (Ferguson, 2008). As investigated by Tomaszewski (2015) for disaster relief issues, GIS works as a tool for organization and administration (Environmental Systems Research Institute, 2010, 2013). Maps as one basic result of GIS analyses are used in the briefing process of task forces and in the field during an operation. However, it is useful to prepare spatially referenced data in advance of a SAR operation to make it quickly available in case of emergency. Information about roads/streets, waterways, elevation, land cover and aerial photography has to be compiled. Information about the current situation needs to be collected by interviews and observations. Next to personal notes, this includes weather forecasts and operation-related data like availability of equipment, people and/or vehicles. Moreover, the application of GIS for SAR needs high expertise in spatial data analytics (Tomaszewski, 2015). Therefore, members of SAR teams, employees of National Parks and computer specialists developed an extension of ArcGIS called MapSAR, enabling efficient management of information and the creation of maps using pre-defined templates. Generating maps with MapSAR is easy, no or basic GIS knowledge is needed. If additional spatial analyses are required in the WiSAR operation, GIS expertise is needed, causing limitations for further implementation. Many approaches are limited to scientific publications, dealing with geostatistical and geotechnical assessment of search areas (Doherty *et al.*, 2014), modeling behaviors of missing persons (Koester, 2008; Lin and Goodrich, 2010; Sava *et al.*, 2016) and planning issues integrating heterogeneous agents (Flushing *et al.*, 2012). The common goal is to provide methods for better organization, quick and successful completion of SAR operations. To make advanced GIS analyses available for the SAR teams despite lacking GIS knowledge, analytical processes can be automated and only results are provided to the teams (Wysokinski *et al.*, 2014).

3.2 GIS network analysis for SAR analysis

The term network is used in numerous fields of science for modeling, and although the underlying concepts vary essentially (Nyerges *et al.*, 2011). In this paper, network is defined as a collection of linear features, roads and trails, where nodes represent intersections and edges represent the paths between intersections (Popovich *et al.*, 2009).

Although network analysis carries a huge potential for WiSAR they are yet rarely applied. Reasons for this are road/trail network density – few linear objects in areas cannot provide meaningful results – the availability of vector data, and different locational conditions worldwide, e.g. US National Parks vs European Alps. Theodore (2009) implemented an application for the search of missing hikers in Yosemite National Park, including 3D and spatial analyses. He applied network analysis primarily for splitting up the search area.

Canadian researchers provided network analysis methods for locating persons with Alzheimer. They combined geotechnical applications, statistical analyses of recent cases and medical knowledge with subject-related information about the patients (Croteau and Belhassine, 2016). Based on a road network, the application provides routes and probabilities of decisions of disoriented patients at intersections including behavioral profiles. The results are presented as probability maps. This integrative application provides a suitable network-based approach in urban areas.

3.3 Data for SAR – precondition and challenge

The acquisition of current, accurate (geo-)data poses a major challenge in projects with geospatial scope. Missing data or data errors can produce misleading results, which may lead to injuries or loss of life. Additionally, data acquisition plays an important role since most SAR teams are nonprofit organizations in Europe. At its best geo-data sets are freely available as governmental or open source services. However, volunteered geographic information covers wider areas to various degrees of detail, completeness and accuracy. Additionally there is the need for situational data as spatial and/or qualitative data.

Statistical data from previous incidents form the basis of defining search areas for all three models. Unfortunately, many localities neglect to collect incident data. The International Search and Rescue Incident Database (ISRID) collects data and organizes the data to control for subject category, ecoregions, terrain and population density in the reported summary data (Koester, 2008). The algorithm that defines subject categories was further refined in 2010 (Koester, 2010). Additional data were collected increasing the database from 50,692 to 143,951 incidents in 2016. This is the new summary data (Table I) used to test the three models. A more detailed description of data requirements, adaptations, implementation and analysis is discussed in Section 4.

4. Three models, three probability maps

A practical example illustrates differences, pros and cons of three models: the Ring Model, the TTCSM and the T2Net. The models are described and calculated for an Austrian mountainous region, showing a high density of roads/trails with unrestricted access to the area. Next to probability maps (Figure 1), the Pden is used to compare the results and evaluate the results of the T2Net (Table II).

The study area, located in the Austrian province of Vorarlberg, is covering an area of 414 km^2, accessible by 1,234 km of roads and 1,138 km of trails. The northwestern part, the Rhine Valley (elevation 400 m), is an urban region, while the remaining areas are mountainous with an elevation up to 2,095 m. The IPP is set along the European long distance trail E4 (Figure 1(a)). Statistical data used to evaluate the three models were taken from ISRID2.0 due to a lack of data from Austrian sources. The methodology of collecting and cleaning the data is identical to the first creation of ISRID, previously described (Koester, 2008). The data were filtered for search incidents only, hikers only, temperate eco domain only, wilderness or rural population density, mountainous terrain only, excluding investigative outcomes, and containing data in either hours of mobility or beeline distance from the IPP.

4.1 Ring Model

The Ring Model using beeline distance is only based on statistical data (Doherty *et al.*, 2014, S. 102; Koester, 2008); no additional spatial information is integrated. Search areas are indicated as concentric circles around the IPP using the distance a hiker can be found with a certain probability as radius. These distances define the probability areas around the IPP and are calculated with GIS multiple-ring buffer analysis, but can simply be obtained with paper and pencil (Table I).

Data sets and tools	Ring Model	TTCSM	T2Net
Geospatial data			
Starting point – IPP	X	X	X
Roads		X	
Paths		X	X
Flowing water bodies		X	
Stagnant water bodies		X	
Digital Elevation Model		X	X
Land-cover classification		X	
Additional data			
Situational data	X	X	X
Statistical data	X	X	X
Tool	Paper and pencil or GIS multiple-ring buffer	GIS raster analysis (raster calculator)	GIS network analysis (service area and routing)

Sources: Adapted from Doherty *et al.* (2014) and Frakes *et al.* (2014)

Table I. Basic data and tools for the Ring Model, TTCSM and T2Net

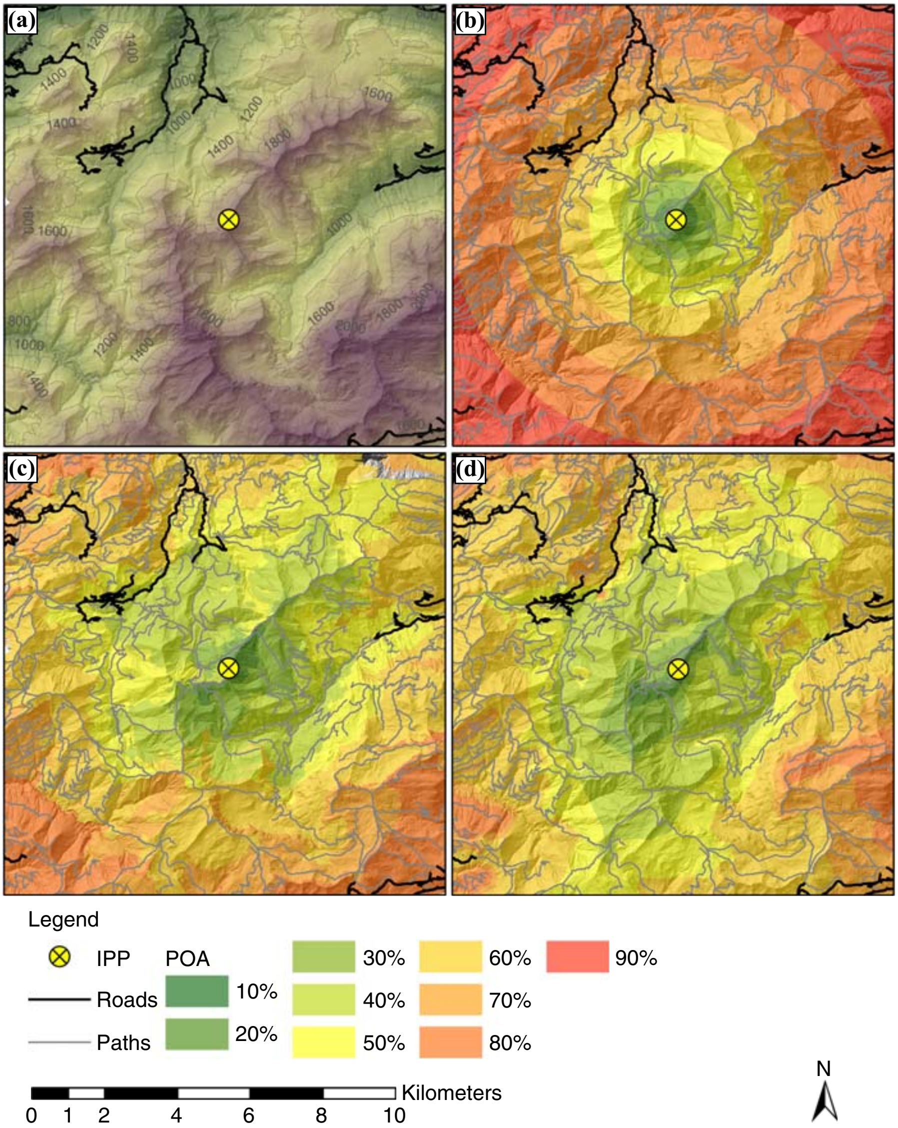

Figure 1.
(a) Location of the IPP at the European long distance trail E4; calculation of probability areas based on the (b) Ring Model, (c) TTCSM, and (d) T2Net

Sources: Koester (2010), VoGIS (2016), Software: ArcGIS 10.5

In total, 1,154 evaluated search operations of ISRID2.0 lead to the following probabilities at 10 percent level (Table II) and are visualized in a probability map (Figure 1(b)). The results indicate that the search area approximately doubles with each 10 percent increase of probability. A missing hiker is found with a probability of 50 percent in a distance of 2.4 km from IPP, which is equal to an area of 18 km^2. Searching the 100 percent probability zone requires covering almost 30 times the study area (11,575 km^2). Since the probability area is not integrating terrain in the model, Figure 1(b) shows that some parts of that area will be difficult or impossible to cover well. The Pden shows higher values compared to the TTCSM and T2Net especially at the 10 percent level (Table II).

4.2 *TTCSM*

The National Park Service of the US Department of Interior (Frakes *et al.*, 2014) developed the TTCSM, also called mobility model, which uses raster data. It is based on the mobility time, indicating how long a person is moving away from the IPP, and visualized in a speed raster. In contrast to the Ring Model, information about terrain and vegetation is implemented as impedance raster (Doherty *et al.*, 2014). This corresponds to a cost-distance approach, calculating the lowest accumulated cost-distance from each cell to the IPP. An algorithm minimizes the total costs based on a speed and resistance grid (Adriansen *et al.*, 2003).

The speed grid uses Tobler's (1993) Hiking Function to integrate the slope and exclude steep areas (> 40°) (Doherty *et al.*, 2014). Grid cells with roads can additionally be weighted with the maximum driving speed (Frakes *et al.*, 2014). Imhof (1950) presumed the speed of a person moving off-roads with 60 percent of the average speed.

The calculation of the resistance grid for the Austrian example involves the following steps:

- An impedance of 0 percent is assigned to grid cells, which are classified as roads/trails.
- An impedance of 100 percent is assigned to non-traversable grid cells (e.g. stagnant water bodies).
- Grid cells of streaming water bodies require a detailed observation and are classified based on Strahler's stream order methodology (Frakes *et al.*, 2014; Strahler, 1952); the impedance increases with the rank of the stream. Water bodies are easier to cross close to their spring than downstream (adopted from Doherty *et al.*, 2014).
- If roads are missing, people need to move cross-country (Frakes *et al.*, 2014). Depending on the land cover, different resistances can be expected and are integrated from CORINE land-cover classification (100 × 100 m resolution) (European Environment Agency, 1995).

Based on the speed and resistance raster the cost surface is calculated, incorporating the maximum speed per cell. Statistical data of ISRID2.0, the mobility time, are added to the model. Koester (2008) estimated that a missing person is generally 1 hour moving away from IPP with a probability of 25 percent, 5 hours with 50 percent, 10 hours with 75 percent

			Ring Model		TTCSM		T2Net	
POA (%)	Distance from IPP (km)	Mobility time (hours)	Area (km^2)	Pden	Area (km^2)	Pden	Area (km^2)	Pden
10	0.1	0	0.03	3.18310	0	0.00	0	0.00000
20	0.6	1	1.13	0.09095	1.37	0.07300	1.41	0.07092
30	1.1	2	3.80	0.03745	7.07	0.01754	7.17	0.01736
40	1.6	4	8.04	0.02358	31.94	0.00402	36.37	0.00342
50	2.4	5	18.10	0.00995	59.36	0.00365	68.48	0.00311
60	3.2	7	32.17	0.00710	135.52	0.00131	175.48	0.00093
70	4.5	8	63.62	0.00318	190.18	0.00183	263.78	0.00113
80	6.2	12	120.76	0.00175	397.93	0.00048	474.46	0.00047
90	10.0	17	314.16	0.00052	na	na	na	na

Table II. Distance and hiking hours gathered from ISRID to calculate probability areas and Pden of the Ring Model, TTCSM and T2Net and 24 hours with 95 percent. The resulting raster can show gaps, e.g. for pixels in inaccessible areas, therefore it is converted to vector polygons, and generalized afterwards.

Compared to the Ring Model, the TTCSM provides results starting with the 20 percent probability area, since at lower probability persons are moving zero hours away from IPP. For the study area, probability areas higher than 90 percent cannot be calculated. The resulting polygons extend the search area and trail data for these areas (Switzerland and Germany) are not available. The Pden shows lower values for the TTCSM than for the Ring Model, dropping quickly after 50 percent (Table II). A missing hiker is found with a probability of 50 percent moving 5 hours away from IPP, which is equal to an area of 59 km^2, which is three times the area of the Ring Model at the given probability (Figure 1(c)).

4.3 T2Net – an alternative approach to support SAR operations

Determining a search area based on linear objects utilizes GIS network analyses. The network includes vector-based data sets of roads/trails, a Digital Elevation Model (DEM) and statistical data. The main impedance factor is the mobility time.

The probability area results as polygon stretched along the roads/trails according to the time moving away from IPP. Additionally, different modes of transportation can be taken into account. If transport infrastructure is available, a person also might use motorized vehicles. The impedance for the road network can be calculated with the maximum speed. One-way streets have to be considered as well as elevation changes along the roads. Speed in the trail network is based on Tobler's Hiking Function, assuming a speed of 5.0 km/h in flat terrain. Hiking uphill or downhill is resulting in different hiking speed (Irtenkauf, 2014). Similar to the TTCSM, slopes more than 40° are excluded (Frakes *et al.*, 2014).

The first step in the T2Net is to prepare the underlying network. Here, it is crucial to define an appropriate graph, ensuring positional accuracy of network elements and connectivity. Network errors and/or gaps will result in a failure of the algorithm. Following steps are integrated:

- Linear features are split in 5 m edges according to the 5 × 5 m slope raster, to ensure a more exact modeling process.
- Elevation of the DEM is assigned to each node. Based on this information, the increase or decrease of elevation is calculated depending on the direction of digitalization and assigned to each edge.
- Using Tobler's Hiking Function, the hiking speed is calculated in and against direction of digitalization.
- If a multimodal approach is chosen, the driving speed is assigned to the road edges.
- Inverting and scaling the result to gather hours per length of edge.
- This gives the amount of time necessary to traverse an edge.

The network data set is generated using hours as impedance/cost factor. The polygons indicating the probability areas are calculated using the service area tool (ArcGIS 10.5) at defined threshold values. Threshold values are mobility times of ISRID2.0. To generate comparable results with the TTCSM, the multimodal approach was not used for the case study. Positions at the intersections of the network and the borders of probability polygons are time accurate according to the mobility time of ISRID.

The generated network supports various analyses in the context of SAR operations. Predominantly two operations can be applied: first, in case of an unknown position of a person, the search area can be visualized using the service area tool. Second, knowing the location of the person, the quickest/easiest/shortest route to this location can be calculated.

Figure 1(d) illustrates the T2Net using ISRID2.0 statistical data. Hiking times between 0 and 24 hours determine the probability areas at 10 percent steps. For the study area, ISRID data show that 50 percent of all missing hikers were found within 68 km^2 from IPP, including 261.34 km trails/roads. Comparing the Pden of the T2Net with the TTCSM presents slightly lower values. The map (Figure 1(d)) shows that the probability areas match the linear features. Especially along the ridge from SW to NE with smooth terrain, an extension of the polygons can be observed.

5. Discussion – pros and cons

The main goal of this paper is to present the T2Net as additional model to calculate search areas for SAR operations. The T2Net is compared with two widely used models, the Ring Model and the TTCSM, to analyze advantages and disadvantages. The results are summarized in Tables II and III.

While the Ring Model does not consider other than different data for mountainous vs non-mountainous terrain or additional information, the TTCSM based on an area approach and the T2Net with a linear basis integrate various additional criteria (see Table I). In contrast to the Ring Model and the TTCSM, the basis of the T2Net is a network of roads and trails. Therefore, the model is suitable for areas where a dense road/trail network is available as well as for small-scaled areas with high relief energy, since it differentiates between hiking up- and downhill. The vector-based data set using linear features can be seen as advantage, since Koester (2008) stated that more than 50 percent of missing hikers are found along road/trail or other linear features, and here 95 percent are located within a distance of 424 m of the linear elements.

The T2Net offers advantages in respect to data, analytical steps and results. The model uses vector data, representing roads/trails and integrates GIS network analysis. One bottleneck of the T2Net is the availability of vector data for trails.

In all three models, the implementation of statistical data is crucial. While statistical data are used to refine the search area, situational data can lead to more exact results, although hard to gather. In the TTCSM, sources of inaccuracies can be named as the low resolution of CORINE land-cover classification, resistance values defined by Sherrill *et al.* (2010) and

	Ring Model	TTCSM	T2Net
Advantages	Easy analysis Cheap and fast No additional information necessary	Movement cross-country included Walking speed included Barriers included Not accessible/traversable areas excluded Detailed result in cross-country areas	Multimodal network possible Few layers Detailed polygon Fast calculation of search areas compared to TTCSM Determination of walking speed according to up- or downhill movement SAR teams can use routing tool for wayfinding to located person
Disadvantages	No additional information (terrain, vegetation) included No linear features (street/trails) included	Many information layers necessary Resulting polygons can include gaps Equal walking speed regardless of walking up- or downhill Resolution depending on input data	(Vector) data on roads/trails necessary

Table III. Advantages and disadvantages of the Ring Model, TTCSM and T2Net flowing water bodies. The Strahler number, for example, does not take seasonal variations of the runoff into account. Modeling the behavior of a person based on statistical data does not consider the critical characteristics of the unique individual. In addition, the distance from the IPP and dispersion angle models does not take the unique characteristics of the terrain into full consideration. The challenge in applying GIS-based models is, next to the modeling process itself, to overcome the gap between an individualized simulation and a too generalized approach.

T2Net involves a fewer number of data sets, but leads to similar results like the TTCSM as the Pden and the map indicate. If the network data set is prepared in advance, in case of emergency only one analytical step – the calculation of the service area – generates the probability area map. The TTCSM involves several analytical steps calculating the probability area, which affords GIS knowledge and time. Since the time is essential for the chance of survival simple, quick methods are preferred.

The walking speed calculated for the T2Net was furthermore evaluated with hiking times provided by the provincial government of Vorarlberg (VoGIS, 2016). The hiking times in VoGIS were conducted in the field through measurement. The comparison of the walking speed calculated with T2Net with the VoGIS data resulted in a variation of ±10 percent. This indicates that the hiking speed derived with the T2Net shows an appropriate results regarding the hiking time.

Finally, the comparison of Pden for the TTCSM and the T2Net shows related results, although the Pden for the T2Net is slightly higher and the Ring Model provides best results.

From a practical perspective, an additional advantage of the T2Net can be seen in the network analysis itself. Similar to a car navigation system the SAR teams can use routing algorithms to calculate routes depending on different impedances, e.g. the quickest or shortest route to the person located. This opens new fields of application, e.g. in case of a hiker’s accident, in case of barriers through landslides, avalanches, etc.

6. Conclusion and further research

The paper presents an alternative approach to define search areas, the T2Net. It compares it with two common models, differing in terms of complexity, data and accuracy. While controlling for the same source of data the Ring Model scores in terms of time, costs and simplicity, TTCSM and T2Net integrate the specification of terrain due to the integration of geo-data. In the TTCSM, large amounts of data lead to time-, cost- and knowledge-intensive analyses, and may result in limited success since time is a critical factor in locating a missing hiker. T2Net methods offer a viable approach, since detailed results are obtained with a comparatively small number of geo-data and a short preparation and calculation time, in case road/trail data are available. They should be preferred, if the region shows a compact network of roads/trails.

One critical issue to generate an appropriate search area is the availability, amount and accuracy of geo and statistical data. As statistical data ISRID, an international statistical data set is integrated into the calculation. Future efforts can be made in combining international with local and open source data, and data mining through SAR teams. One future research issue can be seen in testing the T2Net with local data and compare it with ISRID results.

The integration of elevation changes from IPP or scattering angles of movement along the path will be additional research issues. In terms of GIS analyses, advanced geotechnical modeling algorithms and partly automated computation of search areas are of special interest.

Compared to North America, GIS-based WiSAR operations are not well established in Europe yet. Reasons for this are the lack of data, missing GIS knowledge of rescue teams and different regional settings (small-scaled, dense trail networks). However, the development of new WiSAR approaches should integrate experience of SAR teams and usability should guide the use of theoretical/scientific models. Therefore, extended evaluation of the TTNW with local data has to follow and proof the model in real world scenarios. To cope with the problem of cross-validating results in smaller areas, a more formal metric should be applied, e.g. MapScore (Sava *et al.*, 2016). This will allow calculating statistical parameters in order to compare the models on a more formal level.

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