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Avalanche decision-making frameworks: Classification and description of underlying factors

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ABSTRACT

Snow avalanches are a complex phenomenon and correctly assessing avalanche danger is crucial in order to avoid accidents. To aid the decision-making process, different decision-making frameworks (DMFs) have been developed. However, each DMF assesses different factors. We identified 44 factors included in the ten most commonly used DMFs, supplemented by nine factors regarded as important by avalanche professionals, resulting in 53 factors. We classify and describe each factor's possible strengths, weaknesses and limitations. Many factors are shared by the DMFs, but there are differences when it comes to type of factor and emphasis. The number of factors used by the different DMFs varies from 11 to 31. 81 out of 100 experts who participated in our survey use > 33 factors in their decision-making, and regard other factors as more important than the ones emphasised in most DMFs. We discuss the usage of the factors and provide recommendations. Our classification and description of the factors contribute to a better understanding of why the developers of the different DMFs have included them in their frameworks. This is fundamental for a better understanding of expert use or lack of use of DMFs, and why some DMFs or single factors are preferred to others.

1. Introduction

1.1. Avalanches and decision making

Snow avalanches are a hazard to people in mountainous regions around the world (Furset, 2006; Lied and Kristensen, 2003; Techel et al., 2016a). The victims are, workers, skiers, snowboarders, snowmobilers, snowshoers, soldiers, climbers, hikers, mountain guides and rescuers. The annual fatality rate within Europe and North America is about 140 (Techel et al., 2016a; Brugger et al., 2007; Boyd et al., 2009). Between 80% and 90% of fatal accidents amongst backcountry users were triggered by the victims or someone in their party (Harvey et al., 2018; MCClung and Schaerer, 2006a; Schweizer and Lütschg, 2000). Correctly assessing avalanche danger is crucial for avoiding accidents, and this becomes even more important as the number of people using mountain areas for recreation increases.

Researchers and avalanche experts have developed a range of avalanche decision-making frameworks (DMFs) to support the decision-making in avalanche terrain and reduce risk. Some frameworks structure the decision-making process, whereas others conclude with a go or no-go decision. However, each DMF assesses different factors in the decision-making process.

In this article we examine the ten most commonly-used approaches in Europe and North America. The selection is based on recommended frameworks from national umbrella organisations such as the Swiss core training team for avalanche education (www.slf.ch, KAT) or the Canadian Avalanche Association (CAA), and methods being taught by mountain guide associations, alpine clubs and educational institutions. Other accessible methods exist, but those considered here are the ten most commonly taught and used.

1.2. Objectives

This study is part of a larger research project on decision-making in avalanche terrain. Here, we present a classification of the assessment factors, not an analysis of the decision-making process itself. The objectives are (a) to identify the underlying factors in existing decision-making frameworks, (b) analyse which of these factors are shared amongst several frameworks, and (c) assess which of these factors, and any others are used by experts.

By classifying and describing each factor their possible strengths, weaknesses and limitations become apparent. Since the aim is to assess which factors the experts consult at different stages in their decision-making process, we and an avalanche expert advisory board, identified

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further relevant factors not included in the DMFs, such as different stability tests and information from the avalanche forecast. Finally, we asked a panel of one hundred avalanche experts about their use and opinion on the importance of each factor, presented in detail in the companion article (Landrø et al., 2019, this issue). These two articles represent the first step in examining and comparing different DMFs in this way. Future research will analyse the decision-making process itself, amongst experts and backcountry users.

Given the complexity of this material we have chosen to present it in two accompanying articles. This article provides a classification and analysis of the factors used in avalanche DMFs and factors used by experts. A complementary article presents the experts' knowledge and use of the DMFs and their underlying factors.

1.3. Development of avalanche decision-making frameworks

In 1916, Matthias Zdarsky published his “Elemente der Lawinenkunde” (“Elements of avalanche knowledge”), stating that slope angle, molecular strength and the weight of the snow are essential elements in the release of avalanches (Zdarsky, 1929). This is seen as the starting point of documented practical knowledge about snow and avalanches, leading up to today's decision-making frameworks.

By 1930, the fundamental knowledge concerning snow and avalanches was available for backcountry travellers (Höller, 2016). In the 1940s and 50s, the research focus was on layering and snow metamorphosis, leading to a snow hardness scale and the first international Snow Classification in 1954 (Schaefer et al., 1954). In the following years, snow cover and stability tests, such as Die Norweger Methode (“the Norwegian method”) by Nils Faarlund (Kellermann, 1990) and the Compression test (Jamieson, 1999) were developed, thus providing the important aids for backcountry travellers.

Previously, there was little structure in the evaluation and no decision aids existed. This changed when Swiss mountain guide Werner Munter introduced the 3 × 3 in the 1980s (Munter, 1991), initiating the development of today's use of a range of different frameworks.

2. Methods and data

2.1. Ten decision-making frameworks used in the study

We focus on ten widely used decision-making frameworks. These are; The 3 × 3 (Munter, 1997), The Reduction Method(Munter, 1997), Stop or Go (Larcher, 1999), Snow-card (Engler, 2001), The Graphic Reduction Method (Harvey et al., 2012), The After Ski Method (Brattlien, 2014), NivoTest (Bolognesi, 2000), ALPTRUTh (McCammon, 2006), The Avaluator 2.0 (Haegeli, 2010a), and The Systematic Snowcover Diagnosis (Kronthaler, 2003). A brief description follows of each of these frameworks.

2.1.1. The 3 × 3

The 3 × 3 (3 filter × 3 criteria) is a structured approach to avalanche evaluation. By use of guided questions this method evaluates three main factors 1) avalanche conditions, 2) terrain and 3) human factors. These factors are evaluated across three stages; 1) Regional/trip planning, 2) local/visible area and 3) zonal/slope specific. The 3 × 3 is an integrated part of the Reduction Method and is often used in combination with other frameworks. It should not be regarded as a DMF itself, but more as an overarching structure to organise the decision-making process at different stages.

2.1.2. Reduction method (RM)

The Reduction method (RM) developed by Werner Munter (Munter, 1997) is based on an equation that balances the danger potential against reduction factors. The danger potential is an expression for the probability of hitting a weak spot and triggering an avalanche at each danger level. It is based on a comparison of stability test results (Rutschblock tests) and danger level. According to Munter's calculations the danger potential increases exponentially for each danger level. To reduce risk different safety measures, so-called reduction factors, can be applied. The values of these reduction factors were calculated using data from fatal avalanche accidents in Switzerland. The weight of these factors mirrors Munter's ambition to reduce the amount of avalanche fatalities by 50% from their 1997 levels – a level that would equal accidents in hiking or driving a car, according to Munter.

This accepted residual risk is defined by the ratio of danger potential and the reduction factor. Danger potential is thought to be 2^D (D being the current danger rating), i.e. danger level 3 corresponds to danger potential 8. The reduction factors (RF) are categorised into three classes: RF1 slope angle, RF2 slope aspect, elevation and travel frequency, and RF3 group size and management. Within each class, they have different values, for example, for a slope less than 35° the calculated RF is 4, whereas for the avoidance of north-facing slopes the RF is 2, and for a small group the RF is 2. The reduction factors are then combined and the residual risk is quantified with the equation

$$\textit{Residual risk} = \frac{\textit{Danger potential}}{\textit{Reduction factor} * \textit{Reduction factor} * \textit{Reduction factor}} \leq 1$$

According to Munter, the accepted residual risk should be ≤1. The RM and 3 × 3 are complementary tools that have to be combined to achieve acceptable residual risk.

Munter (Munter, 2003) later introduced several other simplifications of the Reduction Method, such as the Elementary Reduction Method (ERM), to attract novice users. ERM focuses exclusively on terrain restrictions based on combining danger level and inclination.

2.1.3. Stop or Go (SoG)

Stop or Go (SoG) was introduced by Michael Larcher (Larcher, 1999) that has a framework similar to the RM, and uses Munter's risk calculations, but omits the mathematical equation that is used in the RM. The method consists of three components. In check 1, the ERM is applied. In check 2, Larcher added recognition and assessment of what is thought to be the five most crucial contributors to avalanche hazard: new snow, wind-deposited snow, recent avalanches, water saturation and collapsing weak layers making “whumpf” sounds; followed by the question:” are the observed conditions a threat to the group?” Check 3 is similar to the 3 × 3 method in addition to hazard mitigation measures, such as transceiver testing and keeping a safe distance of 10 m apart on slopes steeper than 30° when ascending.

2.1.4. Snowcard (SC)

The SnowCard (SC) method is also derived from Munter's original Reduction Method. The developer, Martin Engler, made a limited statistical study on avalanche incidents, confirming Munter's findings on exponential growth of the risk potential from one danger level to the next. The objective of SC is to determine average risk based on the danger level provided by the avalanche warning, inclination and a distinction between “favourable” and “unfavourable” aspects and elevation bands (Engler, 2001).

Decision-making using SC is done in two stages. In the first stage a graphic version of the ERM showing risk sequences from green to yellow to red is used. The card has a hologram such that the sequences change when the card is tilted depending on whether a slope is considered favourable or unfavourable according to the avalanche forecast. In the second stage, out in the terrain, SC takes level of competence into account. Level one (basic) resembles the avalanche danger assessment done in check 2 in the SoG. In level two (advanced and expert), different parts of the “Factor Check” are used. The “Factor Check” is a checklist for examining the proposed main factors contributing to avalanche incidents. It is used to adjust the local danger level, thus allowing the experienced user more flexibility when it comes to terrain choice.

In later years SC has become an integrated part of the “Lawinen-

Mantra" (Avalanche Mantra) that adds a checklist to the original SC: 1) risk assessment using the SC (as before), 2) Analytic assessment if practical given current avalanche problem, 3) Take gut feeling and human factors into account, 4) Evaluate the consequences, 5) Take sensible safety precautions (Mersch & Behr, 2018).

2.1.5. Graphic reduction method (GRM)

The Graphic Reduction Method (GRM) is another type of reduction method. In the GRM, a risk-check is performed that combines danger level and inclination (Harvey et al., 2012). According to the GRM, the danger level outside the core area (aspect and elevation band given in the forecast) can be reduced by one level. As in the SC, GRM works with the concepts of favourable and unfavourable slopes, but other factors are not taken into account. Also similarly to the SC, the status of the GRM is reduced in route selection and slope specific decision-making for the advanced user. The focus is on evaluation of avalanche conditions, terrain and the human aspect. Avalanche patterns, as used in the avalanche forecast, play an important role (Harvey and Nigg, 2009). However, no structured approach for evaluating these factors is provided.

2.1.6. After ski method (ASM)

The Norwegian After Ski Method (ASM) is similar to the GRM. The difference is a 5° reduction in inclination in relation to danger level (Brattlien, 2014). The ASM recommends avoiding slopes steeper than 30° at danger level 3 – considerable, compared with 35° in the GRM and ERM. The inclination reduction is done to achieve a greater risk reduction. Using the same data set as the one used in (McCammon and Hägeli, 2005) the preventative effect of these terrain recommendations is 93% according to Brattlien (2014).

2.1.7. Nivotest (NT)

The NivoTest is designed for an assessment of the avalanche risk without using an avalanche forecast. Based on 25 yes/no questions regarding weather, snowpack, avalanche activity, route and participants the user can calculate risk for a specific route or terrain (Bolognesi, 2000). Each of the first 20 questions is weighted based on a statistical analysis of > 7000 actual cases. The last five questions are based on the developer's experience. After answering all questions, the result of the avalanche risk assessment is shown in the form of one of three icons: smiley face, uncertain face or sad face.

2.1.8. Checklist sum obvious clues ALP TRUTh (AT)

ALP TRUTh (AT) is the acronym for the seven clues included in the checklist for this method: Avalanche, Loading, Path, Terrain traps, Rating, Unstable snow, Thaw instability (McCammon, 2006). The user adds up the number of obvious clues for the slope in question. If two or fewer obvious clues are observed, normal caution is recommended. With three or four obvious clues present, extra caution is advised. When observing five or more obvious clues, skiing is not recommended.

2.1.9. Avaluator 2.0 (A2.0)

As with SC and GRM, the Avaluator 2.0 (A2.0) has a graphic representation of the estimated risk (green = caution, yellow = extra caution and red = not recommended). Unlike the different reduction methods that combine inclination and danger level, this recommendation is based on an avalanche condition score and a terrain characteristics score. Each factor that constitutes the avalanche condition and terrain characteristics is given a weighting value, e.g. signs of instability: +1, Slope steeper than 35°: +2. The user evaluates the different factors and ends up with a score for avalanche conditions and terrain characteristics. The estimated risk is read from a classic risk matrix, giving one of the initial three categories (Haegeli, 2010b).

2.1.10. Systematic snow-cover diagnosis (SSD)

The Systematic Snow-cover Diagnosis (SSD) is a purely analytical framework (Kronthaler, 2003; Kronthaler and Zenke, 2006; Kronthaler, 2019). It uses three steps to come to a decision. Step one: finding the most prominent weak layer and testing the weak layer - slab combination using the Small Block Test (SBT). This is followed by an evaluation of four weak layer properties (Kronthaler, 2019). The SSD uses many of the same factors as the threshold sum approach when evaluating snow layer properties. Properties that are regarded as unfavourable are: smooth fracture upon light lateral tapping; weak layer is thin (≤ 3 cm) and consists of large crystals (> 1.25 mm); weak layer is within one metre of the snow surface; the overlying snow is soft. Step two: Process thinking, consider the processes that led to the weak layer slab combination observed and distribution of this combination. Step three: Assessment of the situation using a systematic structure of questions and YES or NO answers (loose or slab avalanche; natural release; release by a single skier; release with high additional load; no weak layer). This leads to an interpretation aid that ends with three different recommendations regarding cautions (red: avoid, keep distance to slope, not over 30°; yellow: one-by-one, safety distance; green: standard measures).

2.1.11. Scope

In our presentation of the different DMFs we have focused on the key factors, and given a brief review of the frameworks' overall approaches (analytical or probabilistic), and workflow. The decision-making process within the frameworks is beyond this scope of this article.

2.2. Reasoning methods to assess avalanche risk

Assessing avalanche risk requires integrating a range of factors (Table 2) that are often derived from partial observations, that themselves are uncertain, and is further impeded by the complexity of the interaction between the factors. Strictly speaking, neither deductive nor inductive reasoning is appropriate. Accordingly, reasoning is abductive, i.e. from incomplete observation one makes a best prediction of the avalanche risk, related to but not identical with using a heuristic approach. Abductive reasoning requires deliberate reasoning and is often more challenging than deductive or inductive reasoning. Indeed, the frameworks often use elements from the deductive and inductive approaches to accommodate the abductive approach. To reduce abductive reasoning and exploit deductive reasoning, Munter's method assesses the avalanche risk during the different phases of an outing by providing a set of instructions based on risk calculations. Munter called this approach probabilistic (Munter, 1997). In McCammon and Hägeli (2005) terminology, Munter's probabilistic approach corresponds to rule-based decision-making. (See Fig. 1)

Most DMFs have components from both approaches, i.e. operating with numerical thresholds and checklists to aid in the decision-making process (Table 1).

2.3. Direct and indirect factors

The frameworks are often presented by use of a plastic-coated card or checklist that can be taken on a trip. The factors printed on these cards constitute the basis for making the decision. We refer to these as direct factors. Examples are the six avalanche condition factors (Regional Danger Rating, Persistent Avalanche Problem, Slab Avalanches, Signs of Instability, Recent Loading, and Critical Warming) and four terrain characteristics factors (Slope steepness, Terrain Traps, Slope Shape, Forest Density) printed on the plastic-coated card that comes with the A2.0.

In addition to the plastic-coated card or checklist, most DMFs have some accompanying literature. This can be books or leaflets where the DMF is explained and factors beyond the direct factors are presented. The leaflet Caution Avalanches! (Harvey et al., 2018) that accompanies the GRM, is such an example and gives group management and

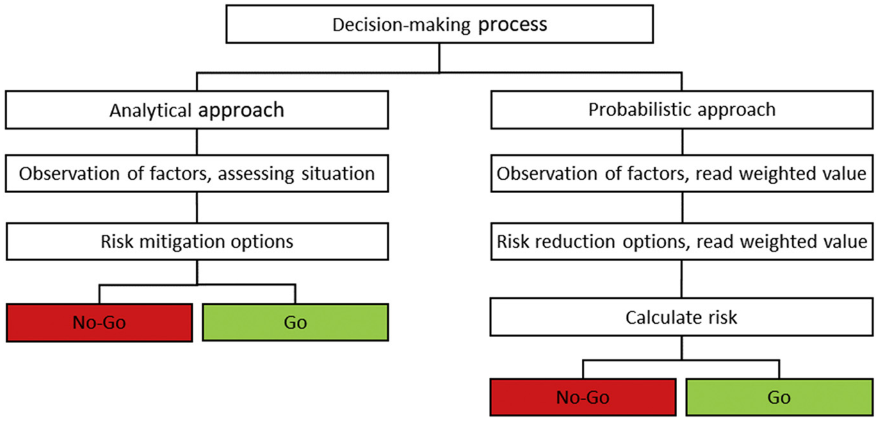

Fig. 1. Illustration of the overall decision-making process in analytic and probabilistic DMFs.

snowpack evaluation factors as well as others. We use the term indirect factor when referring to these since they can be regarded as part of a framework, but do not belong to the direct factors on the cards or checklists.

2.4. *Data on underlying factors in avalanche decision-making frameworks*

We collected the factors included in the checklists, cards or as described in the accompanying literature belonging to the different frameworks. This resulted in 44 different factors. Two of these 44 factors are found in the avalanche forecast, namely the *danger level* and *most exposed height level and aspect*. However, in order to examine whether experts use the forecast we included five additional elements from the avalanche forecast; 1) main message, 2) avalanche problem, 3) mountain weather, 4) snowpack information and 5) travel and terrain advice. Next, we included one factor describing the most used stability tests, because in our experience, their use is quite common amongst experts and they are featured in the literature accompanying some of the DMFs.

The factors were then incorporated into a survey and pretested on a panel of 10 avalanche experts of different nationalities and professional backgrounds. The participants provided instant feedback via online video or in person. Based on the feedback from the pretest we added three additional factors (*how snow feels when moving on skis*; *avalanche sensitivity to triggering; avalanche type)*. This resulted in 53 factors that are grouped thematically into five categories (Table 2).

2.5. *Data from expert survey*

100 people (including10 women), considered experts according to Dreyfus & Dreyfus (2005), completed over 90% of the survey. The respondents were from Scandinavia (n = 32), the German-speaking part of the Alps (n = 32) and North America (n = 35). On average, respondents had 28.2 years of experience in backcountry skiing and spent 50 days backcountry skiing per season of which 73% were in avalanche terrain. The experts rated the 53 factors in terms of use and importance (decisive, relevant or irrelevant). Tables 3–7 present how many of the experts consider each factor as being decisive in their decision-making in at least one of the three stages. For more details please see the accompanying article (Landrø et al., 2019).

Table 2
Categorisation of factors used in ten avalanche decision frameworks in this study.

Category	Number of factors
A. Snow and avalanche	13
B. Snowpack evaluation and stability test	10
C. Avalanche forecast	7
D. Group and group management	13
E. Terrain	10

3. Results

The mapping resulted in 53 different factors, and the frameworks include between 11 and 31 factors. Several factors are shared amongst the frameworks (see Tables 3–7), but differences in type and number of factors are prevalent. The factors are grouped thematically into five categories (Table 2), which is also used to structure the presentation and discussion of the results. Further results from the expert evaluation are presented in the accompanying article (Landrø et al., 2019).

3.1. *Snow and avalanche factors*

Category A (Snow and avalanche) factors are indicators of snow instability and they can be observed in the terrain. In avalanche forecasting observations of these factors are divided into three classes; 1)

Table 1
The ten most common avalanche decision frameworks with description of region of origin, approach (terminology from Munter) and number of included factors.

Framework	Region	Go / no go decision rule	# Factors	Reference
3x3	Alps			(Munter, 1997)
Reduction method (RM)	Alps	Probabilistic. Calculation	15	(Munter, 1997; Munter, 2009)
After ski method (ASM)	Norway	Probabilistic	18	(Brattlien, 2014)
Snow-card (SM)	Alps	Probabilistic[a]	29	(Engler, 2001)
Stop or go (SoG)	Alps	Probabilistic[a]	31	(Larcher, 1999)
NivoTest (NT)	Alps	Probabilistic. Adding and weighting of factors	27	(Bolognesi, 2000)
Avaluator 2.0 (A2.0)	CA	Adding and weighting of factors, probabilistic[a]	27	(Haegeli, 2010a)
Graphic Rreduction method (GRM)	Alps	Probabilistic[a]	31	(Harvey et al., 2012)
ALPTRUTh (AT)	North-America	Adding of factors	11	(McCammon, 2006)
Systematic snow-cover diagnosis (SSD)	Alps	Analytic	27	(Kronthaler, 2003; Kronthaler et al., 2013)

[a] = Includes elements of analytic/deductive avalanche assessments.

Table 3
Snow and avalanche factors by framework and expert usage.

	Direct factor in DMF	Indirect factor in DMF	# use	# decisive	as %
Signs of instability	SoG, AT, A2.0	RM, ASM, SC, GRM, SSD	73	62	85
Loading of new snow	SoG, NT, AT, A2.0	RM, ASM, SC, GRM, SSD	73	54	74
Wind or rain within last 48 h	NT, A2.0	RM, ASM, SC, SoG, GRM, AT, SSD	74	53	72
Critical warming	AT, A2.0, NT	RM, ASM, SC, SoG, GRM, SSD	80	65	81
Signs of slab avalanches within last 48 h	SoG, AT, A2.0, NT, GRM	RM, ASM, SC, SSD	73	50	68
Presence of persistent or deep persistent slab problem(s)	A2.0	RM, ASM, SC, SoG, GRM, NT, SSD	79	66	84
Unusual, infrequently travelled route	NT	RM, SC, SoG, GRM, SSD	53	18	34
Pillows wind-drifted snow/cornices	SoG, NT	RM, ASM, SC, GRM, AT, A2.0, SSD	68	54	79
Deep snow		RM, ASM, SC, SoG, GRM, NT, AT, A2.0, SSD	67	30	45
How snow feels when moving on skis			78	39	50
Potential avalanche size			70	50	71
Avalanche sensitivity to triggering			77	59	77
Possible avalanche type (loose snow, slab avalanche)			75	52	69

Legend. RM = Reduction Method, ASM = After Ski Method, SC = Snow-card, SoG = Stop or Go, NT = NivoTest, A2.0 = Avaluator 2.0, GRM = Graphic Reduction Method, SSD = Systematic Snow-cover Diagnosis, AT = ALPTRUTh. Last three columns: number of experts stating that they use the factor, state it being a decisive factor in any of the 3 stages (planning, route, or slope), and the percentage.

Table 4
Snowpack evaluation in DMFs and by experts.

	Direct factor in DMF	Indirect factor in DMF	# use	# decisive	as %
Hardness of overlaying snow (over weak layer)	SSD	SC, SoG, GRM	78	23	29
Weak layer distance from snow surface	SSD	SC, GRM	80	23	29
Weak layer grain type	SSD	SC, GRM	70	19	27
Hardness difference between layers	SSD	SC, GRM	38	17	45
Weak layer thickness	SSD		62	15	24
Grain size of weak layer	SSD		58	17	29
Fracture character	SSD	A2.0	75	16	21
Test score from stability test(s)	SSD	GRM, A2.0	38	9	24
Stability tests (CT, ECT, hand shear, little block, PST, Rutschblock, ski cut)	SSD (little block)	GRM, A2.0	92	11	12
Combination of different elements	SSD	SC	N/A		

For abbreviation see Table 3.

Table 5
Avalanche forecast factors by DMF and expert usage.

	Direct factor in DMF	Indirect factor in DMF	# use	# decisive	in %
Danger level	RM, ASM, SC, SoG, GRM, A2.0	AT	66	26	39
Main message		SoG	65	21	32
Most exposed height level and aspect	RM, SC, SoG, GRM, A2.0	SSD	66	35	53
Avalanche problem(s)	A2.0	SoG, GRM, SSD, (NT*)	86	47	55
Mountain weather forecast		SC, GRM, A2.0	75	28	37
Snow pack information		SC, SoG, GRM, A2.0, SSD	81	30	37
Travel and terrain advice			21	1	5

For abbreviation see Table 3.

Table 6
Group factors and group management by DMF and expert usage.

	Direct factor in DMF	Indirect factor in DMF	# use	# decisive	in %
Group size (small, large, very large)	RM, SoG	SC, GRM, NT, SSD	98	65	66
Participants with low technical skills	NT	ASM, SC, SoG, GRM, SSD	99	69	70
Participants in bad physical shape	NT	ASM, SC, SoG, GRM	97	63	65
Group not trained in avalanche rescue	NT	ASM, SoG	99	77	78
Participants with avalanche safety equipment	SoG, NT	ASM, GRM, A2.0	99	53	54
One-at-a-time exposed	–	–	75	39	52
Ski at a distance	–	–	57	21	37
Clear directions / plan on where and how to ski	SoG	SC, GRM	84	58	69
stopping at safe spots	A2.0	ASM, SC, GRM	94	53	56
10 m distance from 30° ascending	SoG	SC, GRM, A2.0, SSD	34	10	29
Safety distance ascending		RM, ASM, SC, SoG, GRM, A2.0, SSD	59	17	29
30 m distance when descending	SoG	SC, A2.0, SSD	27	9	33
One-at-a-time from 35° when descending	SoG	SC, A2.0, SSD	28	7	25

For abbreviations see Table 3.

Table 7
Terrain factors by DMF and expert usage.

Category: Terrain factors	Direct factor in DMF	Indirect factor in DMF	# use	# decisive	in %
5° intervals from 30°	RM, ASM, GRM, SC, SoG	A2.0	28	17	61
Danger level/slope inclination	RM, ASM, GRM, SC, SoG		18	12	67
slope between 34 and 36 degree steep			26	14	54
Discriminating between AT /no AT	SSD	NT, A2.0	86	61	71
ATES	A2.0		72	8	11
Use of favourable terrain formations	SoG	GRM, A2.0	94	59	63
Avoiding terrain traps	AT, A2.0	ASM, SC, GRM	95	59	62
Forest density		SoG, AT, A2.0	71	10	14
Convex or unsupported slopes	NT, A2.0	SC	83	45	54
Avoiding known avalanche paths	AT	A2.0	81	19	23
Avoiding exposed routes without protected areas	NT	GRM	88	41	47

For abbreviation, see Table 3. AT = avalanche terrain.

Instability factors; 2) Snowpack structure, and 3) Snow and weather factors at the snow surface, where class 1 factors are the most significant indicators of avalanche danger (MCClung and Schaerer, 2006b). Except for the three factors regarding avalanche type, size and sensitivity to triggering, which are presented at the end, we have grouped our factors according to this three-class division.

We identified 13 factors in this category, of which four are not part of any decision-making framework, but have proven to be important in expert avalanche decision-making (Landrø et al., 2019).

3.1.1. *Factor 1: signs of instability*

In addition to recent avalanches, other signs of instability such as collapsing, whumpfs, cracks and drum-like sounds, are easy accessible information. Signs of instability (class 1) are regarded as direct evidence of snow instability and avalanche danger, and there is little uncertainty associated with their interpretation (MCClung and Schaerer, 2006a).

3.1.2. *Factor 2: loading of new snow*

The loading of new snow is directly associated with meteorological factors (class 3) such as the amount of new snow, precipitation intensity and wind speed. These related factors are less direct evidence in evaluating snow instability (MCClung and Schaerer, 2006a). Loading of new snow will add extra weight to the existing snowpack, potentially increasing stress and instability. However, this is again dependent on the amount of snow, precipitation intensity and wind speed. Its actual effect concerning instability is also heavily dependent on the stability of the old snowpack and the snow surface before the loading. The interaction of these factors is decisive for factor loading of new snow's relevance in avalanche danger assessment. However, the use of this factor in avalanche decision-making depends on interpretation, and carries uncertainty.

3.1.3. *Factor 3: occurrence of wind or rain within the last 48 h*

The evaluation of wind and rain relies on interpretation and is not direct evidence of snow instability. Wind belongs to class 3 whereas rain (precipitation type) belongs to class 2. As well as new snow, wind (snow drift) and rain will also add extra weight to the existing snowpack. Rain can weaken bonding within the snowpack thus reducing its strength and potentially increasing stress and instability.

3.1.4. *Factor 4: critical warming*

Rapid increases in temperature will affect snow metamorphism, reduce strength by weakening bonding within the snowpack and increase stress and instability by affecting the continuous downhill moment of snow called snow creep. When critical warming occurs in combination with snowfall and wind it is commonly referred to as “avalanche weather” due to a high likelihood of avalanches under these conditions. This is also a class 3 factor needing careful interpretation and is accompanied by uncertainty.

3.1.5. *Factor 5: signs of slab avalanches within the last 48 h*

Signs of slab avalanches are easy to observe and are direct evidence of snow instability (class 1). There is little uncertainty associated with their interpretation. However, the time of release may be very difficult to determine under certain conditions in some environments. Some avalanche situations stabilise rather quickly, whilst others last for weeks, affecting the importance of this factor in each case.

3.1.6. *Factor 6: presence of persistent or deep persistent slab problem(s)*

Weak layers are a class 2 factor. Persistent weak layers can form at the snow surface (surface hoar) or in the snowpack and also near the surface due to a high temperature gradient (1 °C / 10 cm) (facets and depth hoar). Deep persistent slab problems often involve thick and hard slabs, and there are often no visible or audible signs of this kind of instability. There is a lot of uncertainty related to weak layers and especially to persistent weak layers. It is probably the hardest avalanche problem to manage in a consistent way, and is sometimes referred to as an expert trap. Common advice is to be very conservative in terrain choice. Avalanches that release on these kinds of layers have the potential to be large, cross-terrain barriers and can have multiple slide paths. Remote triggering and releasing above the trigger are common. This problem stabilises slowly, if at all, and potentially can last an entire season. Depending on the conditions that created this layer, it can be localised at specific elevations and aspects.

3.1.7. *Factor 7: unusual, infrequent travelled route*

Frequent skiing may have a stabilising effect on the snowpack. If a slope is skied during or directly after every snowfall, this will affect bonding between layers, and the distribution and development of weak layers. This means that the part of the slope that is heavily tracked will be more stable than adjacent parts that are not tracked or less tracked. Exceptions to this stabilising effect are snowpacks with deep persistent weak layers and very wet snowpacks. This factor is approached differently amongst the different DMFs. The NT rates *unusual, infrequent travelled route* as negative, giving it 1, max 2 points, whereas in several other DMFs, such as RM, this factor is not rated at all but instead frequently travelled slopes are rated as positive, giving it a reduction factor of 2 (Munter, 2009; Bolognesi, 2013).

3.1.8. *Factor 8: presence of pillows of wind drifted snow or cornices*

When snow is transported by wind, rolling and saltation will decrease snow crystal size considerably. These small crystals will sinter and form cohesive snow layers (dense- or soft-cohesive slab) in lee areas. Pillows of wind-drifted snow and cornices are the result of wind-transported snow and hence say something about wind strength and direction. The pillows indicate extra weight on the existing snowpack, increasing stress and instability to the old snowpack in addition to potentially being a slab in itself. Cornices indicate wind direction and, if they collapse, act as an avalanche trigger to the possible unstable slope below. The evaluation of this factor involves uncertainty and does not provide direct evidence of snow instability. This factor is associated with the factor loading of new snow (class 3).

3.1.9. Factor 9: deep snow

This factor is an indicator of several danger assessment criteria: amount of snow available for wind transportation; ability of the snowpack to support a certain load; avalanche type and potential size; additional load on the existing snowpack. Like the other class 2 factors, it requires careful interpretation, is not free of uncertainty and provides no direct evidence of snow instability.

3.1.10. Factor 10: how snow feels when moving on skis (additional factor, not part of a DMF)

Observing how snow feels when moving on skis can be an important source of information. Experts note crystal forms on the surface, surface roughness, hardness or if the snow is dry, moist or wet, fracture propagation, amount of new snow and its density, how deep one penetrates and, possibly most important, changes in surface snow. This information can be important in determining avalanche type, potential avalanche size and the likelihood of triggering an avalanche. This factor belongs to class 3: Meteorological Factors - surface condition (MCClung and Schaerer, 2006a).

3.1.11. Factor 11: potential avalanche size (additional factor, not part of a DMF)

Avalanches are classified into five categories according to size; 1-small, 2-medium, 3-large, 4-very large and 5-extremely large[1] (EAWS (2019)). In the process of decision-making, this factor is mainly of interest with regard to possible consequences of a release, i.e. potential avalanche size big enough to be of great consequence on a specific slope. Potential slab avalanche size is an estimate built on different combinations of inclination, terrain formation, weak layer, slab thickness, slab stiffness and amount of snow carried along. Potential loose snow avalanche size is estimated by a combination of inclination, terrain formation and amount of accessible loose snow in the avalanche path. In size 1, small avalanches, there is minimal danger of burying. These avalanches will typically stop before the end of a slope. However, depending on terrain, there can be a risk of falling or being carried over cliffs. Size 2, medium, is defined as avalanches that can bury, injure or kill a person. Thus any avalanche larger than size 1 may easily become fatal.

3.1.12. Factor 12: avalanche sensitivity to triggering (additional factor, not part of a DMF)

The sensitivity to triggering describes how easy it is to trigger an avalanche, distinguishing between natural and human triggered avalanches. This factor is part of the workflow when determining danger level in an avalanche forecast when using the Conceptual Model of Avalanche Hazard (Statham et al., 2018) or ADAM (Müller et al., 2016). The sensitivity ranges from unreactive or very hard to trigger to touchy or very easy to trigger. Under unreactive conditions there is no or only a minor avalanche problem, no distinct weak layers and the fractures are hard to initiate or do not propagate. In the touchy condition there is at least one avalanche problem, one or several well-developed weak layers and the fractures can be initiated with low additional load, such as one single skier, and propagates well. Remote triggering is typical.

3.1.13. Factor 13: avalanche type (additional factor, not part of a DMF)

Avalanche type is not included in the process of determining danger level, but due to the differences between slab and loose snow avalanches, they pose different threats and can be of relevance in avalanche danger assessment. Avalanches can be divided roughly into three types; slab, loose, and glide avalanches. Their characteristics differ in terms of how fast the snow stabilises, possibility of remote triggering, typical release zone steepness, release characteristics and destructive force related to size and density (EAWS, 2019).

3.1.14. Summary snow and avalanche factors

To summarise, all the DMFs use factors 1–5 (signs of instability, loading of new snow, wind or rain within the last 48 h, critical warming, signs of slab avalanches within the last 48 h) to some degree. However, not all DMFs use presence of persistent or deep persistent slab problems, how snow feels when moving on skis, unusual, infrequently travelled route, pillows of wind drifted snow or cornices. What distinguishes factor 1–5 from the other factors is that they generally are easier to observe and interpret, i.e. are direct evidence with a high level of certainty, and competence required to evaluate them is moderate.

However, experts use a range of factors but, somewhat surprisingly, not all experts use signs of instability (Table 3).

3.2. Snowpack evaluation and stability test factors

Category B consists of two sub categories; B1) *snowpack evaluation* and B2) *stability tests*. In situations with poor snowpack stability, nature provides us with rather obvious signs. These warning signs, such as recent avalanches, shooting cracks and “whumpfs”, indicate an unstable snowpack and are typically associated with danger level 3 - considerable or higher. The more stable the snowpack, the greater the load it can support before it fails. In these situations, instability can be less obvious and more indirect factors have to be evaluated. A snowpack can have a favourable buildup, e.g. no slab on a weak layer, only loose snow. In these situations, the snowpack is considered stable and no avalanche danger exists.

Factors in subcategory B1 *snowpack evaluation* belong to both class 2 data and class 1 data (MCClung and Schaerer, 2006a). In order to evaluate snow cover and be able to assess the current avalanche situation, knowledge of snow classification is required. Due to the nature of these factors, there is uncertainty and a careful interpretation required.

The descriptions of the factors in this group is based on the threshold sum approach (Jamieson and Schweizer, 2005b; Schweizer and Jamieson, 2002) and a description of the practical application of the SSD (Kronthaler and Zenke, 2006).

3.2.1. Factor 1: hardness of the overlaying snow

By overlaying snow, we mean the snow above a potential weak layer. The hardness of the overlaying snow is one of the factors determining what will affect the weak layer and possibly initiate a fracture that could lead to an avalanche release (Kronthaler, 2003; Kronthaler and Zenke, 2006). Additional load by backcountry travellers, precipitation type, intensity and amount, solar radiation and temperature are all criteria to be taken into consideration when assessing the importance of the hardness. It is also of importance for potential avalanche size.

3.2.2. Factor 2: weak layer distance from snow surface

This factor is evaluated in combination with the factor hardness of overlaying snow, and affects sensitivity to trigger and potential size of an avalanche. The effect of the additional load of a backcountry recreationalist, additional wind loading or precipitation and possible additional weakening by rain or high temperatures on the weak layer are all of importance. There are countless possible combinations of the distance from surface and the hardness of overlying snow, and this has to be assessed for each individual situation. The influence of skiers on a weak layer decreases with increasing depth, i.e. weak layers deeper than 80 cm from snow surface are hardly effected by skiers (Schweizer

[1] Note that as of winter season 2018–2019 the EAWS (European Avalanche Warning Services) has agreed on implementing new names for the different categories. The changes are meant to improve the effectiveness of the avalanche warnings because the new names communicate the danger better.

and Camponovo, 2001). However, additional stress is dependent on riding style, e.g. falls. Dependent on terrain, the depth of snow, and thus the depth of the weak layer, can vary considerably over short distances. This makes the estimation of depth very difficult in practice, as changes in topography, wind-deposited snow depths, inclination etc. may have a strong effect on the importance of the depth to the weak layer.

3.2.3. Factor 3–6: weak layer properties

We present four factors in the same heading because they are evaluated in combination. The four factors are: grain size; grain type; thickness and difference in hardness. One factor, difference in hardness > 1 between layers, is not part of any DMF, was not asked for by any of the experts, and was not included in the survey. However, it is part of the threshold sum approach and hence included in this section.

When analysing the properties of a weak layer grain type, grain size and layer hardness is of importance (Jamieson and Schweizer, 2005a). Grain size > 1.25 mm is regarded as unfavourable. Layers consisting primarily of surface hoar, facets and depth hoar and layer hardness softer than 1F (one finger) are regarded as unfavourable. Also of interest are the properties of the boundaries or interfaces between layers. A differences in grain size > 0.5 mm and a difference in hardness > 1 are regarded as unfavourable. A weak layer thickness of < 3 cm is also considered unfavourable (Kronthaler et al., 2013). Grain size, type and hardness are dependent on the processes affecting snow metamorphosis. By understanding these processes, one can estimate the distribution of a weak layer.

The analysis of weak layer properties can be done systematically and is then called: Threshold sum or yellow flags (Schweizer and Jamieson, 2007). Only minor differences separate the Threshold sum from the analysis of weak layer properties used in the SSD. The analysis of weak layer properties is often combined with stability tests by experts.

3.2.4. Factor 7: fracture character

This factor is evaluated from stability tests. It is important to obtain a better understanding of snow stability / instability. Fracture character / shear quality is significantly less spatially variable than stability test results. This factor is regarded as class 1 data in relation to predicting avalanches. Fracture character is divided into 5 classes, with a corresponding description and code for each class (e.g. Sudden Planar, code SP, description: Planar fracture suddenly crosses column in one loading step and the block slides easily on the weak layer) (van Herwijnen and Jamieson, 2004). It is also common to use the three-class Shear Quality score (Q1, Q2, Q3) which is an expression of how even or uneven the shear surface is (e.g. Q1 clean, planar, smooth and fast shear surface; weak layer may collapse during failure) (MCClung and Schaerer, 2006a). The SSD uses the terms Smooth or Stepped fracture (Glatter oder Gestufter Bruch) (Kronthaler, 2003; Kronthaler et al., 2013).

3.2.5. Factor 8: test score from stability tests

The tests differ in descriptive terms, coding and description of load at failure because they are designed to test different snowpack properties (see below), and have different strengths and weaknesses. For example the Rutschblock test uses 7 load levels, and failure with load levels 1, 2 and 3 stability is rated poor. A detailed description and stability interpretations on the basis of test scores can be found in (MCClung and Schaerer, 2006a; Kronthaler, 2014).

3.2.6. Factor 9: combination of different elements

Evaluating the different snowpack factors in combination constitutes the actual diagnosis in the SSD. This component is thus an assessment of the various factors of a snowpack evaluation (factor 1–8) and the interaction between them. Individually, the different factors do not necessarily imply any instability or danger. What matters is the interaction and properties of the different factors or elements. For example: consider the surface of a stable snowpack with a layer of surface hoar with unfavourable properties (2.5 cm thick layer, 10 mm crystals, fist hardness). This layer is then covered by a 30 cm layer of unbounded, dry, loose, new snow. Even if a weak layer exists, the surface hoar layer, there is no slab avalanche problem because the slab is missing.

3.2.7. Summary B1: snowpack evaluation

Snowpack evaluation requires knowledge, detailed observation, a careful weighing of factors and the interaction between factors. The more distinct the unfavourable snow layer properties and interfaces are, the more unstable is the snowpack. As important and valuable the threshold sum approach may seem, it is accurate only about 60–75% of the time and should be interpreted alongside other information including snowpack distribution over terrain, according to the method developers (Schweizer and Jamieson, 2007). The SSD uses many of the same factors as the threshold sum approach when evaluating snow layer properties, and snowpack evaluation is essential. In a comprehensive real-life test involving 190 test slopes, the accuracy rate was very high (99.34% for stable slopes) (Kronthaler et al., 2013).

As Table 4 shows, the reduction methods ASM, SoG and RM, have no or very little focus on snowpack evaluation. SC and GRM have some focus on this in their accompanying literature (Harvey et al., 2018; Engler et al., 2001), but without offering any structure on how to systemise and interpret these factors. The NT focuses only on the presence of a weak layer, whereas the stability test scores and fracture character are included in the A2.0.

Overall, the DMFs assess snowpack differently. There is not a single factor that is common to all DMFs.

3.2.8. Factor 10: B2, Stability tests

Together with snowpack evaluations, stability tests are an important part of avalanche forecasting (MCClung and Schaerer, 2006a). Observing clear signs of instability implies that travel on similar slopes with similar conditions will be high risk. When instability is less obvious, tests that make the user aware of unstable conditions are highly valuable. Quite often, the spatial distribution of a specific instability is more limited in lower danger situations, i.e. level 1-low or 2-moderate situations, than at higher danger levels. In order to expose these instabilities, it may be necessary to perform several tests to track the instability.

Evaluations and tests are also used to directly assess avalanche danger in the field. We included tests that either are part of a decision-making framework, or frequently involved in evaluation of instability: the Rutschblock Test (RB), Compression test (CT), Extended column test (ECT) and the Small Block Test (SBT). Detailed description of the tests can be found in e.g. (Jamieson, 1999; Kronthaler, 2014; Schweizer, 2002; Simenhois and Birkeland, 2009). We describe also two informal tests; 1) ski cut and 2) hand shear.

3.2.8.1. Small block test (SBT). The SBT is an important factor in snowpack evaluation and decision-making using the SSD. The test is not a stability test in a traditional sense. However, it tests the initial fracture with the amount of force applied and the type fracture with the propagation potential. Other tests consider load levels and scores or descriptive terms (MCClung and Schaerer, 2006a), whereas the SBT core target is to identify potential weak layers within a snowpack and then evaluate its properties. SBT distinguishes only between light, moderate and hard lateral tapping and smooth, rough, and “stepped” fractures (Kronthaler et al., 2013). The SBT is the only test that uses lateral loading/tapping. In a recent study (Kronthaler et al., 2018) significantly more energy had to be applied to initiate a fracture when using vertical load compared with lateral load. In addition, applying vertical load revealed just over half of the weak layers compared to the SBT. Also, the dispersion of stability values was significantly larger using vertical load. The authors concluded that the SBT can be used to make more reliable statements about the properties of the weak layers. However, they also stressed that one test is insufficient in slope specific decision-making independent of lateral or vertical tapping. Therefore they recommend performing several tests and analyses of the weak layer using the threshold sum method or the analysis structure used in SSD.

3.2.8.2. Rutschblock test (RB). An isolated block of snow, preferably on a 30° inclined slope, is loaded by a person in several stages (MCClung and Schaerer, 2006a) and load levels for Rutschblock failure are interpreted in several stages from having poor to good stability. However, it is challenging to find a safe spot to perform the test.

3.2.8.3. Compression test (CT). The test can be used to identify weak layers in the snowpack, and uses loading steps to initiate failure in a weak layer (MCClung and Schaerer, 2006a). The loading is applied vertically on an isolated column measuring 30x30cm. The descriptive terms for failure range from very easy to no failure. Interpretation of results should include shear quality.

3.2.8.4. Extended column test (ECT). This test gives information on fracture initiation and fracture propagation (Simenhois and Birkeland, 2007). Like the CT, vertical loading is applied in different steps. The isolated column measures 30x90cm. Descriptive terms for propagation range from no fracture to fracture propagates during isolation.

3.2.8.5. Propagation saw test (PST). This test indicates how easily a fracture propagates in a chosen weak layer in the snowpack. A column of 30 cm width and 100 cm horizontal length in slope direction is isolated. Vertically it has to be isolated deep enough to include the weak layer. If the weak layer is deeper than 100 cm the length of the column should match the depth of the weak layer. Sawing with the blunt end of a snow saw in the weak layer is done until a fracture propagates through the whole column.

3.2.8.6. Ski cut. Ski cut or ski cutting is not a formal test, has no stepwise loading levels or recording standards. It can be used to test slope stability using skis primarily on smaller slopes. Pro-skiers and expert riders sometimes perform ski cut at the very top of a run in order to release a potential avalanche before exposure to the entire slope. The effectiveness is condition-dependent and not risk-free.

3.2.8.7. Hand shear test. If a weak layer has been identified, and if it is high in the snowpack then it can be tracked using an informal test, the hand shear test. It is performed by isolating the overlaying snow by hand. Next, one evaluates the interface between the weak layer and the isolated column and the weak layer properties. The hand shear test has no defined block size, nor does it imply any stepwise loading levels or recording standards. The test can also be used to determine if the overlaying snow is loose or bonded.

3.2.8.8. Summary stability tests. In the SSD, the key component is finding the most prominent weak layer and testing the weak layer - slab combination using the SBT. Results are interpreted considering the processes that lead to the weak layer slab combination observed. Based on this, the user can assess release probability for the investigated slope. During a comprehensive field campaign, the transferability of the danger assessment to neighboring slopes was tested. Results showed that in situations with low release probability the variability of the prominent weak layer was higher than for situations with high release probability (Kronthaler et al., 2013). Based on their investigation the authors conclude that snowpack evaluation, using the little block test and analysing snowpack and weak layer properties provide robust results in slope specific avalanche danger assessment.

For other DMFs, only the A2.0 and GRM mention stability tests in their accompanying literature (Harvey et al., 2018; Haegeli et al., 2010), but offer no information or structure on how to interpret and use this information. In the ASM, stability would naturally fall under safety wall 1-danger assessment, but is instead presented in a separate chapter called depth knowledge and can therefore not be considered part of the framework (Brattlien, 2014).

The best tests for backcountry travellers will be those having the best balance between time consumption, risk in performing the test, ease of interpretation and reliability in identifying instability relevant for the user. All stability tests are point measurements that can provide high-quality information, but have limited value beyond the area where they are performed. Therefore one should always evaluate them in association with other factors (MCClung and Schaerer, 2006a).

3.3. Avalanche forecast factors

To provide the public with detailed information about the snowpack and current avalanche situation many countries have avalanche warning services publishing avalanche forecasts, also called bulletins (Engeset et al., 2018). Category C includes the factors used in the bulletins (also called warnings and forecasts).

In general avalanche forecasts have similar content and use an information pyramid, presenting the most important information, *the danger level*, first.

3.3.1. Factor 1: danger level

The danger level uses a five-stage scale, ranging from 1-low to 5-very high (5 is labeled extreme in North America). Each danger level is derived from a set of definitions, expressing the interaction between all evaluated factors. The European danger scale is a function of a) probability of avalanche release, b) distribution of hazardous sites and c) avalanche size. European forecasting services use the EAWS Matrix to determine the danger level.

As Table 5 shows, except for the NT and SSD, the danger level retrieved from an avalanche forecast is either a factor on par with other factors (AT and A2.0) or the most prominent factor and starting point in the decision-making process.

3.3.2. Factor 2: main message

Large amounts of data are analysed and the resulting forecast is the condensed presentation of this data. The *Main message*, is not integrated in the information pyramid, but is the forecaster's opportunity to communicate directly with the reader in order to inform and point at key aspects of the avalanche situation in a concise way, relating the message, i.e. “this is what you have to be aware of”. If there are changes in the avalanche problem, important new observations, or significant changes in weather, the main message will include this information.

3.3.3. Factor 3: avalanche prone locations (aspect, elevation and specific terrain features)

Avalanche prone locations are areas where the danger is particularly significant. In the forecast, these areas are described using graphics and text. There are two ways to incorporate this factor into the avalanche assessment; A) as a physical factor, i.e. that the location is of importance for snow metamorphism and snow stability such as effects of temperature dependence on altitude and effects of solar radiation dependence on aspect, or B) as a statistical factor, i.e. taking into account where accidents tend to occur. For example avalanche fatality statistics from the Alps show that a majority of accidents are located in the northern sector. How the DMFs use this factor varies.

3.3.4. Factor 4: avalanche problem

When writing an avalanche forecast, the forecaster can choose between five (Europe, EAWS, 2019) or eight (North America, Statham et al., 2006) different *avalanche problems*. A forecast can contain up to three different avalanche problems. The avalanche problem is third in the information pyramid, but to the experts (Landrø et al., 2019) it is the most important factor in the forecast. Avalanche problems are a good starting point for an analytical danger assessment. Avalanche problems directly influence terrain choice, what type of observations are relevant, procedural choices, and they determine the degree of uncertainty in the current situation.

3.3.5. Factor 5: mountain weather

Weather affects the snowpack and thus the avalanche danger. *Mountain weather* gives information on previous, current and future weather and its effect on avalanche danger. This factor can be of importance for the type of avalanche problem, weak layer formation and development in addition to more general information on what conditions (wind, temperature, precipitation) and visibility one can expect.

3.3.6. Factor 6: snowpack information

In the *snowpack information* part of a forecast, a general description covering both the layering of the snow and the stability is given. This allows understanding of the processes causing the current snowpack, the further development of the snowpack, possible destabilisation, and facilitates managing the avalanche problem.

3.3.7. Factor 7: travel and terrain advice

This factor is especially aimed at snow sports enthusiasts and is in addition to the recommendations defined in the avalanche danger scale. Recommendations are often linked to how to handle different avalanche problems. Experts consider this factor mainly during planning and route-selection. It is of limited use, probably due to the advice being too general or obvious for the expert user.

3.3.8. Summary avalanche forecast

Except for the NT and SSD, the danger level retrieved from an avalanche forecast, is either a factor on par with other factors (AT and A2.0) or the most prominent factor and starting point in the DMFs.

However, reliance on the danger level has been criticised for several reasons:

a. The danger level is not suited for small-area or slope specific descriptions, nor was it developed for that purpose (Nairz, 2010);
b. There is no objective definition of how to determine the danger level, neither in the forecast nor in the field;
c. In reality, danger level changes continuously, not stepwise as in the scale. The steps imply distinct danger level bands;
d. (Lack of) uniformity of the forecast (Müller et al., 2016);
e. Uncertainty related to prediction (forecast) and systematic verification procedures regarding the danger level (Schweizer, 2010; Schweizer et al., 2003a; Techel et al., 2016b);
f. The risk calculation (including the danger level) ignores the total number of people travelling in the backcountry (McCammon and Hägeli, 2005; Kronthaler, 2001);
g. Accident-based risk calculations do not take into account all the cases where an expert has chosen not to enter a specific slope on the basis of his or her avalanche danger assessment. In a calculation, this should have counted as an event;
h. The avalanche problem has no *direct* influence on determining the danger level (e.g. calculations by (Techel and Winkler, 2015) show that the relative risk is 50% higher at the same danger level in situations with persistent weak layers than with other avalanche problems).

3.4. Group and group management factors

Category D consists of two related subcategories; *Group factors* and *group management factors*. *Group factors* can be regarded as a physical factor (weight), statistical factor (accidents), human factors (heuristic traps). How these factors are regarded and used in the DMFs differ. In this category, the skills, level of fitness, safety equipment and training in avalanche rescue of the group are assessed.

Group management factors are concrete measures concerning how a group travels in avalanche terrain to minimize risk. On the one hand, these factors are about exposing as few as possible to avalanche risk at the same time, and on the other hand they are about minimising the extra load backcountry recreationalists exhort on the snowpack. These factors are standard travel measures and are applied independently of the DMFs. However, they are an integrated part of some DMFs.

3.4.1. Factor 1: group size

This factor classifies groups into small (2–4 people), large and very large (Munter, 1997). The NT defines groups > 5 people as negative. Note, that there is no universal definition of large and very large groups. Regarding different heuristic traps, such as the Expert Halo, Social Facilitation and Acceptance (McCammon, 2004), organisation and communication in the group are probably more important than group size.

3.4.2. Factor 2 and 3: group skills and fitness level

Low technical skiing skills increase the likelihood of falling, resulting in high, abrupt additional load on the snowpack, increasing the likelihood of an avalanche release. Skiing skill is also important for keeping the optimal planned line and for stopping at safe spots. Low levels of fitness also increase the physical demand on the skiers leaving less surplus energy for avalanche danger assessments and route selection. There is also extensive evidence suggesting that high levels of physical activity decrease a person's cognitive abilities to make sound decisions (Hetland et al., 2018).

3.4.3. Factor 4 and 5: avalanche rescue skills and safety equipment

These factors belong together and assess whether group members have the necessary safety equipment (transceiver, shovel, and probe) and the skills to rescue a companion (Falk et al., 1994). Avalanche rescue skills essential for efficient companion rescue, thus increasing survival chances in case of an avalanche burial. Using rescue strategies, teaching methods and rescue equipment optimized for novices, companion rescue can be performed very efficient and successful {Genswein, 2008 #154}{Genswein, 2008 #616}, even in complex situations with multiple burials. The three main tools: transceiver, shovel and probe, must be used in combination to function optimally (Stumpert, 2002).

3.4.4. Factor 6–11: standard travel measures, group management techniques

Standard travel measures are the steps to handle avalanche risk. Different DMFs provide variants of factors such as: a) One-at-a-time exposed, b) safety distance when ascending, c) one-at-a-time 35°, d) 30 m distance, e) safety distance 10 m from 30° onwards, f) skiing with distance. These were presented as different items in the survey but have been collapsed into one factor in this analysis. This factor is primarily a risk reduction measure to limit additional loading on the snowpack. It is connected to the definitions in the European Avalanche Danger Scale (EAWS, 2019). In the description of likelihood of triggering, descriptions such as “Triggering is possible, even from low additional loads (danger level 3-considerable)” are used. Low is defined as: individual skier / snowboarder, riding softly, not falling; snowshoer; group with good spacing (minimum 10 m) keeping distances. High load is defined as: two or more skiers / snowboarders etc. without good spacing (or without intervals).

Secondly it is a measure that can limit the number of people caught in an avalanche release. The different variations of the factor, regarding recommendations at different inclination are based on avalanche accident statistics and related to risk calculations. Applying this management strategy in large groups and on long runs costs time, but the benefits outweigh the disadvantages.

3.4.5. Factor 12: clear direction

This is a risk reduction measure optimising line selection in relation to skiing the best snow possible, avoiding terrain traps, avoiding trigger points and especially exposed areas. Clear directions that are heard and understood by the group are an essential factor to manoeuvre groups in avalanche terrain.

3.4.6. Factor 13: Stopping at safe spots

This is a risk reduction measure that ensures safety in case of an avalanche release triggered by someone else in the group.

3.4.7. Summary group factors and group management

All DMFs have recommendations to minimize the risk of getting caught in an avalanche. The primary focus is to avoid avalanche release, not to provide detailed group management strategies in avalanche terrain.

Some DMFs include group management techniques that are mainly slope specific. A few of the DMFs from the Alps, such as SoG and SC, use what is called *Einzugsgebiet* meaning assessment area and it describes the amount of terrain that should be taken into consideration. The assessment area is derived from the danger level. For example, at danger level 2-moderate, track surroundings or areas within 20 m should be considered, and at danger level 3-considerable the entire slope should be considered. This approach may be insufficient when the avalanche problem is associated with a risk of remote triggering (i.e. persistent weak layers), natural releases at lower danger levels and infrequent but long avalanche runouts at lower danger levels. The assessment area concept and the high and low additional load definitions in the EAWS contribute to the different risk reduction measures.

As Table 6 shows, as many as six group factors are used by nearly all experts (> 90%) and four of these are considered decisive by two of more out of three experts. In other words group size, technical skills, physical shape and avalanche rescue training are important.

3.5. Terrain factors

Avalanche hazard is based on evaluating the interaction of four variables – snowpack, weather, person and terrain. *Terrain* is the foundation for avalanches and without an inclination of minimum 30°, avalanches will usually not occur. When assessing avalanche danger, terrain factors can be used as physical factors (e.g. inclination) or a statistical factor (avalanche accidents). Category E includes different factors used to describe the terrain.

Inclination plays an important role in all three processes relevant for dry slab triggering (Schweizer and Camponovo, 2001; Heierli et al., 2008; Heierli et al., 2011; Schweizer et al., 2003b):

- Fracture initiation – likelihood increases with steepness
- Fracture propagation – likelihood increases with steepness (but dependent on several factors)
- Slide - dry snow slides at inclinations steeper than about 30°

However, avalanche statistics show that most accidents happen on slopes between 35° and 40° (measured at the steepest point), independent of avalanche danger level (Harvey et al., 2012).

Apart from inclination, commonly used terrain factors include terrain traps, curvature/convexity, avalanche paths, forest, safe spots, etc.

3.5.1. Factor 1: 5° intervals from 30°

This factor originates from a statistical/probabilistic approach to avalanche danger assessment and decision-making and measures inclination in 5° intervals. Frameworks derived from the RM use it in combination with danger level to reduce risk (Munter, 1997). Inclination belongs to what Munter calls First Class Reduction Factors. For example, at danger level 3-considerable, if the steepest part of the slope is 35°-39° (< 40°) this gives a First class reduction factor with a score of 2.

Similarly, A2.0 differentiates between slopes 30°-35° and slopes steeper than 35° and gives them a score of respectively +1 and + 2 in the terrain characteristics score card.

3.5.2. Factor 2: danger level/slope inclination

This factor corresponds to factor 1 in Category C and factor 1 in Category E.

3.5.3. Factor 3: discriminating between avalanche terrain and non-avalanche terrain

Here, users need to distinguish only between avalanche terrain (terrain steeper than 30° and runout zones) and non-avalanche terrain. Because the total number of people in avalanche terrain (including exact inclination) is unknown, as well as the exposition and danger level it is not possible to calculate an individual's risk. Instead, the inclination at which there are no accidents should be found, up to 40° at danger level 1 and up to 30° at danger levels 2, 3 and 4 (Kronthaler, 2001). This does not take into account groups that have turned around in terrain steeper than 40° at danger level 1-low, due to a local danger assessment.

3.5.4. Factor 4: avalanche terrain exposure scale (ATES)

ATES is a Canadian initiative to classify terrain into three different classes: simple, challenging and complex. The three classes are determined in a technical model that describes exposure to different terrain elements (e.g. inclination, forest density, terrain traps, avalanche frequency). In addition to the technical model, there is a public communication model targeted at a less skilled audience (Statham et al., 2006). ATES is well suited to teach avalanche terrain fundamentals and basic route finding, and can help balance terrain choice, conditions and competence. Guide books or maps showing terrain or routes that have been classified using ATES assist backcountry travellers new to an area to identify terrain that matches their competence and the current avalanche conditions.

3.5.5. Factor 5: use of favourable terrain formations

Use of favourable terrain formations refers to terrain where the impact of the additional load is limited such as thicker snowpack, avoiding high stress areas such as convexities (tension) and concavities (compression), and where the consequences of an avalanche are thought to be less serious as where there is a smooth runout without obstacles and terrain traps.

3.5.6. Factor 6: avoiding terrain traps

This factor has nothing to do with avalanche release, but refers to the consequences of an avalanche. Gullies, cliffs, trees and crevasses are examples of such. Flats at the bottom of steep slopes that may accumulate a deep avalanche deposit on top of an avalanche victim, are another example.

3.5.7. Factor 7: forest density

This factor can be both a positive and a negative factor depending on tree species and forest density. Trees will have an effect on snowpack layering (i.e. temperature, wind, incoming and outgoing radiation, interception of snowfall), can have an anchoring effect (dependent on slab stiffness) reducing avalanche likelihood, or increase the likelihood when their effect is weakening the snowpack (i.e. facets and depth hoar development). When an avalanche releases in or flows into forested terrain, the consequences increase dramatically.

3.5.8. Factor 8: convex or unsupported slopes

Convex and unsupported slopes are terrain features that have an increased likelihood of avalanche release, unless the wind has removed potential weak layers. Convexities add tension to the snowpack and are likely trigger points given additional load or weakened bonds. On unsupported slopes the slab lacks the additional support of the lower lying snow and the concave area. This is especially true for small and medium sized slopes, where forces acting on the slab (shear and compression) play an important role.

3.5.9. Factor 9: avoiding known avalanche paths

This factor originates from avalanche accident statistics. Terrain is obviously steep enough for an avalanche or acts as a runout-zone. Avalanche paths indicate a certain return frequency. In the ATES technical model, Avalanche frequency (events:years) is an important factor. In sparsely populated areas and areas without forests clearly indicating avalanche paths (i.e. sparse birch forest) it can be hard to determine avalanche frequency.

3.5.10. Factor 10: avoiding exposed routes without protected areas

This factor is not related to avalanche release, but to consequence. By exposed routes, we understand exposure to avalanche prone slopes. The use of protected areas (safe spots) is a means to reduce risk (see category D). Safe spots are used to limit the number of people exposed to risk at the same time. Especially in larger runs and complex / convoluted terrain this is a commonly used group management technique.

3.5.11. Summary terrain factors

Terrain as a factor in its entirety is important to all DMFs but usage varies. In some DMFs it is a one-dimensional physical factor, inclination. In other DMFs it is more complex, e.g. ATES. Terrain factors can be physical, necessary for or increasing the likelihood of avalanche release or a statistical factor stating the probability based on avalanche accident statistics. In DMFs derived from the RM inclination is a core factor, and together with danger level the avalanche risk is calculated. Inclination can be measured objectively, but there is still measurement error and uncertainty how “large” the steepest part has to be (Würtl, 2016):

- Maps and inclination maps masking the actual steepness by means of elevation lines. The elevation lines can have the same distance, but in reality the terrain can be much steeper in the range of up to 40 m than can be shown by the map.
- The maximum possible accuracy of measuring inclination on high quality maps is 4–5° (± 2°)
- The ability to read inclination correctly requires training using a precise inclinometer to ensure accurate feedback on estimates during training
- A meaningful inclination estimate presupposes an optimal reference area. In practice, the steepest areas of a slope with a coherent size of approx. 20 m × 20 m (400 m^2) is recommended. It can be relatively unproblematic to estimate inclination in smaller slopes, but poses serious potential risk in larger slopes.
- There are no standards regarding inclination measurements in avalanche accident investigations. These can be determined using maps, implying the sources of error described above. Whether inclination is measured on the snow surface, bed surface or ground is up to the expert assessment of the situation. In principle, only inclination of the snow surface should be considered as this is the only one that can be assessed by a backcountry recreationalist.

As Table 7 shows, only two terrain factors (terrain formations and traps) are used by nearly all experts (> 90%). However, discriminating avalanche terrain, convexities, avalanche paths and exposure also matters.

3.6. Expert use

We gathered data from experts on their use of the above reviewed factors. The full results are presented in Landrø et al. (2019). Tables 3–7 summarises the use and importance of the different factors. Factors can be used but not deemed decisive, e.g. avoiding terrain traps. In category A, *signs of instability* and *loading of new snow* are used by 3 out 4 experts. We refrain from speculating why not all experts use signs of instability but using an anonymous survey may elicit more honest answers than interviews.

Seven out of 10 factors in category B (snow evaluation) are used by > 2 out of 3 experts, but each individual factor is considered decisive by far fewer experts than category A factors. Given some overlap between the factors, and the categories, this is unsurprising, particularly since many experts also indicated the factors as relevant and situation-dependent.

In category C (avalanche forecast), all factors but travel advice are used by more than two out of three experts. However, these factors are not decisive for the majority. A possible explanation could be that avalanche forecasts are provided for areas (much) larger than 100 km^2, and thus do not translate directly to making decisions on the slope-scale.

Six out of 13 factors in category D (group factors) are used by practically all experts, highlighting the importance of the human factor. Many of these factors were also considered decisive by at least half of the experts.

For category E (terrain), inclination is not a prominent factor. More than half of the experts rely on *discriminating avalanche terrain - not avalanche terrain*, *ATES*, *favourable terrain formations* and *avoiding terrain traps*.

3.7. Network analysis

The DMFs can also be analysed as networks in order to explore the relationships between them based on their factors. We coded whether the DMF uses the factor in its decision-making or not. By assigning binary coding as 0 = not included and 1 = factor included. When a factor can be regarded as part of a framework because it is included in accompanying literature, or is used indirectly (i.e. all snow and avalanche factors are indirectly a part of the SSD because they are a part of process thinking) we coded it as 0.5 instead of 1. The results are identical.

We used the network analysis function in jasp (jasp-stats.org). Unsurprisingly (see Fig. 2), the reduction method is a central node from which several DMFs derive. There is also a strong relationship between AT and A2.0. SSD and NT are not related to the reduction method family network. Thus, the analysis of the factors in the frameworks

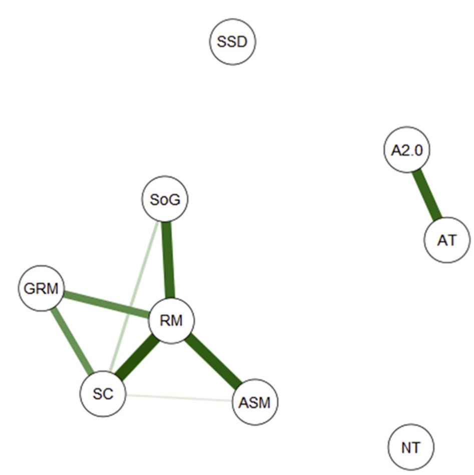

Fig. 2. Network analysis of the different DMFs based on shared factors. The line thickness and color strength indicate the positive correlation between the DMFs. Distance between the DMFs is of no importance.
RM = Reduction Method, ASM = After Ski Method, SC = Snow-card, SoG = Stop or Go, NT = NivoTest, A2.0 = Avaluator 2.0, GRM = Graphic Reduction Method, SSD = Systematic Snow-cover Diagnosis, AT = ALPTRUTh.

resonates well with the historical emergence and philosophical background of the decision-making frameworks. More details on the network analysis can be found at https://osf.io/2z95n/

4. Discussion

In the current paper we present the first comparative and comprehensive overview of the factors described in the ten most commonly used DMFs and complemented by factors suggested by an avalanche expert advisory board. This resulted in 53 factors used in avalanche decision making. We grouped these factors into five different categories: A) snow and avalanche factors, B) snowpack evaluation and stability test, C) avalanche forecast, D) group factors and group management and E) terrain factors.

4.1. Comparing the frameworks

Our analysis shows that the frameworks differ in terms of number, type of factors and how they emphasise the factors they assess. The number of factors used by the different DMFs varies between 11 (AT) and 31 (GRM, SoG). There is no single factor that is shared by all DMFs, reflecting different decision approaches, varying in their degree of abductive reasoning. Frameworks belonging to the RM family resemble each other, varying only in minor details (Tables 3–7). The NT uses other factors than those in the RM family and also applies different calculations. AT and A2.0 share many of the same factors, but A2.0 gives the factors a score, uses more factors, includes analytic elements and is a considerably more comprehensive framework. The SSD is the only purely analytic framework. It differs from all the other frameworks on factors included and how these factors are assessed.

4.2. Snow and avalanche factors

The snow and avalanche category factors are the ones shared by most DMFs, especially those that are easiest to interpret, commonly called signs of instability. In some DMFs these factors are core factors on par with others, whereas in other DMFs, they are less important or used only indirectly (included in accompanying literature) and without offering any structure on how these factors should be systemised and interpreted. However, the developers of the frameworks appear to agree that factors belonging to this category are of importance and should be part of avalanche danger assessment and decision-making.

4.3. Snowpack evaluation and stability test factors

The largest difference amongst the DMFs is found in this category. The primarily probabilistic approaches (RM family and NT) do not include these factors, or at most use these factors indirectly. If included, they do not provide the user with any guidance or assessment structure. In contrast, the purely analytic SSD requires a thorough understanding of these factors.

4.4. Avalanche forecast factors

An avalanche forecast contains many factors. The main factor in the probabilistic DMFs (the RM family and NT) is the danger level, and secondary is the avalanche prone locations. Only the A2.0 uses avalanche problems as a factor. For the remaining factors there is only limited and indirect use, e.g. the RM, ASM, SC, SoG, GRM, NT and SSD indirectly include the existence of a slab problem. The danger level is a good indication of the situation one most likely will meet. However, the avalanche forecast is much more than danger level, and the avalanche problem and snowpack information have the potential of becoming important factors.

4.5. Group and group management factors

The human factor is absent in a range of DMFs, particularly in those of the RM family. A range of factors concerning group management are considered in the SoG and NT includes group factors such as assessing knowledge, skills and level of fitness. Given the inherent uncertainty and complexity in avalanche assessment it is striking that travel techniques like spacing out or stopping at safe spots are not included as a prominent measure in all DMFs. They are effective measures for handling residual risk and may determine the difference between an avalanche incident and fatal accident, as seen in their use by experts.

4.6. Terrain factors

As simplification, many DMFs have reduced terrain assessment to a measure of inclination. Even though inclination may be the most objective factor that can be measured, the complexity should not be reduced to one single factor. For example, terrain traps may increase the consequences of even small avalanches. Furthermore, measuring slope angle accurately in snow-covered terrain can be very challenging. Choosing terrain wisely according to the given condition may be one of the most important measure in avalanche decision-making.

4.7. Consequences

There are differences in the number, type and importance of factors amongst existing decision-making frameworks for avalanche terrain. The consequences of these differences are:

- Different DMFs can give conflicting results when it comes to go / no-go decisions
- Different DMFs pose different demands on user knowledge and competence
- DMFs differ in ease of use
- DMFs differ in level of residual risk they accept
- DMFs differ in the amount of terrain regarded as accessible given current conditions.

Our analysis shows that the factors included in the different frameworks range from simple to complex as well as simplifications of complex factors. Some factors are used from a statistical perspective in some frameworks, whereas others assess the same factors as a physical factor. The descriptions of each factor lay the foundation for a future assessment of their ease of use, importance, reliability and significance. Even use of the factor regarded as most objective, inclination, comes with challenges. This confirms that avalanche danger assessment involves reducible and irreducible uncertainty, and that there can never be absolutely certainty in assessing the avalanche risk.

4.8. Limitations

The presented frameworks undergo revisions, and our analysis is based on the latest versions we were aware of at the time of this analysis.

We did not review the decision-making processes of each DMF in detail, as our focus was on collecting the various factors and their use by experts. The natural next step is an analysis of the decision-making process itself.

5. Conclusion

A correct assessment of avalanche danger is crucial in order to avoid accidents. Researchers and avalanche experts have developed a range of avalanche decision-making frameworks to support decision-making in avalanche terrain and reduce fatalities. These frameworks rely on and assess different factors to provide a go or no go decision. We identified

44 factors included in the checklists, cards or described in the accompanying literature belonging to the different frameworks. Nine other factors were added based on feedback from pretesting our survey, resulting in 53 factors.

The frameworks were developed to make informed and ultimately safe decisions but the disagreement amongst the frameworks and factors used by experts warrant reconsideration and revisions. By collecting and reviewing the relevant factors in avalanche decision-making we provide the foundation to improve the decision process.

Declaration of Competing Interest

All authors declare that they do not have any conflict of interest.

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