An overview of avalanche forecasting models and methods

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ABSTRACT. This overview resumes first the historical development of avalanche forecasting in different countries of the world. It yields the most basic definitions like „avalanche danger" and presents the major problems of avalanche forecasting. Because avalanche forecasting is often compared with weather forecasting a comparison of these two forecasting problems is given. Due to the small-scale variations present in every snowcover, avalanche forecasting suffers from adequate data procurement mainly as far as the snow cover data are concerned. The necessary extrapolation from few point measurements imposes a serious restriction on the feasibility of avalanche forecasting. Also the long-lasting problem of defining a reasonable „avalanche"-output-variable and its verification „a posteriori" is addressed. The various, over four decades concepted avalanche forecasting methods and models are described and valuated. Forecast-verification results are presented for the different approaches, whenever such results are available and declaretive. It clearly shows up that a detailed description or simulation of the snowcover on slopes seems mandatory if reliable forecasting results shall be obtained. Additionally an expert system approach, considering the heuristic aspects of forecasting, helps to overcome the complex problem of approximating the snow cover stability and fixing thereof definite danger degrees.

1. INTRODUCTION

Avalanche forecasting and warning programs have been initiated in the last 60 years worldwide in order to reduce excessive loss of life and property by avalanches. Along extended and endangered traffic lines, in ski areas and in the backcountry this passive prevention method is often the only one applicable. In Switzerland, which has a tremendous amount of avalanche terrain compared to its size (about 50% endangered), such programs started during the World War II, in the other Alpine countries between 1950 and 1970. In North America such programs were initiated first at Rogers Pass, BC, Canada, in 1962 and then gradually spread out to several US states and to the neighboring provinces in Canada. In Norway forecasting programs started in the early seventies mainly in connection with mines and traffic lines. In other countries like Iceland, Scotland, Spain, Chile, New Zealand, India, Japan and Russia, such programs are confined to singular regions and time periods, where avalanches at times are a major threat.

The scope of this paper is to present the major principles and problems of avalanche forecasting, to give an overview of the present forecasting models and methods and to point to trends in forecasting theory and practice.

2. DEFINITIONS

- Avalanche danger: The probability that small or large avalanches will release or may be triggered in a given space and time. The avalanche danger may be approximated by the product of a release probability and the probability of a certain avalanche volume or mass. The internationally adopted danger scale consists of the following five degrees (Table 1.):

Danger degree	Avalanche release probability, avalanche size and local distribution of dangerous slopes.
1 low	Triggering is generally possible only with high additional loads and on few steep extreme slopes. Only a few small natural avalanches (sluffs) possible.
2 moderate	Triggering possible in particular with high additional loads, particularly on the steep slopes. Large natural avalanches are not likely.
3 considerable	Triggering possible even with low additional loads, particularly on the steep slopes indicated in the warning. In some conditions, medium and occasionally large natural avalanches may occur.
4 high	Triggering probable even with low additional loads on many steep slopes. In some conditions, many medium and several large natural avalanches are likely.
5 very high	Numerous large natural avalanches are likely, even in moderately steep terrain.

Table 1. International avalanche-danger degree scale

- Avalanche forecast: An estimate of the avalanche danger in a given region for a time span of hours or days. Avalanche forecasting in a local scale, i.e. foreseeing of singular avalanches is only possible under special circumstances and will not be commented here.

3. THE PROBLEM OF AVALANCHE FORECASTING

Roughly half a century ago the scientific attention focused also on methods of forecasting avalanches. Even though, at first sight, avalanche forecasting may be compared with weather forecasting, it shows up that avalanche forecasting is much more complex. The reasons are as follows:

- Avalanches start or get started in a snowcover which changes their layering and snow grain structure within hours or days in an order of magnitude of some hundred meters whereas the atmosphere stays more or less homogeneous for 10 to 50 km. Additionally, non-destructive repeatedly sampling is impossible in snow, in contrast to measurements in the atmosphere.
- Man may trigger avalanches, i.e. provoke or intensify the natural phenomenon whereas meteorological events like precipitation or radiation are not dependent on human actions.
- Avalanches have a „memory". An avalanche which has been triggered today, will probably not be released for weeks or months because the snowpack has to rebuild until it is „ripe" for a new avalanche cycle. Memory effects in meteorology last at the most for a few days.
- The potential for avalanches, i.e. the real avalanche danger can only be verified by special procedures (Föhn and Schweizer, 1995, Leuthold et al., 1996, Cagnati et al., 1997,) and hence by specialists or experienced mountain men whereas the weather forecast may be verified by every reasonable person.
- Finally the public demand for reliable weather forecasts has always been much larger than for avalanche forecasts so many thousand scientists have been working for more than 100 years on these problems. The field of avalanche forecasting is young and is tackled worldwide only by a few small organizations.

4. ADEQUATE DATA ACQUISITION AND MODEL DEVELOPMENTS

No matter if we forecast avalanches in the conventional way or with the help of models, we need to know, firstly, the state of the snowcover on slopes at any day and, secondly, the physical laws which govern the changes of that state. Because avalanches are local phenomena and the mathematical equations expressing the physical laws are too complex in this local scale, we have to make extrapolations and simplifications to a large extent.
This fact alone imposes a serious restriction on the feasibility of avalanche forecasting. From this it is clear that research organizations which develop avalanche forecasting models of any kind have to dispose over an detailed network of meteorological and snowcover measurements and additional avalanche observations. Any model conception is dominated by a strong element of determinism based on the interaction of weather with physical processes in the snow cover, which lead to avalanche formation. However a large and intensive network of meteorological stations, as LaChapelle already pointed out in 1980, yields a large body of potential information (high entropy) which is mainly useful for an office-based forecaster responsible e.g. for a large-scale warning program, but of minor importance for an organization responsible for avalanche forecasting in a regional or local scale (Fig. 1). Here locally measurable quantities about the structural and mechanical state of the snow cover are more important for the forecasters (and model builders) and allow more certainty for the former ones and more detailed insight into the prevailing processes for the later ones.

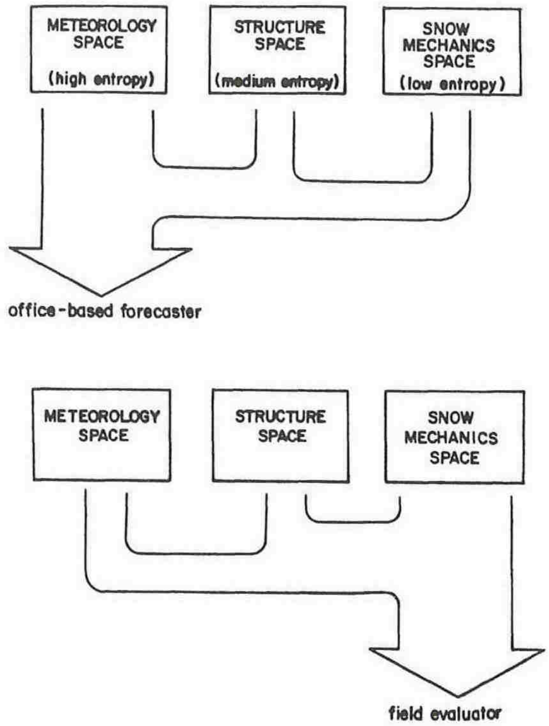

Fig. 1. The relative amounts of low-, medium-, and high-entropy data used for two basically different kinds of avalanche forecasting (acc. LaChappelle, 1980).

5. AVALANCHE FORECASTING APPROACHES

In old days the intuitive grasp of unstable snow conditions together with experience led to crude but still useful avalanche forecasting results. The first official avalanche warnings, released in the forties and fifties, were based on a mix of meteorology, snow knowledge and empirical experience. Gradually statistical and deterministic methods or a mixture of them have been introduced, however with varying success. Finally in the last ten years expert systems have been developed in order to fill the obvious decision gap between purely statistical and purely deterministic reasoning. The relationship between the different methods is displayed on Figure 2.

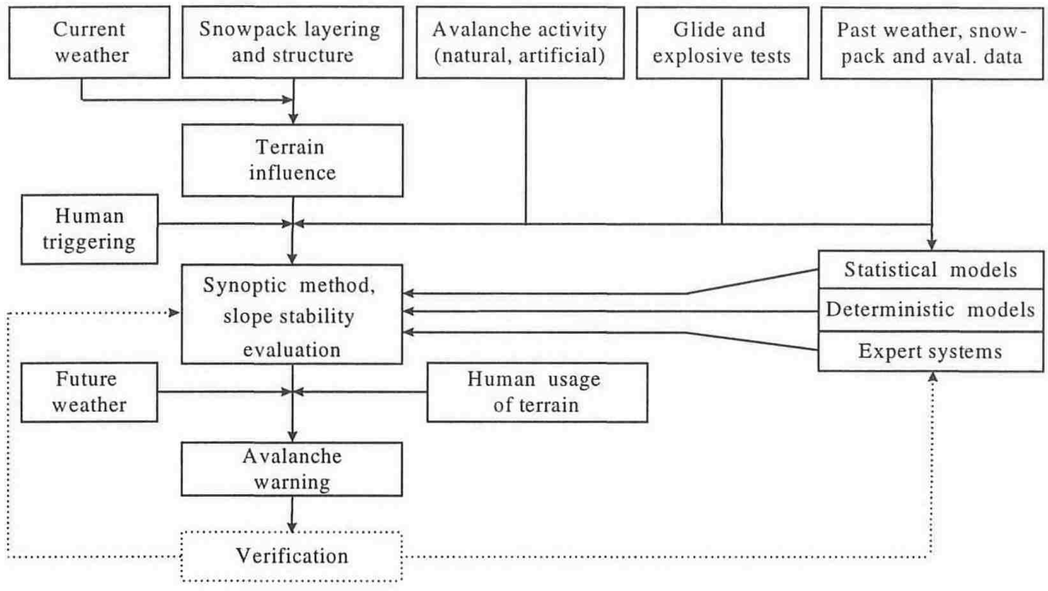

Fig. 2. Basic scheme of the avalanche forecasting process. Main input data, succession of stages, supporting numerical tools (statistical, deterministic, expert models), output product and verification

5.1 Conventional, synoptic avalanche forecasting

The nowadays still most widely-practiced method of avalanche forecasting is the so-called *synoptic or conventional method.* The synopsis of all major avalanche factors measured or observed at many representative locations in a given region, allows an approximation of the prevailing degree of snowpack stability and hence of its inverse function: the avalanche danger. This approach has been described mainly by LaChapelle (1980), Williams (1980), Föhn (1985) and more recently by McClung and Schaerer (1993).

The evaluation of all factors (represented on Figure 2) by human experts, using their knowledge and long-term experience combined with individual intuition, yields -for a regional scale- reasonable results.

However this method has clearly its limits, when vast mountain areas have to be forecasted, where the direct insight into the daily snowpack processes and the contact with the terrain is no more possible.

It is symptomatic of this method that verification of the forecast results was a long time missing because the partly intuitive forecasting decisions, contained in continuously changing „hazard-terminology", were not easy accessible for quantification and hence verification. The first verification of forecast results, assessed for the conventional method, have been published by Föhn et al. (1977), however in rather vague units of „avalanche day probabilities". Such units were used in the seventies to describe the avalanche danger in context with statistical avalanche forecasting programs.

Meanwhile it is possible to present verification results of all forecasting methods by use of the international „avalanche danger classification scheme", which was concepted in 1985 (e.g. Föhn, 1985) and in 1993 adopted by the international community of avalanche forecasters.

Verification results from two regions in Switzerland show that scores of 65 to 70% are within reach (Remund, 1993; Schweizer and Föhn, 1996). The *conventional method* shows the greatest drawback during fast changing and extreme weather situations (heavy snowfalls, fast weather changes, fast warming up), when insight into beginning avalanche activity and direct snowpack measurements are not possible. Forecasting performance results sometimes reported in annual reports in a range of 80 to 95 % are misleading and indicate that the avalanche danger has been verified mainly in long periods of low to moderate danger, when forecasting is trivial. The synoptic method, based on sound knowledge of avalanche formation processes, is the only „wholistic" method and will survive in its base in combination with new numerical methods.

5.2 Statistical models

Departing form statistical models, used in hydrology, various statistical models to forecast avalanches or „avalanche days" have been developed in the seventies, the first models were conceptually simple and smoothed the

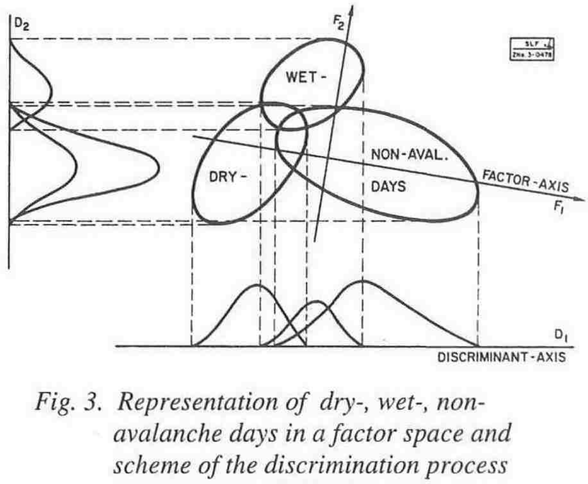

Fig. 3. Representation of dry-, wet-, non-avalanche days in a factor space and scheme of the discrimination process (acc. Föhn et al. 1977)

way for quantitative approaches in a field where the subjective interpretation could hardly handle the increased data which additionally contain large amounts of scatter. In the beginning avalanche hazard was correlated with singular or combined avalanche factors (Perla (1970), Judson and Erickson (1973), Bois and Obled (1973)).

Lateron , Bois et al. (1975), Föhn et al. (1977) switched to multivariate data analysis. Discriminating between „avalanche days“ (a day on which at least one natural avalanche has been observed) and „non-avalanche days“ was in the beginning the only practicable „danger“- output unit due to incomplete avalanche observations per day in a given region. Later avalanche days have been additionally subdivided in days with „dry snow“-avalanches and days with „wet snow“ -avalanches. This subdivision is displayed on Figure 3. In order to support the memory and the decision process of mainly local forecasters Buser et al.(1987), developed a similarity-model, which starts a „nearest neighbours“ search in the past data: Days with weather, snowpack and avalanche characteristics similar to the forecast day are determined. The probably actual avalanche activity may then be deduced by analogy, e.g. by analyzing the 10 nearest neighbor days compared to the actual day. Operationally this detailed comparison work is very tedious for operational forecasters and therefore only applicable in a local scale. Additionally information about the avalanche activity alone does not suffice to determine the avalanche danger degree, especially in times with „low“ or „moderate“ avalanche danger.
All these models taking into consideration mainly the probability aspects of avalanche events were successful to describe distinct avalanche cycles (e.g. periods of dry snow avalanches caused by precipitation and wind) but could not cope with all the various causes and magnitude of avalanche cycles producing a few large or many small climax avalanches.
For avalanche forecasters „avalanche day“-probabilities are difficult to interpret in terms of avalanche danger. This because the questions „where“, „how many“ and „how big“ the avalanches could be, remain unanswered. The „nearest neighbors“ approach also answers these questions mentioned, but only if the used avalanche observations in a given region are homogeneous and complete for long periods. The information content of this approach may be analyzed by Fig. 4.

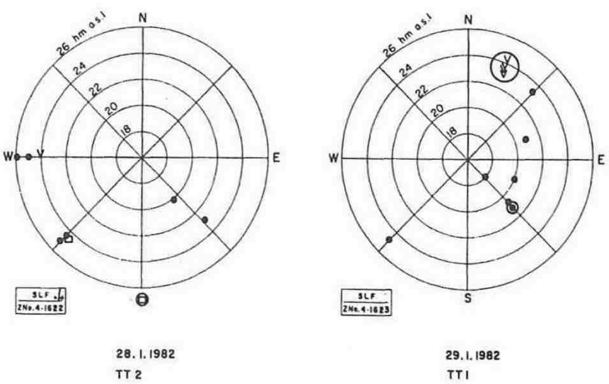

Fig. 4. Forecast-results for two high winter days of the „nearest-day“-approach , indicating „altitude“ and „aspect“ zones in a region with forecasted avalanches (circled events) and avalanches from 20-year records (uncircled). TT1, TT2, are weather types. **v**: *bombed avalanches;* • *: natural avalanches;* ❑ *:other types of avalanches, e.g. skier-triggered (acc.Buser et al., 1987).*

5.3 Deterministic models

The ultimate desire of any avalanche forecaster would be to have a detailed simulation of the daily snowcover states on all major slopes (altitude-aspect-related), a simulation of thereof based potential avalanches (snowtype, size) and the probability of those avalanches. Whereas the the most relevant snowcover processes may already be modeled in a scale of mountain regions (Brun and others 1989,1992), it will probably still take many years to formulate adequate rupture criteria in order to synthesize the most probable avalanches.
First attempts to model physical processes of the snowcover were initiated by Föhn and Hächler (1978) and Judson et al. (1980). The thereof based avalanche danger ratings were calculated by statistical relationships. Both approaches were confined to special conditions as new snow accumulation by snowfall, settling, and wind action, and in the second case additionally to the depth hoar formation process.
In 1983 the French Institute CEN started under the leadership of J. Lafeuille and later of E. Brun (Lafeuille and Brun, 1988) a new program to simulate the snow cover in order to help the forecasters to make more accurate and reliable avalanche forecasts in areas and altitude zones where no direct snowcover measurements are available. Their deterministic model simulates the energetic and morphological behavior of the snowpack. It calculates heat conduction, water percolation, settlement, phase changes in the inner layers and the most important metamorphic processes. It takes into account radiative and turbulent transfers at the top, discharge and geothermal flux at the bottom of the snowpack. The basic procedures of the 1-D snowpack are displayed on Fig. 5.

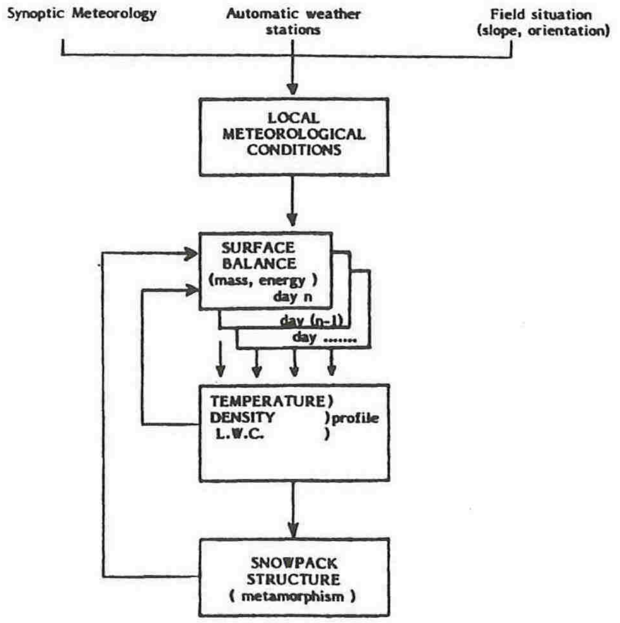

Fig. 5. Data sources and basic components of the one-dimensional snowpack model, which calculates synthetic snowprofiles on slopes of desired inclination, aspect and altitude (acc. Lafeuille and Brun, 1988).

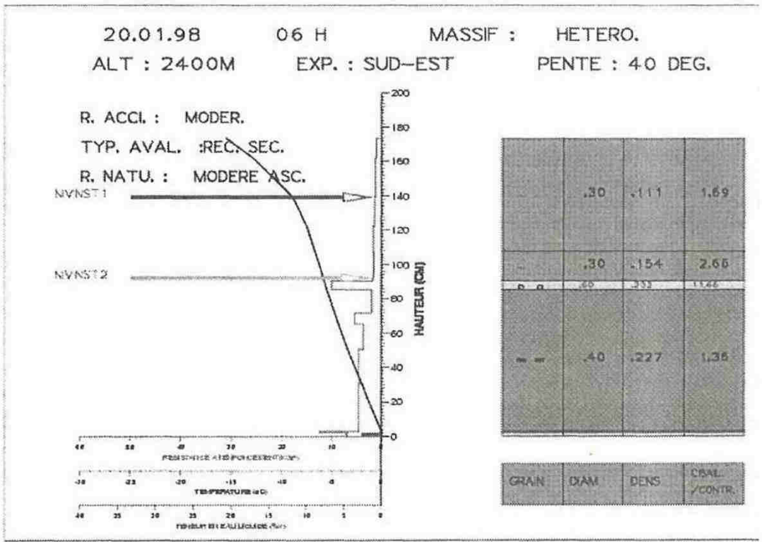

Fig. 6. Graphical output of a simulated snow profile on a slope facing SE, with an inclination of 40° and at an altitude of 2400 m a.s.l.(acc. personal communication from CEN Grenoble).

This model has been tested at several locations in the French Alps. The comparison between calculated and measured snow profiles shows reasonable results, although the wind influence and fine structural features as thin weak layers, e.g. from surface hoar or ice, are not yet included in the snow layering. An example of such a synthetic snow profile is represented on Fig. 6. Most probably unstable layers are indicated by arrows.

Having at disposition realistic snowprofiles from slopes in the release zones of avalanches (either measured or synthesized) we are in a state to analyze the mechanical (and rupture) characteristics of the described snowcover (stress, strain, strength, anchoring, ..). However up to now nobody explored an operational, deterministic mechanical solution for this problem, so still simplified rupture criteria like the stability index (e.g. Föhn, 1987, Giraud, 1991, Brun et al. 1992) have to be used to close this painful gap. As also explored by the French colleagues, an expert approach may help to find lead to a preliminary solution: The output of such an expert approach in terms of avalanche danger degrees („risk of naturally or artificially triggered avalanches") for a given day is presented on Figure 7.

The danger verification of deterministic or combined models is today only partially realized, although this family of models is well suited for verification. This because once an avalanche danger degree is calculated, it may be verified by known and adequate procedures as indicated in section 3.

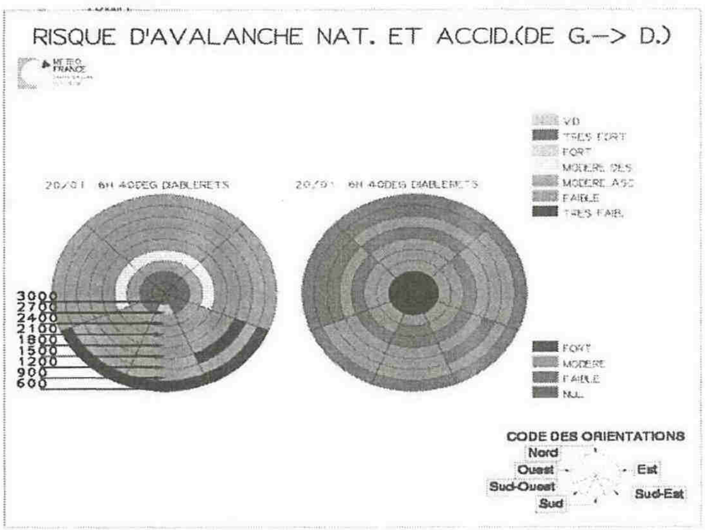

Fig. 7. Two cones, represented from the „birds view" with natural (left side) and artificial danger levels (right side) in a mountain region. The degree scale for the „artificial" danger is represented on the upper right, the 4-degree natural danger scale on the lower right. The altitude a.s.l is shown on the left side „cone"-shaped mountain (acc. personal communication from CEN, Grenoble).

5.4 Expert systems

Heuristic expert know-how may be complementary to statistical or deterministic reasoning when complex parts of a system are not enough transparent in order to conceive statistical or deterministic models.
In the last 10 years several expert systems have been developed for avalanche forecasting to get a diagnostic tool for the fixation of the avalanche danger (Giraud et al., 1991; Bolognesi, 1993; Schweizer M. et al., 1994; McClung, 1995; Schweizer J. and Föhn, 1996).
An expert system is basically a computerised program which simulates the thinking and decision-making process of an expert. It contains:

1. A knowledge base with facts and rules
2. An inference machine exploring and connection facts with rules and yielding the desired results.
3. And explanation component, which explains „how" certain results have been found
4. A dialog manager, which translates and/or represents the results.
5. Knowledge acquisition unit to integrate newly gained knowledge to improve the system.

As indicated on Fig. 2 the various „supporting" forecasting methods (statistical, deterministic, expert models) may also be used in parallel or in series to get optimal results. For instance:
The French model chain SAFRAN, CROCUS, MEPRA, concepted by Brun et al. (1989), Giraud (1991), and Durand et al. (1993), contains a deterministic snow cover model and an expert model in series to determine the degree of avalanche danger. In contrast the approach NX-LOG by Bolognesi (1993) and the one of McClung (1995) combine both an initial statistical model and a rule-based expert system to solve the more heuristic problem of fixing an appropriate snowpack stability index and a hereof dependent avalanche danger degree.
To elucidate the expert approach further two Swiss expert approaches COGENSIS ™ (Schweizer J. and Föhn, 1996) and ALUDES (Schweizer M. et al., 1994) are briefly presented.
The various submodels of COGENSIS™, concepted and tested between 1989 and 1994, use commercially available software, the so-called expert-system shell COGENSIS™, which does not yet contain a forecast knowledge base nor rules, but a „intelligent" judgment processor, which is primarily used in the finance and insurance world. The expert defines the most relevant data, data ranges and categories and „teaches" the judgment processor by entering examples (realistic data) and interpreting the avalanche situation and the danger degree represented by those examples. By observing the relationship between the data and the expert's decisions, the judgment processor builds a logical model that allows it to copy the expert's decisions. The more complex the problem the more training situations are needed. In the later forecast-situation the system proposes a possible solution on the basis of the past known situations. The quality of a proposed „system"-decision, is additionally identified by a „confidence-level", an indicator how certain the system is with respect to the correctness of that interpretation: „very confident", „reasonably confident", „not confident". If the system is not able to make a judgment on the basis of the present knowledge base it gives the result „no interpretation". The judgment problem is to choose an avalanche danger degree out of the 5 degrees (low, moderate, considerable, high, very high), a band of endangered altitudes and the main aspects of expected avalanches.
The firstly concepted family of submodels „DAVOS 1- 4" is exclusively data based and uses 13 weather, snow and snow-cover parameters, the later-on developed version „MODUL" is both data- and rule-based and uses 30 input parameters stepwise. The „expert"-data base consists of 9 years of input and output data.
The decision-making process of the version „MODUL" is represented on Fig. 8.

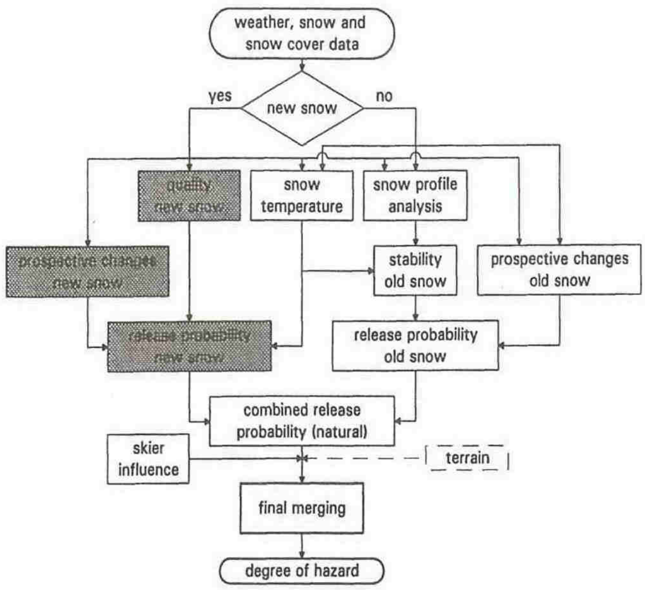

Fig. 8. Representation of the stepwise analysis of „judgment" sub-problems and their relations. Shaded boxes are only considered in the case of new snow (acc. Schweizer J. and Föhn, 1996).

As we see from above Fig. 8 the „MODUL" - system tries to model the decision-making process of an expert avalanche forecaster. Whereas „DAVOS" submodels are based on rather traditional input parameters, the version „MODUL" uses traditional parameters, elaborated parameters (sums, differences, other combinations), prognostic data and special snow-cover data (e.g. results of the Rutschblock test).
The results of the various expert-models (DAVOS 1-4, MODUL), the avalanche warning bulletin and two versions of the earlier commented nearest-neighbors approach are displayed on Fig. 9. The model „MODUL", integrating 30 weather parameters and a rule-basis shows the best performance. Finally a new approach, the neural expert system ALUDES shall be presented (Schweizer M. et al., 1994), which uses the same weather, snow and snow cower data and avalanche danger ratings as the previously described expert model COGENSIS™, Davos. This model has been designed by M. Schweizer, as

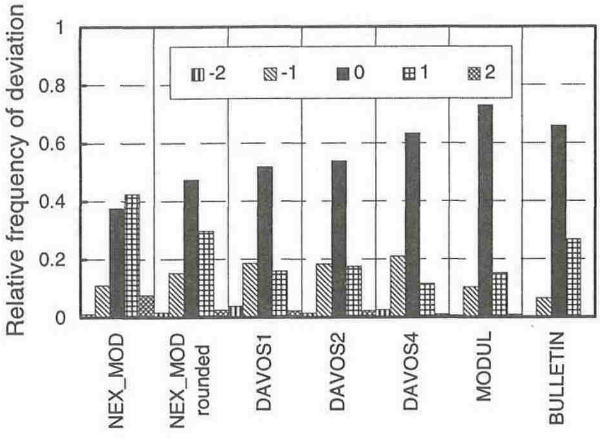

Fig. 9. Comparison of the performance of the nearest-neighbor forecast model NEX_MOD, of four different forecast models DAVOS1, DAVOS2, DAVOS4 and MODUL, and of the public warning BULLETIN during the three winters 1991-92 to 1993-94. The relative frequency of the deviation from the verified degree of hazard in the Davos area is given (acc. Schweizer J. and Föhn, 1996).

part of his thesis work in close collaboration with the authors of the COGENSIS™ - approach.
This approach connects input data and output data (avalanche danger degree) in a similar way by a learning algorithm as the human brain proceeds and is therefor able to *generalize*, to work with *incomplete* or *inconsistent* data as an expert.
The procedure of the knowledge acquisition is shown in Fig. 10.

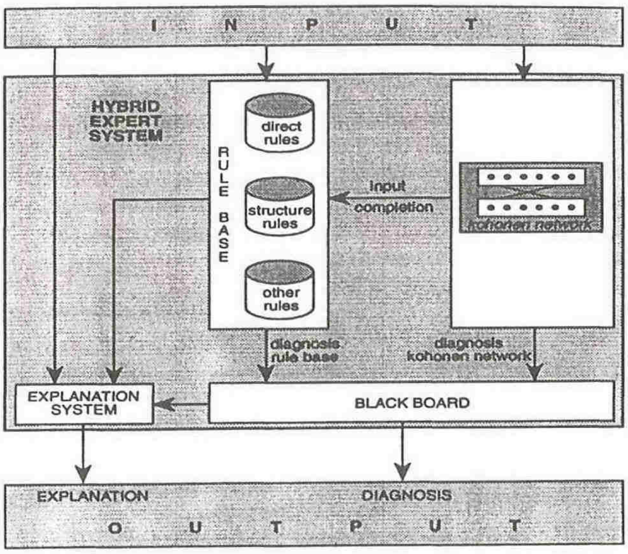

Fig. 10 Architecture of hybrid neural expert system (acc. Schweizer M. et al., 1994)

As the Figure shows the system consists of an „explanation" and a „diagnosis" part. It extracts out of the case base *direct rules*, then *structure rules*, using a learning algorithm, which is base on the Matrix method (Ultsch, 1993) and *other (expert-) rules*. The final diagnosis in terms of the avalanche danger degree is then given by this rule base and /or by a self-organizing neural Kohonen-network. The overall performance of this neural network system is similar as for the methods previously presented, i.e. about 70% of the system-diagnosis are correct. The endangered altitude zones and the most endangered aspects are forecasted with a slightly reduced performance. The test set is based on the mean of 3 winters sets, while the learn set was composed of 8 winters. The results are given in Table2.

sets (# cases)	% correct	% to low	% to high
learn set (1210)	80	10	10
test set (mean of 3 sets of 151 days)	69	17	14

Table 2. Performance of the neural network(acc. Schweizer M. et al., 1994)

It is obvious that these expert methods have a great potential for future developments and would benefit and fast improve by adding more winters as learn set. Unfortunately this research program has been abandoned in 1994, so no further winters could be added to the learn sets to improve this promising approach.

6. CONCLUSIONS

After almost 40 years of hard but not very focussed search for the best forecasting approach, the field of avalanche forecasting gains finally solid ground:

- The initial snow cover state and its evolution in time (but not in space!) may be approximated by snow cover models.
- Looking at the many small- scale variations present in a mountain snow cover, only a regional forecasting is reasonable (costs) and adequate (resolution in space).
- The goal of regional avalanche forecasting does not consist of getting avalanche indices nor avalanche day probabilities but of determining appropriate danger degrees which have to be supplemented with indications about the most endangered slopes (altitude zones, sectors of aspects).
- The 5-degree avalanche danger scale is internationally adopted, „what might happen" in a given degree is defined and the methods to verify these degrees are approved and published.
- The most important input variables for snow cover simulations are known and measurable. However it is obvious that direct snow cover measurements like „new snow", snow height" are still needed to check the model performance.
- Many physical snow cover processes, which condition the snow cover to be stable or to release avalanches can be approximated. But there are some processes which are not yet clear enough: snow accumulation due to wind, subsurface melt, formation of thin weak layers (surface hoar, near surface faceted crystals, ice layers), layer dependent water percolation.

- The mechanical behaviour of many snow types is scarcely known and rupture criteria are still missing. So the physical avalanche release mechanisms may not yet be modelled.

All these points lead to the conclusion that today the best avalanche forecasting approach consists of simulating the snow cover on typical slopes (altitude- and aspect related) and to overcome the unsolved problem of avalanche formation by calculating stability indices, which shall be integrated into the decision process of an expert system. This combined approach copies an experienced forecaster with the important difference that more and finally more accurate data and process oriented results contribute to the decision process. However to gradually approach the magic 80% performance limit, all important physical snow cover processes have to be simulated and adequate rupture criteria have to be integrated into the avalanche formation part.

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