Two expert systems to forecast the avalanche hazard for a given region

Jürg Schweizer and Paul M.B. Föhn

Swiss Federal Institute for Snow and Avalanche Research
CH-7260 Weissfluhjoch / Davos, Switzerland
phone: +41 81 417 0222, fax: +41 81 417 0220

Abstract. *A commercially available software, CYBERTEK-COGENSYS™ Judgment Processor for inductive decision-making, was used to develop two different expert systems as supporting tools to forecast the avalanche hazard for a given region. Using weather, snow and snow cover data as input parameters the systems evaluate the degree of hazard, the aspect and altitude of the most dangerous slopes. So the output result is exactly what the avalanche forecaster needs. The avalanche hazard we use in the data base, is the verified hazard or the so-called verification, i.e. the day-to-day critical "a posteriori" assessment of the avalanche hazard. The new models were developed, tested and rated in the Davos region (Swiss Alps) for several years from beginning of December to end of April. The first model may partially be compared to statistically based systems. However the differences are: more input information about the snow cover including snow profiles and Rutschblock tests, the concise output result and the knowledge base that includes the verified degree of avalanche hazard. The performance is about 60%, i.e. the predicted degree of avalanche hazard coincides on 6 out of 10 days with the later on verified degree of hazard. The second model is more process oriented and includes partially implicit rules; it may be compared to a deterministic system. The system tries to model the decision making process of a pragmatic expert. It has a performance of 70 to 75%. In both models the snow cover data proved to be most decisive. Since some of the input parameters are not conventional measurements, the models do not run fully automatically, but the interactive use is highly instructive.*

1 Introduction

Avalanche forecasting means the daily assessment of the avalanche hazard for a given region. The thereof derived warnings should describe the avalanche situation, i.e. give information about the place, the time and the probability of release for a specific type of avalanches (slab or sluff, large or small, wet or dry). The most convenient way to handle this sort of information is to summarize it in a

degree of avalanche hazard. In Switzerland the degree of hazard is defined since 1985 in descending order by the release probability, the areal extent of the instabilities and the size of avalanches (Föhn, 1985). Any expert system for regional avalanche forecasting should profit from this concept that has been adopted in 1993 by the working group of the European avalanche warning services.
Since dry slab avalanches represent the most important threat for skiers and back country travellers, we focused on the hazard of dry slab avalanches. LaChapelle (1980) described the technique for assessing the avalanche hazard: Weather, snow and snow cover data daily observed and measured at several locations representative for a given area are evaluated by human experts using their knowledge and long-term experience combined with individual intuition. Since then the procedure did not change much. The core is still formed by the so-called synoptical method supplemented by different sorts of supporting tools (Figure 1). Despite a lot of electronic tools included nowadays in the process of avalanche forecasting the avalanche hazard can not (yet?) fully be calculated in a strict sense (by algorithms). The task remains difficult and involves great responsibility. Any tools assisting the expert in the decision making process are welcome.

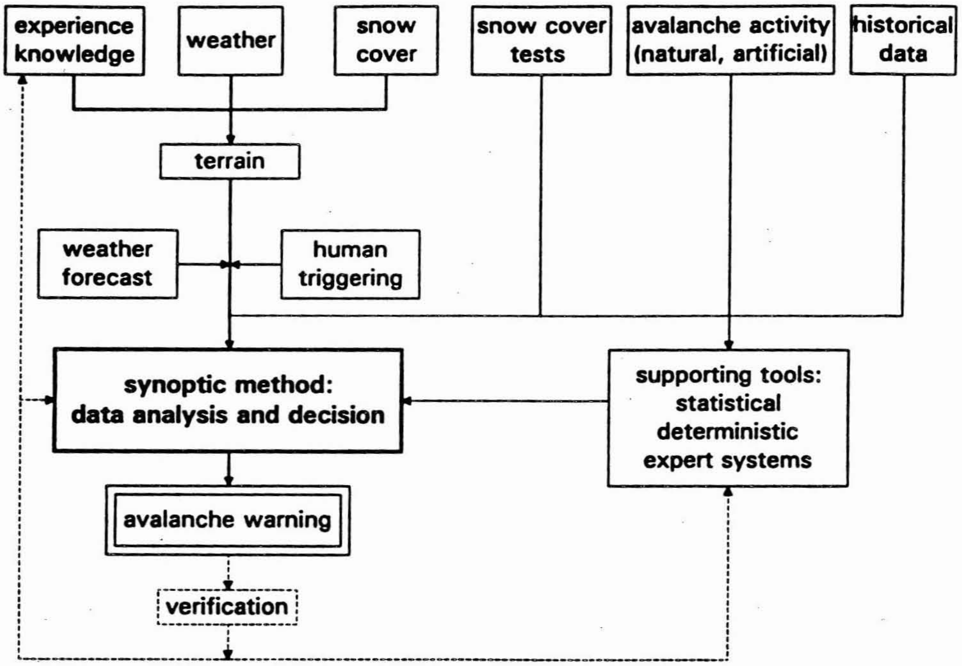

Figure 1. The synoptical method for forecasting the avalanche hazard supplemented with different supporting tools; input parameters and their relation.

2 Present approaches

The ***synoptical*** technique to assess the avalanche hazard for a given region still forms the basis of the decision making procedure of most avalanche forecast services. None of the supporting tools are, until now, reliable enough to substitute the human expert and will probably never be. But they may become an objective partner for "discussing"? A general overview of different methods is given in Föhn et al. (1977), Buser et al. (1985) and recently in McClung and Schaerer (1993) and

Schweizer and Föhn (1994). In the following only some models and tools are mentioned.

Operational systems based on the ***statistical*** approach using a long term data base were developed in several countries and are widely used (Buser et al., 1987; Navarre et al., 1987; Mérindol, 1992, McClung and Tweedy, 1994) both for local and for regional avalanche forecasting. The two most popular methods are the *discriminant analysis* and the *nearest neighbours* (McClung and Schaerer, 1993). Snow and weather data is usually used together with observations of avalanche activity. It is assumed that similar snow and weather conditions should lead to similar avalanche situations. The output is the avalanche activity (i.e. the observed avalanches) of the similar historic situations found in the data base, often in the form of a prediction of "avalanche or non-avalanche day". In the case of regional avalanche forecasting this sort of output is difficult to relate to the actual hazard. Hence it is difficult to assess the real quality of these forecast models. They certainly improve the reflections of unexperienced forecasters and may influence experienced forecasters, but may rarely be called a decisive help in determining the degree of hazard for a region.

The aim of the purely ***deterministic*** approach is to simulate the avalanche release. On the basis of a snow cover model the avalanche formation is modelled using principles of fracture mechanics (Gubler and Bader, 1989). However, the present deterministic approaches are far from being able to link the single avalanche event to the regional avalanche hazard. Probably most successful is the french approach combining a snow cover model (Brun et al., 1992) with an expert system.

A combined approach, containing deterministic and statistical components has been developed by Föhn and Haechler (1978). The total loading by snowfall, wind action and the settlement is simulated in order to forecast large, dry snow avalanches.

Expert systems represent the idea of simulating the decision making process of an expert. Most of them are symbolic computing systems, i.e. use rules which were formulated explicitly by human experts e.g. MEPRA (Giraud, 1991) and AVALOG (Bolognesi, 1993).

The French system MEPRA analyzes the snow cover stratigraphy; the snow profiles are simulated by the snow cover model CROCUS (Brun et al. 1989) running with meteorological data provided by SAFRAN (Durand et al., 1993), a model for optimal interpolation of meteorological data.

Recently a hybrid expert system was developed using a neural network and rules extracted from the data base with neural network techniques (Schweizer et al., 1994).

3 A new approach using the CYBERTEK-COGENSYS^{TM} Judgment Processor

In 1989 we started a new approach with the idea of building a system for regional avalanche forecasting comparable to the statistical ones but with optimized input and output parameters: called DAVOS. We tried to include some of the relevant physical processes, i.e. elaborated input parameters, and to give as result directly what the avalanche forecaster would like to have: the degree of hazard. (Schweizer et al., 1992).

In 1991 we worked out a completely new approach, more physically based, comparable to a deterministic system, that tries to model the reasoning of the avalanche forecaster: called MODUL. Both systems are based on a software for inductive decision making: CYBERTEK-COGENSYS™ Judgment Processor, details are given in Schweizer and Föhn (1994).

The CYBERTEK-COGENSYS™ ***Judgment Processor*** is a commercially available software for inductive automatic decision making. It is based on the fact that pragmatic experts decide using their experience and intuition rather than explicit rules. The more complex a problem, the less structured is the knowledge. An expert is able to decide correctly and fast in a real situation. However he is usually not able to explain his decision completely by exact rules. The expert's approach is to choose the relevant data (which differs substantially from one situation to another), to classify and to analyze the data and finally to make a conclusion.
The expert building up the system defines the input data needed to reach a particular decision, the output, and the criteria that are used to categorize or evaluate the data; each input parameter has to be grouped in logical ranges (up to five ranges). The expert "teaches" the Judgment Processor by entering examples and interpreting the situations represented by those examples.
The Judgment Processor calculates the logical importance of each input parameter based on the observation of the mentor's decision. The logical importance is a measure of how a particular input parameter contributes to the logical model as a whole, based on how many situations within the knowledge base would become indistinguishable if that input parameter was removed. Based on the logical importance, given as a number from 1 ... 100, the parameters are classified as *major* or *minor*. The logical importance is continuously updated, so the system learns incrementally.
If a new situation is encountered the system tries to give a proposition for the possible decision on the basis of the past known situations. The similar situations are found by using the condition of similarity that prescribes that the majority of the values of the major input parameters has to be each in the same logical range. The quality of the proposed decision is described by the so-called confidence level, an indicator of how certain the system is that its interpretation is appropriate to the current situation: an exclamation mark (!) for very confident, a period (.) for reasonably confident or a question mark (?) for not confident. A low level of confidence suggests that there are few situations that the system considers to be logically similar, or that those situations that are similar have conflicting interpretations. Additionally the similar situations that are used to derive the decision with the according assertion level are also given. If the system is not able to find a decision on the basis of the present knowledge base it gives the result "not possible to make an interpretation", in the following simply called "n.i." (CYBERTEK-COGENSYS™, 1991).
The Judgment Processor's algorithm is not known in all details. Since the search for similar situations forms the core of the method, it may be called, in the broadest sense, a nearest neighbour method. However, the metric to search for similar situations differs substantially from the commonly used distance measure, e.g. the euclidian distance. The categorization of the input data, the classification into major and minor parameters and the metric to search similar situations are all non linear. The method is appropriate to deal with not independent, not normally distributed data. Briefly summarized the system weights and classifies the categorized data, searches for similar situations using strongly the classification and

categorization, derives a result from the similar situations, describes the quality of the result and finally lists the similar situations used for deriving the result together with the pertinent similarity measure. The advantage of the method is the strong concentration on the input parameters that are considered as important.

In our case the judgment problem is the ***avalanche hazard*** and the input parameters are e.g. the 3-day-sum of new snow depth or the air temperature. A real situation is hence described by the set of input parameter values (weather and snow data) for the given day. The logical ranges in the case of the 3-day-sum of new snow depth are e.g. 0...10, 10...30, 30...60, 60...120 and more than 120cm. Finally, the decision or interpretation is the degree of hazard and additionally in the DAVOS model (see below) the altitude and the aspect of the most dangerous slopes.

The ***input parameters*** were chosen from a data set with 21 values which are believed to be representative for the region considered: 7 quantities are measured in the morning in the experimental plots of SFISAR at Weissfluhjoch 2600 m.a.s.l., 4 are prospective values for the day considered and 10 values describe the actual state of the snow cover based on slope measurements performed about every ten days. These principal data is given in Table 1.

I: Measurements

D, M	new snow depth
D, M	total snow depth
D, M	penetration depth
D, M	wind speed and wind direction
D, M	air temperature
M	snow temperature
M	new snow density

II: Prognostic data

D, M	air temperature at noon
D, M	index of radiation for today
M	mean wind speed for today
M	new snow depth in the evening

III: Snow cover data

D	index of snow cover stability
D	depth of critical layer
M	result of Rutschblock test
M	type of release (RB test)
M	type of critical layer (RB test)
M	total slab thickness (RB test)
M	new snow slab thickness (RB test)
M	type of profile (RB test)
M	snow depth at the test site (RB test)
M	date of Rutschblock test

D: Data used in the model DAVOS

M: Data used in the model MODUL

Table 1. Principal data used in the two different models DAVOS and MODUL.

To each data set consisting of the above weather, snow and snow cover data belongs the description of the avalanche hazard, the ***output parameter***. It seems most appropriate to choose as output of an expert system exactly the structure that is usually used by forecasters. So the assisting tool "speaks" the same language as the forecaster.

The avalanche hazard is formulated first of all as degree of hazard (*1...7*). Secondly, the lower limit of the primarily endangered altitudes is given in steps of usually 200m (*>1200, >1600, >1800, >2000, >2200, >2400, >2500, >2600, >2800 m.a.s.l.*). Thirdly, the main aspect is described as either one of the mean directions (*N, NE, E, SE, S, NW*) and an according sector (± *45°*, ± *67°*, ± *90°*) or as *extreme* slopes or *all* slopes. If the hazard is given e.g. as *4, > 2400 m.a.s.l., NE* ± *90°* this means high hazard on slopes with aspect from north-west to south-east above 2400 m.a.s.l.

The avalanche hazard, as we use it, is the result of an "a posteriori" critical assessment of the hazard, the so-called ***verification***. The verification has again the same structure as the warning. It is hardly possible to verify the avalanche hazard otherwise. Several studies on the verification of the avalanche hazard with the help of the so-called avalanche activity index were not sufficiently successful (Judson and King, 1985; Giraud et al. 1987; Remund, 1993). One reason is that in the case when no avalanches are present or observed, the avalanche hazard is not necessarily inexistent or very low. Hence it is obviously wrong to use the observed avalanche activity as sole output parameter in an assisting tool for regional avalanche forecasting.

Operationally the verification has been done some days later considering the observed avalanche activity (naturally and artificially released), the past weather conditions, the additional snow cover tests, the backcountry skiing activity and several other, partly personal observations. Snow cover tests form an important part of the verification work. The verification is an expert task itself and describes the avalanche situation for a given day probably still not yet exactly, but more accurately than the public avalanche forecast. Whereas the avalanche forecast is correct in about 70% of the days, the verification may be correct in about 90% of the days. By the way, the weather forecast achieves 80 to 85% of correct diagnosis.

4 Models

Using the CYBERTEK-COGENSYS™ Judgment Processing System we developed two different types of models: DAVOS and MODUL. The DAVOS type uses 13 weather, snow and snow cover parameters and evaluates the degree of hazard, the altitude and the aspect of the most dangerous slopes. The system is similar to a statistical model. In contrast the model MODUL is rather comparable to a deterministic system. It uses 30 input parameters stepwise and the evaluation of the degree of hazard is the result of 11 interconnected judgment problems that are formulated according to the relevant processes. The system tries to model the decision making process of an expert avalanche forecaster.

Model DAVOS

The DAVOS model uses the ***input parameters*** given in Table 2. Most of the values are calculated from 9 principal values (Table 1) according to our experience. The idea was to take into account certain relevant processes, e.g. the new snow settlement. Details are given in Schweizer and Föhn (1994). New input parameters are in particular the *Index of snow cover stability* (1 to 5) and the *Depth of critical layer*. These data are mainly gained by snow profiles and Rutschblock tests. In all the different versions of the model DAVOS the input parameters describing the state of the snow cover proved to be very important.

input parameters	boundaries/choices	DAVOS1	DAVOS2
sum of new snow depth (3 days)	10/30/60/120cm	0	**100**
penetration depth	5/15/30/50cm	**83**	28
total snow depth (3 days before)	70/100/150/200cm	**83**	**65**
settlement quotient	0.01/0.5/0.8/0.99	**50**	21
penetration quotient	0.4/0.8/1.2/3.0	**41**	24
sum of blowing snow (3 days)	2/5/10/15cm	**66**	33
air temperature	-15/-8/-3/0°C	**66**	23
air temperature difference	-5/0/5/10°C	**24**	15
sum of the positive temperature at noon 2000m.a.s.l. (3 days)	0.01/3/6/10°C	**41**	29
index of radiation	1,2,3	**44**	11
index of snow cover stability	1,2,3,4,5	**100**	**86**
mean wind direction	NW, NE, SE, SW,00	**33**	26
depth of critical layer	20/40/60/90cm	**79**	**51**

Table 2. Input parameters and the logical ranges of the model DAVOS. Also given the logical importance of two different versions of the DAVOS model; bold figures indicate *major* parameters (see below).

Beside the input parameters we also have chosen the ranges for each of the input parameters according to our experience (Table 2). Based on the 9 year data base we are finally able to check whether the chosen ranges were reasonable or not. One example, the 3-day-sum of new snow depth, is given in Figure 2. The situations with sum of new snow between 30 to 60cm and 60 to 120cm seem to be quite similar. In most situations the degree of hazard is 3 for both ranges. Hence it seems that these ranges do not categorize well. However, it is clear that the sum of new snow depth is only one of the input parameters that are all interconnected somehow, and that the avalanche hazard can not be determined by a sole input parameter.

The ***output parameter*** or result is the avalanche hazard described as degree of hazard, altitude and aspect of the most dangerous slopes.

The ***knowledge base*** of the DAVOS model consists of only real situations: the daily data of 9 winters (1 December to 30 April), totalling 1361 situations; 22 situations are two by two identical.

The original version of the model DAVOS was called DAVOS1. The experience with this version has given rise to develop further ***different versions*** (Schweizer and Föhn, 1994). The versions DAVOS2 concentrates on the first output result, the degree of hazard, whereas in the original version DAVOS1 all three results are equally important. In the DAVOS2 version the values of the logical importance seem to be closer to the general experience than in the DAVOS1 version where e.g. the 3-day-sum of new snow depth has no importance at all. The values of the logical importance of the original version DAVOS1 (Table 2) show clearly that this version is hardly able to discriminate. This fact seems definitely to be due to the desired output result that consists of three independent components.

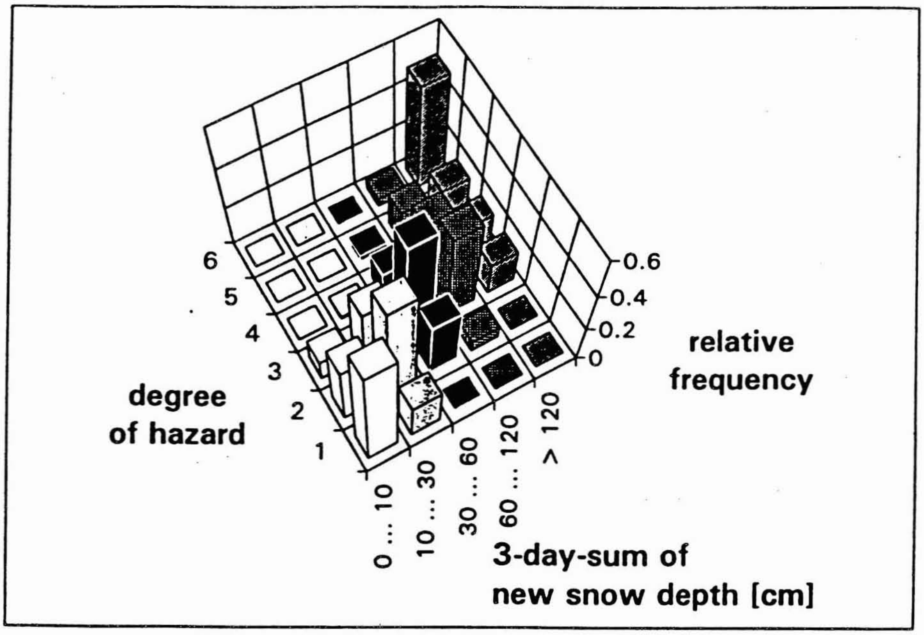

Figure 2. Comparison of the *3-day-sum of the new snow depth* with the *degree of hazard* for all situations (1361) in the last 9 winters to check whether the logical ranges chosen categorize the data appropriately.

DAVOS31 and DAVOS32 were born from the idea that it is generally important whether for a given day there is new snow or not. Accordingly the knowledge base was split into situations without new snow and ones with new snow.
Finally we tested a version (DAVOS4) that only gives the degree of hazard, and not also the altitude and the aspect of the most dangerous slopes. Due to the single type of output the version DAVOS4 should discriminate better than the other versions and hence should give better results.

Model MODUL

Using the model DAVOS we realized that the problem seems too complex or the method and/or approach not good enough to make a substantial step forward. The model seems only partly to be able to recognize the hidden structure of reasoning. So we decided to help the system by structuring the input data. The idea was to build up an expert system following the reasoning of an avalanche forecaster that, before deciding, structures the input data according to the prevailing conditions and on the basis of the physical processes involved. The modular ***structure*** consisting of 11 subproblems using 30 input parameters is shown in Figure 3.
First of all it is decisive whether there is new snow or not. Either the forecaster has to assess the new snow stability or he directly assesses - without new snow - the old snow stability which is often similar to the stability one day before, except if there is e.g. a large increase of heat transport and/or radiation. So he structures the input data according to the different steps in the decision process. If both the new snow stability and the old snow stability, including both the effect of the weather as forecast for today, are decided, the two release probabilities are combined. Taking into account the effect of the terrain and of the skier as trigger the degree of hazard is finally determined. At the moment only the degree of hazard is given; the altitude and the aspect as given in the DAVOS model is not yet implemented.

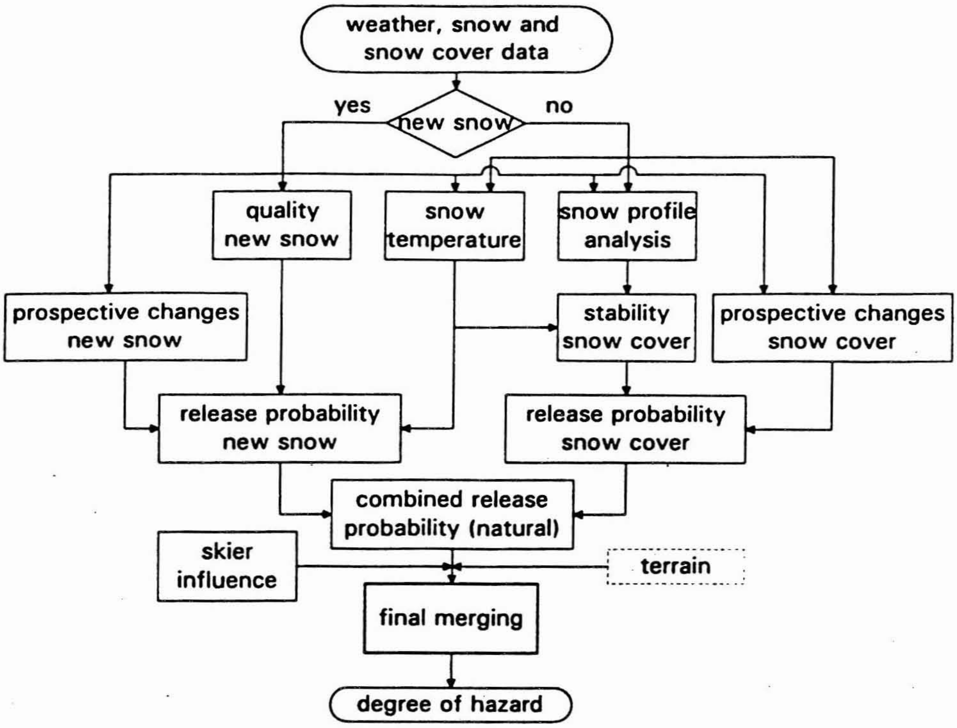

Figure 3. Structure of the model MODUL: 11 subproblems and their relation.

Each of the ***subproblems*** as e.g. *Quality of new snow* or *Stability of old snow* represents a judgment problem, as described above, and is hence principally structured as the model DAVOS. The different subproblems are just smaller than the DAVOS model, i.e. consist of only 3 to 8 input parameters. Often only 3 of the input parameters are considered as major parameters. This is a large advantage, since a much smaller knowledge base is necessary to get good interpretations and the system usually learns faster and better the logic behind the decision process. It is even possible to not only build up the knowledge base with real situations, but to construct realistic situations by varying the major input parameters in a reasonable sense. This is impossible in the DAVOS model. So if the expert feels sure in one of the subproblems about the influence of one of the input parameters maybe in combination with another one, he may systematically construct realistic situations and decide systematically. But this means nothing else than including a rule, not explicitly, but implicitly. An example of such an ***implicit rule*** used in the subproblem *Final merging* is given in Table 3. This is of course a rather exhausting work, but the advantage is that the expert is more flexible in his decision as if he would use a strict explicit rule. It is easy e.g. to include non-linear relations. Furthermore it is possible to construct extreme, but still realistic situations that usually are rare, but of course very important. So one of the disadvantages of principally statistically based models using real data may be overcome. Finally you end up with a knowledge base that is a mixture of real, historic situations decided according to the verified hazard in those times and realistic situations directly decided according to the general knowledge and experience.

30 ***input parameters*** (Table 4) are used in 11 subproblems interconnected partially by rules. Some of the data are conventional data or mainly so-called low entropy data (LaChapelle, 1980), some are estimates of the weather development and

more than one third is data on the structure of the snow cover. Hence to get all the data a user with certain skills and experience is required.

Influence of skier \ Combined release probability	very low	low	moderate	high
low	1	1	2	4
moderate	1	2	3	4
high	2	3	4	4

valuable, if overall critical depth H_{crit} = 15...50cm,
else, if H_{crit} < 15cm, 1 degree of hazard less
or if $H_{crit} \geq$ 50cm and combined release probability ≥ *high*, then degree of hazard = 6 or 7
and if depth of stable old snow H_{bound} > 60 cm,
else, if H_{bound} = 30...60cm, then 1 degree of hazard less
or if H_{bound} < 30cm, then 2 degrees of hazard less
except if Combined release probability = *moderate*, no reduction of hazard

Table 3. General decision rule to decide on the degree of hazard in the subproblem *Final merging*; principally dependent on the *Combined (natural) release probability* and the *Influence of the skier*, but also dependent on the *Overall critical depth* by the potential avalanche size and volume and on the *Depth of stable old snow* by the terrain roughness.

A: conventional data
new snow depth
sum of new snow depth (3 days)
density of new snow
snow depth
change of snow depth (3 days)
coefficient of settlement (3 days)
penetration depth
coefficient of penetration depth
snow temperature
mean wind speed (3 days)
sum of blowing snow (3 days)
air temperature
temperature difference

B: prognostic data
new snow depth in the evening
temperature development until noon
mean wind speed for today
index of radiation for today

C: special snow cover data
result of Rutschblock test
type of release (RB test)
type of critical layer (RB test)
total slab thickness (RB test)
new snow slab thickness (RB test)
type of profile (RB test)
age of Rutschblock test
change of snow depth since Rutschblock test
critical depth of new snow slab
critical depth of old snow slab
overall critical depth
effective critical depth for skier triggering
depth of stable old snow

Table 4. Input parameters used in the model MODUL.

The output result of a subproblem is usually used as input parameter in another subproblem that appears later on in the decision process.

Many of the input parameter values are calculated using rules that depend themselves on the input values. The *Overall critical depth* e.g. depends on the *3-day-sum of blowing snow depth* that is only considered in certain situations when snow drift is likely.

Due to the modular structure it is easily possible to make ***modifications*** in any of the subproblems. Additionally the relatively small number of input parameters in each subproblem enables the knowledge base to adapt rapidly to any modification, as e.g. adding a new input parameter.

So the important subproblem *Influence of the skier* is steadily improved according to the results of the specific study on the slab avalanche release triggered by the skier (Schweizer, 1993). In the subproblem *Snow profile analysis* the snow profile with Rutschblock test, representative for the region considered, is roughly interpreted, an aim that actually would need an expert system itself. 8 principal values (Table 1) are used exclusively for solving this subproblem. It should substitute together with the subproblem *Stability of old snow* the most important input parameter *Index of snow cover stability* in the DAVOS model. So this subproblem is under permanent improvement, too. Recently the *Type of release* and the *Quality of the critical layer* were introduced as input parameters.

In **operational use,** the model has to be run interactively by an experienced user. The model stops if the proposed decision in one of the subproblems does not have a high confidence level, and the user has to confirm the decision before the model continues to run. The final output result, the degree of hazard, is well explained by the output results of the different subproblems. If the model proposes a different degree of hazard than the user has independently estimated, the difference becomes usually obvious by inspecting the output results of the subproblems. Due to this feature the model is not at all a black box system, but a real supporting tool for the forecaster. The interactive use of the model proved to be very instructive.

5 Results

The models were built up successively during the last five winters and the knowledge base increased accordingly. At the end of each winter the different versions of the models are rated day-to-day: the interpretation is compared to the verification. A disadvantage of this method is that the results are not homogenous since the results of the different winters were based on different states of the knowledge base. This is especially true for the results of the first winters with the versions of the model DAVOS.

Model DAVOS

We have now five years of real-time experience with the versions DAVOS1 and DAVOS2. For consistency between the different models and versions we will in the following only present the results of the last three winters (1991/92, 1992/93 and 1993/94).

To rate the interpretations provided by the system we defined the requirements of quality given in Table 5. Four steps of quality for the given interpretations are defined: *good, fair, poor,* and *wrong*. If the verified aspect is e.g. NE ± 45°, the rating in the following cases N ± 67°, NW ± 90° and S ± 90° would be *about right*, *not completely wrong* and *wrong* respectively.

quality	deviation: degree of hazard	deviation: altitude	deviation: aspect
good	0	± 400m	about right
fair	0	± 400m	not completely wrong
	0	wrong (any result)	wrong (any result)
	± 1	± 400m	about right
poor	± 1	± 400m	not completely wrong
	± 1	> ± 400m	wrong (any result)
wrong	> ± 1	(any result)	(any result)

Table 5. Quality requirements for determining the performance of the DAVOS model.

Considering the degree of hazard, the altitude and the aspect, the versions DAVOS1 and DAVOS2 have on the average a performance of about 65% and 70% *good* or *fair* (see Table 5 for definitions) interpretations respectively (Schweizer and Föhn, 1994).

To be able to compare the results of the versions DAVOS1 and DAVOS2 to the results of different systems, it is more convenient to only consider the degree of hazard. In that case in 52% and 54% of all situations the degree of hazard was correct compared to the verification for DAVOS1 and DAVOS2 respectively. 86% and 89% of all situations respectively are correct or deviate ± 1 degree of hazard from the verification.

The versions DAVOS31 and DAVOS32, being complementary to one another, represent a certain improvement; the combined average performance is 61%.

The version DAVOS4 that only predicts the degree of hazard is on the average correct in 63% of all situations. This result represents the best performance of the different versions of model DAVOS. However, considering the performance degree by degree the result is rather disillusioning. The performance for the intermediate degrees 2 and 3 is only 55% and 57%, respectively. These degrees are of course most difficult to forecast. In the case of low or very high hazard the data is more often unambiguous. The extremes are easier to decide. However, since the extreme events at the upper margin of the scale are rare, the correctness is also not too good for these degrees of hazard (59%).

The performance results show quite clearly that probably all statistically based models based on real situations are not able to predict exceptional situations correctly, since this sort of situations are rare.

Model MODUL

Generally the results of the model MODUL are better than those of the model DAVOS. This follows from the deterministic concept, more input parameters, especially on the snow cover, and much more knowledge in the form of the structure (subproblems) and of implicit rules. We also have now three winters of experience. During this time the model was continuously ameliorated, e.g. the calculation of certain input parameters was changed according to the prevailing conditions. So the performance got better. As the model runs interactively, the expert may slightly influence the result during the operational use. So the performance given below may not be quite comparable to the more rigorously determined performance of the model DAVOS and might be slightly too optimistic. The average performance during the last three winters was 73% correct interpretations, i.e. the proposed degree of hazard did not deviate from the verification. All days were interpreted, i.e. the result *no interpretation* did not occur. Deviations of more than one degree of hazard are rare, in less than 2% of all situations. An example of the performance during a whole winter season is presented in Figure 4. The model follows quite exactly the verified degree of hazard, also in times of increasing or decreasing hazard.

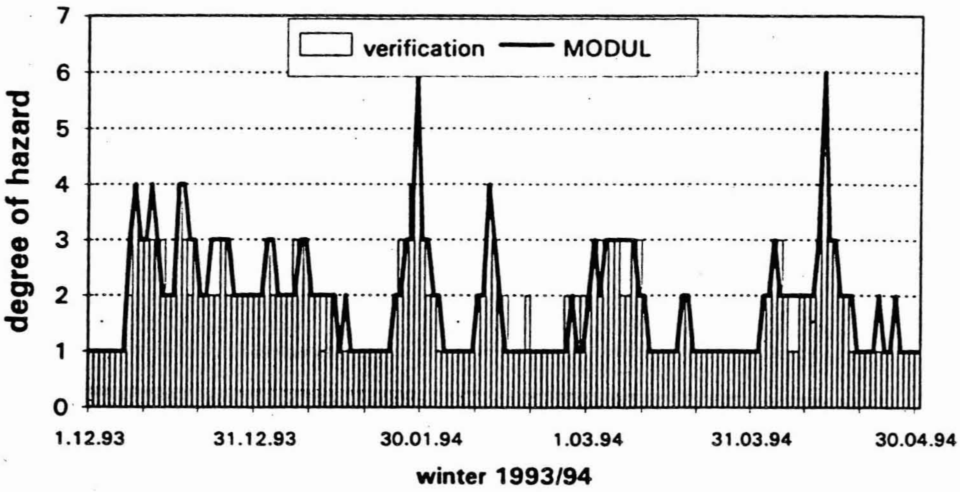

Figure 4. The degree of hazard proposed by the model MODUL compared to the verified degree of hazard for the winter 1993/94 in the Davos area.

The experience shows that the more deterministic model MODUL is much more sensitive to single input parameters. A wrong input parameter or a wrong decision in one of the subproblems may have substantial consequences at the end, i.e. a change in the degree of hazard of 1 or 2 steps. So the reaction on a small change may sometimes be drastic. This is especially due to the smaller number of input parameters treated at once in a subproblem, also due to the fact that the output result of a subproblem often is used again as input in another subproblem, and partially due to the fact that the input data is strictly categorized. The latter problem might be removed by introducing fuzzy logic, i.e. defining blurred categories.

Figure 5 is a comparison of the correctness compared to the verified degree of hazard for the different forecasting models DAVOS1, DAVOS2, DAVOS4 and MODUL for the Davos area during the last three winters (1991/92 to 1993/94). It is clear that the more input parameters or the less complex the result, the better the performance.

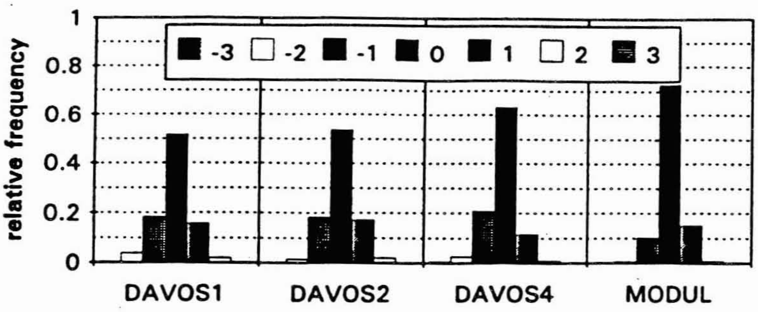

Figure 5. Comparison of the performance of the four different forecast models DAVOS1, DAVOS2, DAVOS4 and MODUL during the three winters 1991/92 to 1993/94. The deviation from the verified degree of hazard in the Davos area is given.

6 Conclusions

The CYBERTEK-COGENSYS™ Judgment Processor - following the idea of inductive decision making - proved to be a useful software for developing specific applications in the field of avalanche hazard assessment. Using weather, snow and snow cover data as input parameters the developed models evaluate the avalanche hazard for a given region. The new features are the choice of elaborated input parameters, especially more snow cover data, the categorization of the input data, the specific algorithm for the search for similar situations, and finally the concise output result. The avalanche hazard described as degree of hazard, altitude and aspect of the most endangered slopes, for the first time according to the scale used in the forecasts. This sort of output result is most efficient for the purpose of avalanche forecasting; it is much more appropriate to the problem than e.g. the output "avalanche/non-avalanche day". The use of observational avalanche data alone is insufficient for both the forecasting and the verification. The given output result is possible due to the effort of permanently verifying the avalanche hazard. The verification is the most striking feature and makes the data set - at the present time nine winters of weather, snow and snow cover data with the corresponding verified degree of hazard - a probably unique series.

The snow cover data proved to be very important. Actually it is well known that avalanche forecasting depends strongly on the state of the snow cover. However, except the French model MEPRA, until now none of the present models took into account this obvious fact. Of course this sort of data is not easily available but it is an illusion to expect that a supporting tool without any snow cover data is as powerful as the expert forecaster. Meteorology plays an important role, but not the decisive one.

The interactive use of the models proved to be a substantial advantage as especially the model MODUL is very instructive. It is well appropriate for the training of junior forecasters with a certain basic knowledge.

The model DAVOS - comparable to a statistical model - and the model MODUL - more comparable to a deterministic type of model - achieved a performance of about 60% and 70 to 75%, respectively. There exist no comparable or similar results, based on a long term operational test, of any different system for regional avalanche forecasting.

The application of the models in a different region to assess the performance will be the next step in the development. Additionally several of the subproblems will be further improved and it is planned to determine the altitude and the aspect of the most dangerous slopes also in the model MODUL. The corresponding subproblems have to be developed. Finally the hazard by wet snow avalanches in spring time will be taken into account. The model MODUL contains a great potential for future developments.

Acknowledgements

We thank the former director of our institute, Claude Jaccard, for his encouragement at the beginning of this study. Ulrich Guggisberg, head of the INFEXPERT company that sells the software used, promoted the work with a lot of enthusiasm. Various members and trainees, in particular Christian Plüss, from SFISAR assisted during the field work, the data management and the operational use.

References

Bolognesi, R. 1993. Artificial intelligence and local avalanche forecasting: the system AVALOG. Proc. Int. Emergency and Engineering Conference 1993, Arlington., U.S.A.

Brun, E., David, P., Sudul, M. and Brunot, G. 1992. A numerical model to simulate snow cover stratigraphy for operational avalanche forecasting. J. Glaciol., 38 (128). 13-22.

Buser, O., Föhn, P., Good, W., Gubler, H., Salm, B. 1985. Different methods for the assessmentof avalanche danger. Cold Reg. Sci. Tech.,10,199-218.

Buser, O., Bütler, M. and Good, W. 1987. Avalanche forecast by the nearest neighbours method. IAHS-Publ. 162. 557-569.

CYBERTEK-COGENSYS™. 1991. COGENSYS - The Judgment Processor. User's manual, Release 18. CYBERTEK-COGENSYS™ Corporation.

Durand, Y., Brun E., Merindol, L., Guyomar'ch, G., Lesaffre, B. and Martin E. 1993. A meteorological estimation of relevant parameters for snow models. Ann. Glaciol., 18. 65-71.

Föhn, P. 1985. Das Schweizerische Lawinenbulletin - Eine Interpretationshilfe für den Benützer. Mitteilung des Eidgenössischen Institutes für Schnee- und Lawinenforschung, Weissfluhjoch-Davos, Nr. 38.

Föhn, P., Good, W. Bois, P. and Obled, C. 1977. Evaluation and comparison of statistical and conventional methods of forecasting avalanche hazard. J. Glaciol. 19 (81). 375-387.

Föhn, P. and Haechler, P. 1978. Prévision de grosses avalanches au moyen d'un modèle deterministe-statistique. ANENA, Comptes Rendues du 2e Rencontre Int. sur la Neige et les Avalanches, Grenoble, 12-14 Avril 1978. 151-165.

Giraud, G. 1991. MEPRA: Modèle expert d'aide à la prévision du risque d'avalanches. ANENA, Comptes rendues Syposium de Chamonix CISA-IKAR, Juin 1991. Grenoble, France. 248-254.

Giraud, G., Lafeuille, J. and Pahaut, E. 1987. Evaluation de la qualité de la prévision du risque d'avalanche. IAHS Publ. 162. 583-591.

Gubler, H. and Bader, H.P. 1989. A model of initial failure in slab avalanche release. Ann. Glaciol., 13. 90-95.

Judson, A. and King, R.M. 1985. An index of regional snow-pack stability based on natural slab avalanches. J. Glaciol., 31 (108), 67-73.

LaChapelle, E.R. 1980. The fundamental process in conventional avalanche forecasting. J. Glaciol. 26 (94), 75-84.

McClung, D. and Schaerer, P. 1993. The Avalanche Handbook. The Mountaineers, Seattle, U.S.A.

McClung D.M. and Tweedy, J. 1994. Numerical avalanche prediction: Kootenay Pass, British Columbia, Canada. J. Galciol. 40 (135). 350-359.

Mérindol, L. 1992. Analogous models for avalanche risk forecasting. Comptes rendues de l'Université européene sur les Risques naturels Session 92: Neige et avalanches, 14-25 Sept. 1992, Chamonix, France.

Navarre, J.P., Guyomar'ch G. and Giraud, G. 1987. Un modèle statistique pour la prévision locale des avalanches. IAHS-Publ. 162. 571-580.

Remund, J. 1993. Verifikation der regionalen Lawinengefahrenprognose. Diplomarbeit. Geographisches Institut, ETH Zürich.

Schweizer, J. 1993. The influence of the layered character of the snow cover on the triggering of slab avalanches. Ann. Glaciol., 18. 193-198.

Schweizer, J., Föhn, P. and Plüss, Ch. 1992. COGENSYS Judgment Processor (Paradocs) als Hilfsmittel für die Lawinenwarnung. Eidgenössisches Institut für Schnee- und Lawinenforschung, Weissfluhjoch-Davos. Interner Bericht Nr. 675.

Schweizer, J. and Föhn, P.M.B. 1994. Avalanche forecasting - an expert system approach. submitted to Journal of Glaciology.

Schweizer, M., Föhn, P.M.B. and Schweizer, J. 1994. Integrating neural networks and rule based systems to build an avalanche forecasting system. Proc. IASTED Int. Conf.: Artificial Intelligence, Expert Systems and Neuronal Networks, 4-6 July 1994, Zürich, Switzerland.