Uncertainties and fuzziness in analysing risk related to natural hazards: a case study in the Ortles Alps, South Tyrol, Italy

A. Zischg, S. Fuchs & J. Stötter
Department of Geography, University of Innsbruck, Austria

Abstract

Uncertainty and fuzziness in the input parameters needed for the determination of the collective risk induced by alpine natural hazards are investigated for the Sulden road between Prad and Sulden in the Ortles Area, South Tyrol, Italy. The road is the access road to the major skiing area in the Vinschgau region and has therefore a high importance for winter tourism. It is endangered by 17 snow avalanche paths. The determination of the collective risk on roads is based on the analysis of the fatality risk. In this work the uncertainties in the risk parameters were quantified using a normal distribution and a Monte Carlo simulation. Handling every imprecise parameter as a fuzzy number is another possibility to compute them with the operators of the fuzzy set theory and provides the consideration of uncertainties when managing risks. The use of fuzzy logic illustrated that the approximations of risk parameters could be represented transparently and systematically when vagueness associated with numeric quantities occurs. The uncertainties in the risk analysis have a significant influence on the subsequent procedures in risk management, i.e. risk communication processes. Therefore, the established method of risk analysis has been extended taking the uncertainties into consideration.
Keywords: risk analysis, snow avalanches, roads, uncertainty, Monte Carlo simulation, fuzzy logic, natural hazards, Sulden, South Tyrol, Ortles Alps.

1 Introduction

Roads in the Alps, during wintertime, are often exposed to snow avalanche hazards. As a consequence, most of these roads have to be closed temporarily or permanently. The analysis of the risk of demise resulting from snow avalanches is a useful instrument to quantify the avalanche risk. These ideas were first outlined in Wilhelm [1, 2]. Later, this approach has been standardised as a

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guideline in Switzerland [3, 4]. Thus, the method has been established as an amplification of the information basis of decision makers in land-use planning [5]. The approach [1] defines the death risk on roads as the product of the probability of occurrence of an avalanche event and the probability of the presence of persons in areas endangered by those avalanches. The number of persons potentially affected results from the average daily traffic during the winter months, the mean number of passengers per car, the speed of the vehicles crossing the avalanche paths, its mean widths, and the probability of death in vehicles [1]. The risk calculated for every avalanche path is summed up to the collective risk for the whole road section. Basis of the procedure is an inventory of the existing avalanche paths. Most of the necessary risk parameters described above often have to be estimated due to a lack in data. Thus, the result of the risk analysis is subjected to a certain degree of uncertainty. While dealing with natural hazards, however, uncertainty is part of most approaches [6, 7]. Uncertainty can be classified into three main types [8, 9]: First, uncertainty is based on the lack of knowledge of the future state of a system. This type of uncertainty is subject to randomness (stochastic uncertainty). Second, uncertainty arises due the lack of information about the system behaviour (vagueness, ambiguity, fuzziness). Third, uncertainty is based on inexactness of measurements (impreciseness, fuzziness). Probability theory provides methods to deal with the first nature of uncertainty related to randomness, while fuzzy logic provides mathematical methods to deal with the second group of uncertainty (impreciseness) [10]. In comparison to the results of stochastic events, which can either be true or false; results of fuzzy events can be quantified by a degree of truth [11].

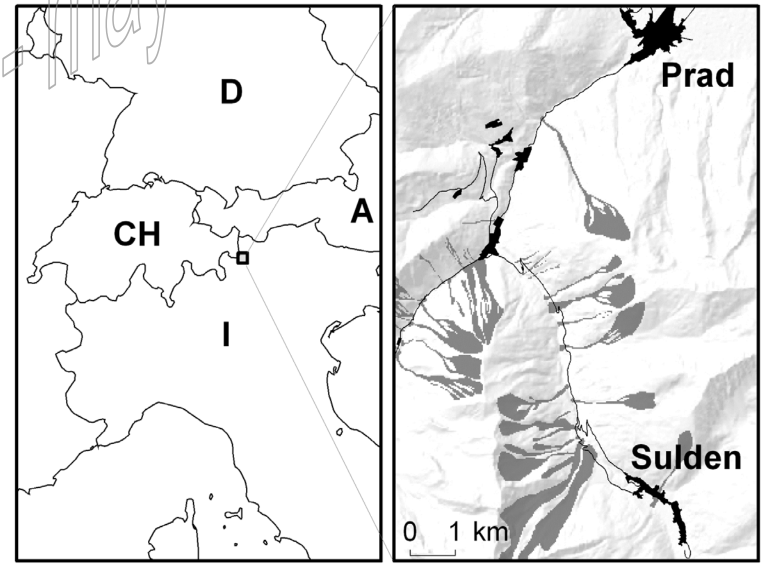

Figure 1: Study area Sulden Road, Ortles Alps, South Tyrol, Italy.

In this study, the uncertainties related to the method of risk analysis were pointed out and quantified as illustrated above in the case study of the Sulden road in the South Tyrolean part of the Ortles Alps, Italy. The main purpose of the study was to extend the established method of risk analysis outlined in Wilhelm [1] taking into consideration the uncertainties due to the lack of databases. The focus was placed on the application of two different methods to compute the two types of uncertainty in risk analysis, such as probability theory suited for stochastic uncertainties and fuzzy logic for the impreciseness of the data. The results of the risk analysis based on these two approaches were compared, and suggestions for the consideration of uncertainty in the risk analysis were deduced. The use of fuzzy logic illustrated, that the approximations of risk parameters could be represented transparently and systematically when a non-random impreciseness or vagueness associated with numeric quantities occurs.

2 Methods

2.1 Established method of risk analysis

The analysis of the collective risk due to natural hazards consists of three main steps [12, 13]. The first step in risk analysis on high alpine roads is the definition of the purpose of the study and the delimitation of the observed system in the research area. The system delimitation includes all elements in a research area, which are relevant for the estimation of risks as well as their causal relationships. In this study only the risk of demise due to snow avalanches is considered. Indirect losses or damage to infrastructure and cars are not taken into account. The object under investigation was the Sulden road between Prad and Sulden in the Ortles Alps, South Tyrol, Italy. The road serves as access road to the major skiing area in the Vinschgau region and has therefore a high importance for the winter tourism. At a length of 20 km, the road is endangered by 17 snow avalanche paths. Second, the avalanche situation was characterized based on analyses of past avalanche events observed by the local forest authorities since 1978. The analyses of historical data combined with on site investigations lead to an identification of the relevant avalanche paths and, as a result, to a compilation of the hazard map [5]. For every avalanche path, the return period (T) was calculated, as well as the mean width with which every avalanche path harms the road (g). The third step of the risk analysis process is the quantification of the potentially affected persons. The following risk parameters are necessary to compute the collective risk, expressed in the expected number of fatalities per year: The probability of presence of persons on the endangered road sections, calculated by the average daily winter traffic (WDT), the average number of passengers per car (β), the probability of death in vehicles (λ), and the average speed of vehicles (v) along the avalanche paths [5]. For every avalanche path the product of the risk parameters was calculated. The collective risk (R_o) on the object under investigation was retrieved summing up the risks in each of the avalanche paths (see eqn. 1). This computed risk value represents the initial state

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of the system. The effect of risk reduction resulting from the closure of the road has not been taken into account.

$$R_0 = \frac{WDT \cdot \beta}{24h} \sum_{i=1}^{n} \frac{g_i}{T_i \cdot v_i} \cdot \lambda_i \qquad (1)$$

i = 1, 2…n avalanche paths

Following eqn. 1, it becomes apparent that all parameters have a linear influence on the result of risk analysis. Thus, the uncertainties related to the input parameters regulate the uncertainty in the result. While a few risk parameters can be estimated on the basis of empirical data, other parameters have to be approximated. The return period (T) was empirically estimated on the basis of observation data from the avalanche warning service [14]. The average traffic volume (WDT) was estimated on the basis of counting statistics [15]. The mean width of the avalanche crossing the road (g), the average speed of cars (v) and the average number of passengers per car (β) were estimated on the basis of field studies. The probability of death in vehicles (λ) was estimated following the suggestions of Wilhelm [4]. The applied values of the risk parameters are shown in table 1. The collective risk was carried out on the basis of these average values. In a subsequent step, a worst case scenario was calculated based on the maximum and minimum values for those parameters. This step allowed the evaluation of the possible ranges in the result of risk analysis considering the uncertainties of all parameters.

Table 1: Values for the risk parameters and the related probability distributions.

Avalanche path no.	**T [years]**	**g [km]**	**v [km/h]**	**λ (mean)**	**WDT [cars/day]**	**β [pers./car]**
84076	9	0.275	60	0.18	1,136	2
84070	27	0.020	50	0.40	1,136	2
84069	27	0.055	60	0.40	1,136	2
84068	2.08	0.125	30	0.40	1,136	2
84067	27	0.060	50	0.18	1,136	2
84066	13.5	0.015	40	0.18	1,136	2
84063	13.5	0.030	50	0.18	1,136	2
84039	13.5	0.100	50	0.18	1,136	2
84040	13.5	0.050	55	0.18	1,136	2
84042	27	0.080	50	0.18	1,136	2
84043	27	0.080	50	0.18	1,136	2
84044	6.75	0.035	30	0.40	1,136	2
84045	13.5	0.125	30	0.40	1,136	2
84046	27	0.125	30	0.40	1,136	2
84047	27	0.400	35	0.40	1,136	2
84048	27	0.300	60	0.18	1,136	2
applied standard deviation	*1*	*0.020*	*10*	*0.10*	*481*	*1*

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2.2 Monte Carlo simulation

To analyse the uncertainties of stochastic nature resulting from the data, the Monte Carlo simulation approach was applied. This sampling-analysis procedure describes the probabilities of the results of a given model, using probability distributions of relevant variables in the risk analysis process. A sample of 10,000 scenarios was created based on randomly generated values resulting from the probability distributions of every parameter. For the representation of the uncertain quantities the normal distribution was used. This probability distribution describes an uncertain symmetrical quantity specified by the mean and the standard deviation [16]. In table 1 the chosen characteristics of the probability distributions are presented for every risk parameter. The simulation results are described by a probability distribution of the sample. The collective risk on the observed road expressed in fatalities per year results by the average of all simulation results. The uncertainty of the resulting values is described by the standard deviation. Thus, the reliability of the risk analysis can be assessed.

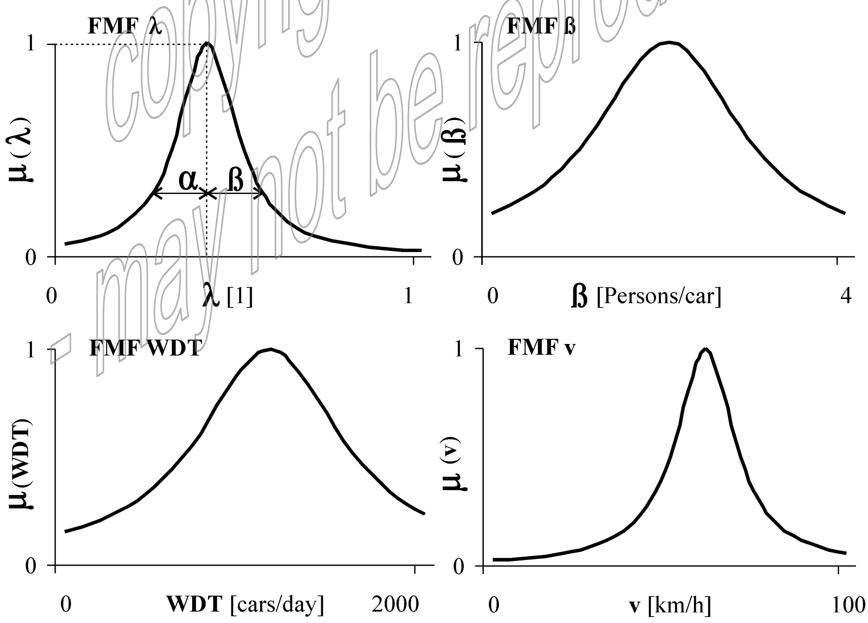

Figure 2: Membership functions of the risk parameters.

2.3 Fuzzy logic

Another method to obtain information on the uncertainties in the risk analysis procedure is the representation of the vagueness related to the risk parameters by fuzzy numbers. Fuzzy numbers represent and approximate numeric quantities [10, 17, 18, 19, 20]. Fuzzy numbers extend crisp values, using a range of values instead of a single numerical value. The fuzziness of the variable is described by its membership function. The membership degrees have values between 0 and 1. By definition, a fuzzy number has one single point, where the membership degree is 1, and decreasing membership degrees on both sides of the mean value [19, 21]. Operations on fuzzy numbers are outlined by Dubois & Prade [19, 20] and Delgado *et al.* [21]. The Beta Curves were used as a method to represent the membership function of a fuzzy number. The Beta curved fuzzy number is defined by two parameters: The range of the curve around the centre of the fuzzy number and the distance to the inflection point (β) (see fig. 2, [10]). The values of the standard deviation of the risk parameters were used as the values for the spread of the function (β), as presented in table 1. Fig. 2 shows the chosen membership functions of the variables. The risk is carried out in the same way as described in eqn. 1, considering the extension principle of Zadeh [11] and following the rules of fuzzy operations according to Dubois & Prade [19]. A fuzzy number with a membership function determined by the combination of all membership functions of the risk parameters results. The value with a membership degree of one corresponds with the result of the risk analysis considering crisp values. The membership values represent the degree of compatibility of the result to the concept defined in the system delimitation.

3 Results

3.1 Established method of risk analysis

The collective risk on the object under investigation (Sulden road) due to snow avalanches was calculated as 0.137 fatalities per year, following the method outlined in Wilhelm [1]. The result of the worst case scenario was calculated as 3.035 fatalities per year, when for all parameters except the probability of occurrence of avalanche the maximum values were used. Assuming that the road is harmed by every avalanche path twice per year, a worst case scenario of 35.667 annual fatalities was calculated. The worst case scenario is 27-fold respective 315-fold higher than the result based on the average values. The results ranged between 0 and 35.667. Thus, the uncertainty in the result is delimitated by a lower and an upper limit.

Table 2: Descriptive statistics about the simulation results.

Parameter	**Value**
Mean	0.181208
Standard Deviation	0.223186
Median	0.144593
Maximum	11.835995
Minimum	0.000220
Range	11.835775
Confidence Interval (95%)	0.004374
Simulations	*10,000*

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3.2 Monte Carlo simulation

The Monte Carlo simulation showed more differentiated results: The result of a Monte Carlo simulation is a sample dataset of 10,000 calculated crisp values. The resulting values computed by 10,000 simulations were illustrated in a histogram and specified by descriptive statistics. Fig. 3 shows the distribution of the simulation results. The average risk calculated by 10,000 simulations resulted in a value of 0.181 fatalities per year. The maximum value was 11.835, the minimum value 0.0002 (see table 1). A standard deviation of 0.223 was calculated. In comparison to the method described above, more information about the uncertainty in the result could be obtained.

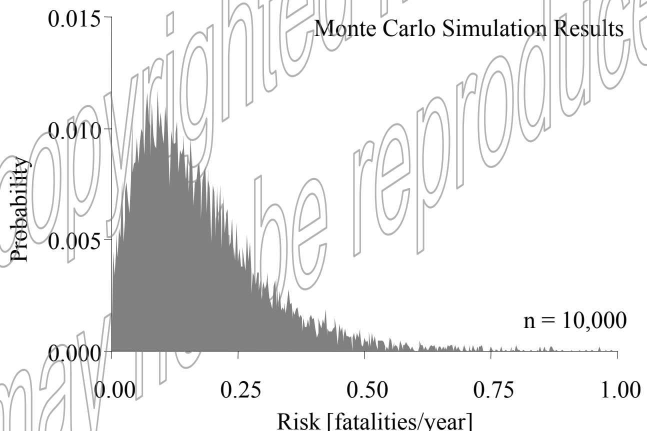

Figure 3: Result of the risk analysis based on a Monte Carlo simulation.

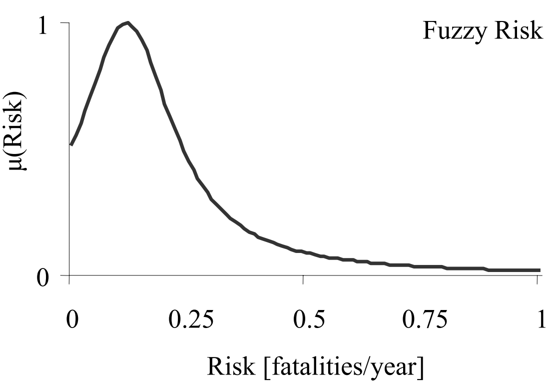

Figure 4: Result of the risk analysis on the basis of fuzzy numbers.

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3.3 Fuzzy logic

The determination of the collective risk based on the methods of fuzzy logic resulted in a fuzzy number with a membership degree of one at the risk level of 0.137 annual fatalities. The fuzziness of the result is determined by combining the membership functions of all variables. As presented in fig. 4, the values for the annual number of fatalities ranged from 0 to 0.25, with a membership degree of > 0.5. In comparison to the methods described above, where the results consisted of 1 respectively 10,000 crisp estimations, the result of this approach consisted of a continuous valued estimation, expressed by the membership function of the computed risk.

4 Discussion

Applying the method outlined in Wilhelm [1], an annual fatality rate of 0.137 resulted. The uncertainty in the result is delimitated by a lower and an upper limit, specified by the optimal respective the worst case scenario. Applying a Monte Carlo simulation, an average annual fatality rate of 0.181 resulted. In comparison to the established method, the uncertainty in the result could be specified by a histogram and descriptive statistics. Thus, more information about the uncertainty was obtained. The probability distribution of the simulation results describes the character of the uncertainty more detailed as the range between extreme scenarios. Applying fuzzy logic, an annual fatality rate of 0.137 resulted. The uncertainty in the result is described by the membership function of the computed fuzzy value. In comparison to the results of the other two methods, the result consists of a continuous valued estimation. Nevertheless, the calculated fuzzy numbers are directly comparable with crisp results of risk analysis on other objects under investigation. As originally assumed, the Monte Carlo simulation as well as the fuzzy logic approach, are both appropriate to extend the established method of risk analysis taking into consideration the uncertainties due to the lack of database. In the case study described in this paper, the uncertainties in the risk parameters were based on impreciseness, more than on randomness. Therefore, fuzzy logic is appropriate to deal with approximations in the analysis of snow avalanche risk on roads. In comparison to Monte Carlo simulation, fuzzy logic is easy to compute. However, it is outlined that the uncertainties in the risk analysis are not in a negligible dimension. According to Chongfu [22] and Gheorge *et al.* [23], the consideration of uncertainty and impreciseness enhances the quality and reliability of risk analysis. This information can be communicated as a type of metadata. The method may be adapted for other natural hazard processes, further research must focus on the probability distributions or membership functions of the risk parameters.

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References

[1] Wilhelm, C., Wirtschaftlichkeit im Lawinenschutz. Methodik und Erhebungen zur Beurteilung von Schutzmassnahmen mittels quantitativer Risikoanalyse und ökonomischer Bewertung. *Mitteilungen SLF 54*, Davos, 1997.

[2] Wilhelm, C., Quantitative risk analysis for evaluation of avalanche protection projects, Norwegian Geotechnical Institute Publication no. 203, Oslo, pp. 288-293, 1998.

[3] Borter, P., Risikoanalyse bei gravitativen Naturgefahren - Methode. *Umwelt-Materialien Nr. 107/I Naturgefahren*, ed. BUWAL, Bern, 1999.

[4] Wilhelm, C., Kosten-Wirksamkeit von Lawinenschutzmassnahmen an Verkehrsachsen. *Praxishilfe*, ed. BUWAL, Bern, 1999.

[5] Margreth, S., Stoffel, L., & Wilhelm, C., Winter opening of high alpine pass roads - Analysis and case studies from the Swiss Alps. Proceedings ISSW 2002 International Snow Science Workshop, Penticton, BC, Canada, 29 Sept - 4 Oct, ed. Stevens, J.R., 2002.

[6] Bell, R. & Glade, T., Quantitative risk analysis for landslides – Examples from Bildudalur, NW-Iceland. Natural Hazards and Earth System Sciences, 4, pp. 117-131, 2004.

[7] Barbolini, M., Natale, L. & Savi, F., Effects of Release Conditions Uncertainty on Avalanche. *Natural Hazards*, **25**, pp. 225–244, 2002.

[8] Zimmermann, H.J., An application-oriented view of modelling uncertainty. *European Journal of Operational Research*, **122(2)**, pp. 190-198, 2000.

[9] Zimmermann, H.J., *Fuzzy Technologien. Prinzipien, Werkzeuge, Potentiale*. VDI Verlag: Düsseldorf, 1993.

[10] Cox, E., *The fuzzy systems handbook.* AP Professional, New York, 1999.

[11] Zadeh, L.A., Fuzzy sets as a basis for a theory of possibility. *Fuzzy Sets and Systems* **1(1)**, pp. 3-28, 1978.

[12] Heinimann, H., Hollenstein, K., Kienholz, H., Krummenacher, B., & Mani, P., Methoden zur Analyse und Bewertung von Naturgefahren. *Umwelt-Materialien 85*, ed. BUWAL, Bern, 1998.

[13] Hollenstein, K., *Analyse, Bewertung und Management von Naturrisiken.* Hochschulverlag ETH Zürich, 1997.

[14] Autonomous Province of Bolzano – South Tyrol, Avalanche Warning Service, *Avalanche Atlas*, 2002.

[15] Autonomous Province of Bolzano – South Tyrol, Provincial Statistics Institute (ASTAT), *Traffic Database*, 2004.

Risk Analysis IV, C. A. Brebbia (Editor)

[16] Powell, S.G. & Baker, K.R., *The Art of Modeling with Spreadsheets. Management Science, Spreadsheet Engineering, and Modeling Craft*. John Wiley & Sons, Hoboken, NJ, 2004.
[17] Zadeh, L.A., Fuzzy sets. *Information and Control*, **8**, pp.338–353, 1965.
[18] Zadeh, L.A. The concept of a linguistic variable and its application to approximate reasoning--I. *Information Sciences*, **8(3)**, pp. 199-249, 1975.
[19] Dubois, D. & Prade, H., Operations on fuzzy numbers. *International Journal of Systems Science*, **9(6)**, pp. 613-626, 1978.
[20] Dubois, D. & Prade, H., Fuzzy relation equations and causal reasoning. *Fuzzy Sets and Systems* **75(2)**, pp. 119-134, 1995.
[21] Delgado, M., Verdegay, J.L. & Vila, M.A., Fuzzy Numbers, Definitions and Properties. *Mathware & Soft Computing*, **1**, pp. 31-43, 1994.
[22] Chongfu, H., Fuzzy risk assessment of urban natural hazards. *Fuzzy sets and systems*, **83**, pp. 271-282, 1996.
[23] Gheorge, A.V., Mock, R. & Kröger, W., Risk assessment of regional systems. *Reliability Engineering and System Safety*, **70**, pp. 141–156, 2000.

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