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CRISTAL: A FRAMEWORK AND TOOLS FOR RESPONSIBLE DECISION-MAKING

Frédéric Pourraz^{*1,3}, Alain Duclos^{2,3}, and Gregory Coubat^{2,3}

¹LISTIC - University Savoie Mont Blanc - Annecy - France

²ALEA - Avalanches: Localisation, Etudes, Actions - Aussois - France

³data-avalanche association - Aussois - France

ABSTRACT: As avalanche triggering is impossible to predict fairly and accurately, risk assessment is still too much influenced by so-called "human factors". Such cognitive biases often prevent us from seeing obvious dangers. The **CRISTAL** approach aims at helping us make a conscious decision, from conception at home to technical choices on the field. Based on six observable and tangible criteria leading to four distinct vigilance modes, this iterative approach has four key steps: (i) the evaluation of the six criteria is factual, to avoid integrating any unexplained "feeling", and must also be independent of the group size and its expertise level; (ii) it leads to the determination of a minimal vigilance mode to be adopted on the field, which evolves along the route; (iii) the analysis completes the identification of the vigilance mode by also considering some human factors (experience, objective, group size, ...), as well as the topographical environment (terrain traps, ...). Such an analysis is in itself quite subjective because the resulting decision is bounded for each vigilance mode; (iv) the decision phase then ends the process... before it is restarted for the rest of the project. Developed and practiced for about two decades, this approach is now subject to research studies. A fuzzy rule-based system is being validated so that this transition from the six criteria to the adapted vigilance mode is no longer totally delegated to the user end.

KEYWORDS: Decision-making, criteria, vigilance mode, avoiding any surprise effect.

1. INTRODUCTION

Initiated in the 90s by Werner Munter, several methods have been developed to attempt to reduce risk while navigating avalanche terrain. From the inception of the first Professional and Elementary Reduction Methods [Munter, 1997], the main focus was to establish a gradual scale of "frequentable" slope steepness based on the danger level from the snow bulletin. A whole range of methods were then constructed following this premise: Graphic Reduction Method [Harvey and Nigg, 2009], After Ski Method [Brattlien, 2008]; although sometimes supplemented by other criteria for certain methods: Stop or Go [Larcher, 1999], SnowCard [Engler and Mersch, 2001], Avaluator [Haegeli and McCammon, 2006], Quantitative Reduction Method [Schmudlach et al., 2018].

* Corresponding author address:

Frédéric Pourraz

LISTIC - University Savoie Mont Blanc

5 chemin de bellevue

74944 Annecy-le-Vieux

FRANCE

tel: +33 450 666 002,

email: frederic.pourraz@univ-smb.fr

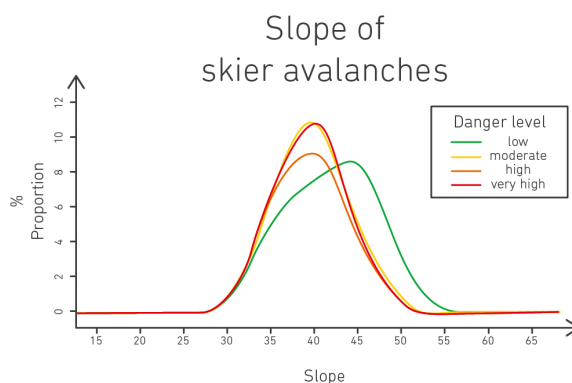


Figure 1: Distribution of avalanches, regarding slope steepness, for each danger level
ORTOVOX - Safety Academy - Lab Snow
(Source: S. Harvey)

However, as depicted in Figure 1, the distribution of avalanches based on slope steepness is very similar, whether by danger levels 2, 3, or 4. As stated in [Ortovox, 2023], for all three danger levels, the average slope steepness is 38°, "Therefore, it would be wrong to assume that a lower danger level means a greater slope steepness is required for an avalanche to be triggered.". The initial premise generally adopted is thus strongly challenged.

Another type of method is initiated by Ian McCammon in the early 2000s. The stated aim is to counter biases induced by human factors, based on the observation that our decisions can be heavily influenced by cognitive biases,

"This results in ballistic behavior where people appear to ignore obvious clues that they are making a mistake." [McCammon, 2000]. The systematic evaluation of tangible and observable criteria then becomes necessary, initiated by the Obvious Clues Method [McCammon, 2006] and later taken up in the Avaluator [Haegeli and McCammon, 2006]. This new paradigm is further refined later on with the Bounded Vigilance Model, which "assumes that engaged awareness of a relatively small number of carefully-chosen cues will guide users to higher levels of situational awareness and more consciously formulated decisions regarding avalanche risk." [McCammon, 2009].

This approach was expanded upon and complemented by [Duclos, 2012], whose primary objective remains to reduce risk-taking, but above all, to avoid the element of surprise by characterizing four distinct vigilance modes. After undergoing extensive refinement to mature the approach, it is now called **CRISTAL** and has multiple objectives, namely:

1. Prevent the element of surprise by limiting the influence of cognitive biases.
2. Decrease risk based on clear foundations.
3. Completely avoid danger if that is the desired outcome.
4. Become aware of the unpredictable factor.

CRISTAL, the subject of this article, is based on six tangible and observable criteria, which will be presented in Section 2. We will then focus on explaining the four vigilance modes in Section 3. The limitations of the approach and ongoing efforts to develop it into a fully-fledged method will be discussed in Section 4, before concluding in Section 5.

2. THE SIX CRITERIA

As humans and therefore fallible, our judgment and decisions are daily influenced by our cognitive biases, which sometimes blind us and prevent us from seeing obvious signs of danger. One way to guard against this is to objectively and systematically measure and observe our surrounding environment. As this phase is iterative: at home or in the refuge, during the approach, and throughout the route, we can only consider a limited number of criteria. The complexity of the phenomenon requires simplification, as our brains have limited capabilities for multi-criteria analysis. As seen in the introduction, this simplification cannot be confined to the danger level and slope steepness alone. The **CRISTAL** approach

is therefore based on six criteria that either play a key role in the physics of avalanche triggering or reflect ongoing instability.



Figure 2: **CRISTAL**'s sticker of the six criteria (printable version can be found on cristal-avalanche.org)

To make them easier to memorize and to systematize their evaluation, we have created a sticker representing these six criteria (see Figure 2) to be affixed to the tips of skis. Graphically represented in the form of a fresh snow crystal (hence the name of the approach), these six criteria can be assessed in a random order but must be evaluated in their entirety. In the field, it's all about awakening our senses (sight, hearing, and touch), as we will see in the presentation of these six criteria.

2.1 Slopes steeper than 30°

A slope steeper than 30° is a recognized axiom for avalanche triggering. It is now easy to consult online maps and digital terrain models (albeit fraught with uncertainties) to assess the slope steepness right from the preliminary phase of the project. Also accessible in the field via a Smartphone, this information can be validated or corrected on-site using ski poles or an inclinometer. It is important not to focus solely on the slope directly underfoot but to have an overall view of the surrounding slopes. Indeed, in the case of a remote trigger, slopes above or just below the route can also reach or carry away the group. Spontaneous avalanches, likely to start more or less far above the route, must also be considered. Sometimes, a map showing the avalanche history of the area (such as the CLPA map in France) can provide valuable information about the potential extent of an avalanche. As we will see later (see

Section 3), this notion of potential scale can influence our decision-making.

2.2 Recent avalanches observed

As Bruce Tremper stated in *The Avalanche Review*, "*the best sign of avalanche danger are avalanches*". Being aware of avalanches observed in the days preceding a field outing provides crucial information for decision-making. This is indeed the least equivocal criterion among the six. It informs us about the type of avalanche we can expect, the presence of sensitive weak layers, the potential scale of upcoming avalanches, and the critical altitudes and aspects of the moment. This information is not always accessible and is often incomplete, but it would be a missed opportunity to ignore it given its richness. In France, this is the purpose of the data-avalanche association: www.data-avalanche.org/now, which compiles and disseminates all avalanche observations reported by practitioners. The limitation of this criterion primarily occurs during and just after disturbed episodes when few or no avalanches have yet been observed and recorded.

2.3 A possible buried weak layer

This is likely the most difficult criterion to grasp, but it is also one of the most important (there are no slab avalanches without weak layers, except in the case of gliding slab releases). Learning to perceive the presence of a weak layer within the snowpack is thus an essential skill for moving more confidently in snowy and potentially exposed terrain (see criterion 2.1). Regularly probing the snowpack with our ski pole helps detect potential heterogeneity (layers of different hardnesses), a sign of the probable presence of a weak layer. This should clearly alert us to the potential instability of the traversed slope. However, the mere presence of a weak layer is not enough: it also requires that the dynamic stress induced by one or more skiers can trigger its collapse and that this collapse propagates within it. We have seen that recent avalanche observations were an accessible way for everyone to be informed about the presence of this phenomenon. Another indication is the perception of a "whoomp" sound (a collapse has just occurred and propagated). For more experienced practitioners, snow tests are also a way to characterize this phenomenon.

2.4 Temperature increase, snow thawing

A rise in temperature within the snowpack always leads to a change in the mechanical properties of the snow, sometimes resulting in avalanche flooding. This can involve spontaneous releases due

to wetting of the snowpack, as well as slab releases, with or without tangible wetting. While wetting is easily detectable in situ, the temperature rise within the snowpack, without melting, is more difficult to comprehend, as it is not always correlated with air temperature (as felt by the practitioner). For example, measurements from automatic stations at around 3000 meters altitude in France show differences exceeding 20 °C between air temperature and snow surface temperature.

2.5 New overloading

Whether caused by wind-driven snow accumulation, by fresh snow associated with a weather disturbance, or even by rain, overloading the snowpack is almost always an aggravating factor. It is primarily the increase in the slab's mass, above a weak layer, that facilitates the propagation of its collapse. In addition to this overloading effect, rain changes the mechanical properties of the slab by disrupting its structure (see the previous criterion). Data from snow and meteorological stations are very useful for assessing this criterion. Depending on the type of station, two snow depth sensors are sometimes installed, one on the windward side and the other on the leeward side, to better assess the amount of transported snow [Bourgeois et al., 2013]. Indeed, a simple wind speed sensor is not sufficient to determine whether or not snow has been transported, as it also strongly depends on the hardness and type of surface grains. Some stations, equipped with FlowCapt-type acoustic sensors, provide this indication directly.

2.6 Danger level

The danger level is considered as an input in most avalanche danger assessment methods, and practitioners are accustomed to referring to it. That's why it was essential to include it in the *CRISTAL* approach. However, it only illustrates the average situation of a mountain range and can conceal a highly heterogeneous situation (fatal accidents have occurred at both danger levels 1 and 2, sometimes due to large-scale avalanches). Although presented as one of the six criteria, it stands out due to its non-observable nature (it's already a synthesis of analysis by a third party). However, the text of the associated bulletin often contains information that can inform one or more of the other five criteria.

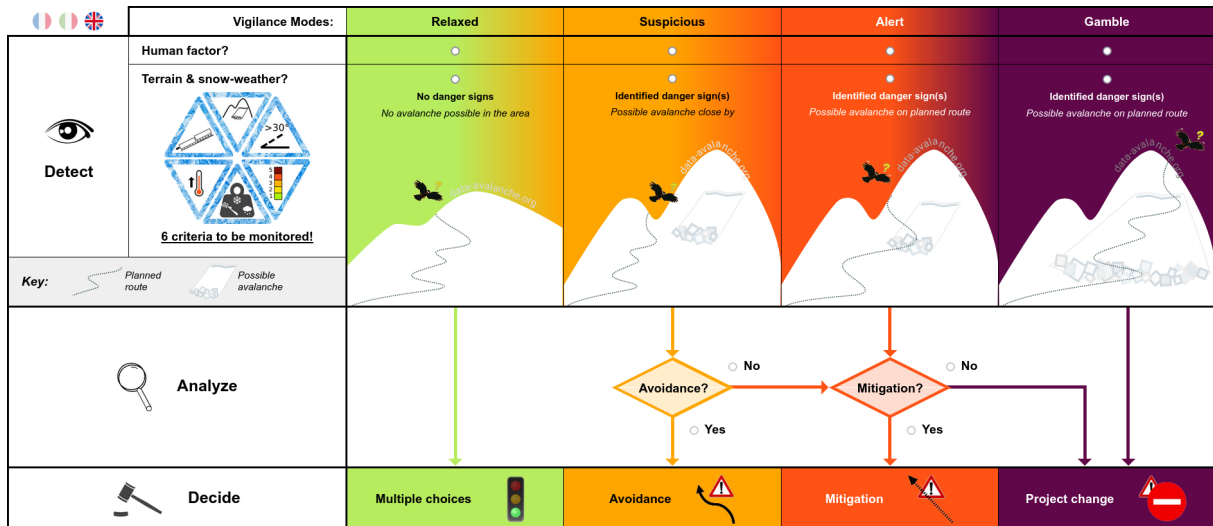


Figure 3: **CRISTAL**'s tool supporting the framework

3. THE FOUR VIGILANCE MODES

The six criteria we have just described serve as the entry point for the **CRISTAL** approach. Their systematic evaluation, as objectively as possible, is essential for making informed and conscious decisions. This is the first phase of the approach, which consists of three phases (see Figure 3): **Detect**, **Analyze**, and finally **Decide**, as this is the ultimate goal.

The first detection phase aims to be factual and entirely independent of the group's level and size, terrain traps, objectives, or even weather conditions. It relies solely on the observation and evaluation of the six criteria. Although work is underway (see Section 4) to partially automate this process, the task is currently dedicated to humans. The aim is to determine the appropriate vigilance mode for the situation, which should be the same for a given situation, whether one is a professional or an amateur. It's important to note that this mode may fluctuate throughout the route, depending on the evolution of each of the six criteria. At this point, human factors are mentioned in the sense of [Mccammon, 2004], to always keep in mind that they can influence our evaluation of the criteria and our perception of the environment.

The second phase is analysis. Once the vigilance mode is determined, this phase allows us to consider elements other than avalanche danger. After all, we move in a complex environment, often with companions who are also complex. This analysis phase is therefore always indispensable. This is where subjectivity comes into play, as our desires and risk acceptance can vary greatly. Depending on the vigilance

mode, this analysis focuses on the possibility or desire to completely avoid danger or to reduce risk. In all cases, the prior evaluation of the six criteria allows us to carry out this analysis with full knowledge of the facts.

The third, essential phase is the decision phase, which is not subjective but rather bounded for each vigilance mode. However, its implementation requires the skills of the group of practitioners (discussed during the analysis phase). Paradoxically, it often turns out, after an accident, that this phase was neglected.

3.1 *Relaxed*

Detect: The **Relaxed** mode means that no signs of danger have been detected, and therefore, no avalanche is possible in the frequented area. This is the case, for example, when no slope exceeds 30°. If this is not the case, it means that all other criteria have been assessed without consequences, implying that no dangerous snowpack instability is present.

Analyse: This is then very straightforward and only focuses on the group's desires.

Decide: At this moment, all choices are still on the table until a potential mode change.

3.2 *Alert*

In Figure 3, the second mode is the **Suspicious** mode. We chose to present it last because this mode is specific, and gradually, the **Alert** mode follows the **Relaxed** mode.

Detect: The **Alert** mode means that one or more signs of danger have been detected,

and therefore, an avalanche is possible in the planned area. However, the potential scale of the avalanche remains moderate.

Analyse: We are aware that the avalanche danger is real, and therefore, we are exposed to risk if we proceed on this section of the route. It's up to each individual to accept or decline this risk, depending on our objectives. If accepted, the challenge is to minimize this risk as much as possible so that, in the worst-case scenario, only one person would be affected by an avalanche. The analysis focuses on reduction possibilities: the presence of safe gathering zones (before and after the section), a safe acceptable distance, etc. As mentioned earlier, factors like level and group size, terrain traps, weather conditions, come into consideration. For instance, if the route overhangs a rocky ledge, regardless of the practitioners' skill levels, the outcome would be the same; however, if the passage is technically challenging, the analysis would consider the group members' abilities to navigate confidently. Visibility and the time required to implement this risk reduction would also be critical points to analyze. If this reduction is not possible or not desired, proceeding with the project would entail transitioning into the **Gamble** mode.

Decide: Having accepted the commitment, the decision is bounded to risk reduction. All actions discussed during the analysis phase need to be implemented, and the group should be prepared to rescue a potential victim.

3.3 *Gamble*

Detect: Similar to the **Alert** mode, the **Gamble** mode indicates that one or more signs of danger have been detected, and therefore, an avalanche is possible in the frequented area. The distinctiveness here is that in case of an avalanche, it would be of significant scale, and a severe accident would be unavoidable.

Analyse: No more analysis is possible. If we proceed, we can only rely on luck.

Decide: Let's make the wise decision to change the plan while there's still time. This decision could also have been prompted by the analysis phase of the **Alert** mode, for instance, in the case of a potential avalanche of moderate or even small scale, but in an extremely unfavorable environment (e.g., a rocky ledge or a stream immediately downstream).

3.4 *Suspicious*

Detect: In this mode, the focus shifts from examining the six parameters to assess danger where I am currently, to where I could be in the short term, assuming any possibility of danger in the area is not ruled out (unlike the **Relaxed** mode). The concept of spatio-temporal "buffer" that we introduce extends the examination of conditions both in time and space: where I might be later. We've arbitrarily depicted it as a disk (illustrated by the orange circle in Figure 4), centered on my current location. Its diameter varies (from a few meters to several hundred) depending on the direction of movement (ascent/descent), group size, or visibility. In the example provided (see Figure 4), we base this on the GPS track of an ascent progression (backcountry skiing) in potentially dangerous snow conditions (new overloading and possible buried weak layers). The **Suspicious** mode was necessary for the highlighted track section in red (from the point marked at 2335 meters) to (i) avoid danger and transition into **Alert** mode while progressing between short inclined slopes exceeding 30° (which was done correctly); (ii) consider whether or not to continue the project at the end of the section, necessitating a transition into **Alert** or **Gamble** mode (the choice, highly debatable, was to continue the project). Even if I am relaxed when stationary and no immediate danger threatens me, the buffer intersects objective dangers that require a mode change. As soon as I start moving, I must constantly pay attention to my path to either avoid these dangers or transition into a higher vigilance mode (**Alert** or **Gamble**).

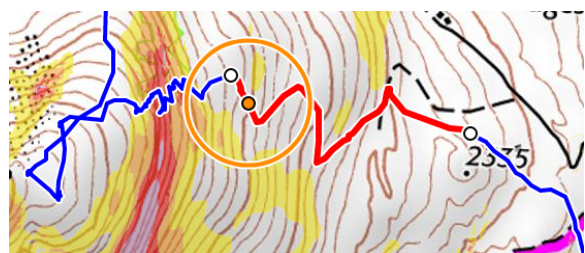


Figure 4: Spatial and temporal buffer of the suspicious mode

Analyse: We are aware that objective dangers are nearby and that we must remain attentive to anticipate and avoid them if we wish to avoid risk. In this case, the analysis focuses on the possibilities of avoiding the danger. If avoidance is not possible or not desired, we will need to change modes and transition into the **Alert** or **Gamble** mode. Avoidance of danger is typically the best option during ascent (reducing risk can be challenging). Transitioning into the **Alert** mode is often acceptable during descent (risk

reduction is often feasible due to greater agility, and significant gains can be made if the chosen objective knowingly includes steep slope sections).

Decide: Having chosen not to expose ourselves to danger, the decision is therefore limited to avoiding all critical zones.

4. DISCUSSION

As we've just seen, the *CRISTAL* approach provides a framework for making decisions consciously rather than being driven by emotions or feelings. Applicable throughout the itinerary, the approach is also suitable for all stages of the 3x3 [Munter, 1997]. Ultimately, our goal is to transform this approach into a fully-fledged decision-support method. To achieve this, we need to reduce the subjectivity induced by human evaluation of the six criteria and the successive vigilance modes adopted throughout the journey. Aware of the current limitations of the approach, we have already begun the process of transformation.

The first step was to formalize a graduated scale of values for each criterion, except the danger level. Therefore, we focused solely on five criteria. With each criterion having 3 to 4 gradual values, the number of possible combinations reaches 432 [Pagnier et al., 2022]. In order to represent the uncertain and imprecise nature of evaluating these criteria, we formalized them using fuzzy set theory [Zadeh, 1965]. Consequently, we also expressed the rules for combining these five criteria in order to automatically deduce the appropriate vigilance mode for the situation. These fuzzy rules have been developed through expert analysis of concrete situations (like the example in Figure 4) which, among other things, led to the emergence of the spatio-temporal "buffer" (as discussed in Section 3.4).

Although each criterion is tangible and observable, none are trivial. This was evident with the criterion of slope steepness exceeding 30°, which encompasses the slope directly underfoot, slopes above the route and if an avalanche triggered there can reach us, slopes just below us and if an avalanche triggered there can sweep us away, the historical behavior of that slope (has it previously avalanched?), and finally, the potential extent of an avalanche if triggered (as discussed in Section 2.1). These components are what we refer to as sub-criteria. As each of the five criteria can be decomposed into

sub-criteria, we also formalized these using fuzzy subsets and then, once again, defined fuzzy rules to combine them and obtain a fuzzy value for each criterion. Thus, there are different levels of combination, one for transitioning from sub-criteria to associated criteria, and another for transitioning from the five criteria to the four vigilance modes [Pagnier et al., 2022].

This entire process is now largely automated but requires a crucial and significant validation step before it can be more reliably used by practitioners. All these expert rules need to be tested on a wide range of known historical situations to be validated or challenged. The ultimate goal of all these efforts is, for a given itinerary, to achieve the most automated evaluation possible of all sub-criteria using all the information available through our online tool: *SYNTHESIS* (which is the specific subject of another article in this ISSW issue). After applying the various levels of combination, a semi-automated evaluation of the appropriate vigilance mode to adopt will be provided to the user. Unlike current deep learning approaches, the advantage of using fuzzy logic is that, at the end of this step, the result (vigilance mode) is explainable. This means that the most influential sub-criteria in achieving this mode can be explicitly described to the end user. If desired, the user can then re-evaluate some or all of these sub-criteria to refine the result and incorporate their own expertise into evaluating the appropriate vigilance mode. This semi-automation will only affect *CRISTAL*'s detection phase. The analysis and decision-making phases will remain human-driven, as *CRISTAL* is only intended to be a decision-support method.

5. CONCLUSION & PERSPECTIVES

The *CRISTAL* approach, now formalized and supported by the graphical representation provided earlier (see Figure 3), is based on three distinct phases: **Detect**, **Analyze**, and **Decide**. The first detection phase aims to systematize the objective assessment of **six tangible and observable criteria** to avoid surprise and limit the influence of cognitive biases in decision-making. This assessment results in the detection of an appropriate **vigilance mode** to adopt in the field, which can evolve throughout the journey. The **Relaxed** and **Gamble** modes bracket the **Suspicious** and **Alert** modes. These latter modes respectively allow for complete avoidance of danger (if desired) and reduction of risk on clear bases. The **Suspicious** mode also introduces the innovative concept of **spatio-temporal "buffer"**. This "buffer" embodies evaluating

danger where I could be in the short term, rather than only where I am, ensuring continuous anticipation and, again, avoiding surprises. The analysis phase then takes into account all other elements complementary to avalanche danger to make the most suitable decision while remaining consistent with our objectives.

This *CRISTAL* approach should ultimately become a comprehensive decision-support method. Through the work already done, the formalization of criteria and rules for detecting the appropriate vigilance mode have been established using fuzzy logic (a mathematical tool for considering notions of gradualness, imprecision, and uncertainty). One of our main goals is to maintain a "white-box" approach, ensuring complete explainability of the result. Already largely tooled, these efforts are at the validation stage, on numerous concrete cases, before being offered to the mountaineering community.

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