Identifying operation-specific ski run classes and their acceptability for skiing from avalanche risk management decisions in mechanized skiing

by

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Abstract

While mountain guides in mechanized skiing operations use a well-established terrain selection process to manage the physical risk from avalanches, the relationship between the acceptability of ski runs for guest skiing and the terrain character is complex. First, this thesis presents a new approach for deriving ski run types from daily terrain assessment records of two operations in British Columbia, Canada. It uses a combination of self-organizing maps and hierarchical clustering to identify groups of runs that have been assessed similarly in the past and organizes them into operation-specific run hierarchies. The thesis then uses this foundation and applies a general linear mixed effects model to explore the relationship between acceptable skiing terrain (i.e., status open) and avalanche hazard conditions. Expressing this relationship numerically provides an important step towards the development of meaningful decision aids, which can assist commercial operations to manage their avalanche risk more effectively and efficiently.

Keywords: Self-organizing maps, Mixed effects model, Avalanche risk management, Terrain selection, Decision making, Conceptual model of avalanche hazard

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Chapter 1.

Introduction

While each chapter included in this thesis has its own introduction to put the work into context, the objective of this introduction chapter is to provide general background that applies to the thesis as a whole.

1.1. Background

British Columbia is world-renowned for powder-skiing and the mechanized backcountry skiing industry, which uses helicopters or snowcats to access remote untracked power slopes, is well-established. The industry accounts for approximately 100,000 skier days per year, with gross revenues exceeding $160 million annually (HeliCat Canada, 2016). The first commercial heli-skiing operation was started by Hans Gmoser and Leo Grillmaier in the Bugaboos in 1964. The first snowcats shuttled skiers up untracked snow slopes in the backcountry in 1975. Today, HeliCat Canada, the trade association of the Canadian helicopter and snowcat skiing industry, has 19 heli-skiing and 11 snowcat-skiing operation members, representing the majority of the total 45 operations in Canada (HeliCat Canada, 2016).

Avalanches are the greatest natural hazard affecting the daily operations of the mechanized backcountry skiing industry in Canada (Bruns, 1996). Operations aim to provide their guests with a high-quality skiing experience without exposing them to an unacceptable level of risk from avalanches (Israelson, 2015; McClung, 2002). Fundamentally, the physical risk from avalanches is managed by assessing the severity, character and spatial distribution avalanche hazard and applying relevant mitigation measures to either reduce the hazard, manage exposure to the hazard or reducing the vulnerability of elements at risk (McClung & Schaerer, 2006). Backcountry skiing operations therefore continuously assess avalanche hazard through the analysis of the local weather, snowpack, and recent avalanche activity and minimize the exposure to the identified hazard by carefully choosing terrain and travel procedures.

The commercial backcountry skiing industry in Canada has developed tremendous expertise in avalanche risk management. The industry has worked closely with the avalanche research community, and safety procedures have been improved continuously (e.g., Gmoser, 1976, 1980). Using a dataset that spans the period from 1970 to 2016, Walcher et al. (under review) showed that the avalanche mortality rate for both guest and guides has been decreasing steadily since the 1970s and is now at 10.4 fatalities per one million skier days (i.e., one million guest and guides skiing one day). However, a recent study by Greene et al. (2014) showed that professional avalanche workers in Northern America (e.g., guides, ski patrollers, highway avalanche safety technicians) are among the occupations with the highest fatality rates and the community continues to explore possibilities for further improving the safety of guests and guides.

To identify potential weaknesses and improve existing practices in avalanche risk management, current practices must be captured and examined in detail. However, the existing professional decision-making expertise regarding terrain choices in avalanche terrain is primarily experiential and stored as tacit knowledge within the community. While this knowledge has been passed from generation to generation via training courses and mentorship, the employed rules have so far not been described explicitly. This lack of systematic description poses a significant hurdle for assessing existing practices in a quantitative way and developing meaningful evidence-based decision aids.

Avalanche safety research has traditionally been rooted in snow science and has primarily focused on improving our understanding of slope stability and avalanche release. Research efforts in this area have produced improved snowpack tests, enhanced our understanding of the spatial variability in the snowpack, and strengthened our ability to assess avalanche hazard (see, e.g., ISSW (2018) for an overview on recent developments). Research directly examining the hazard assessment and risk management processes is much rarer. Examples include studies classifying avalanche terrain for backcountry decisions (e.g., Campbell & Gould, 2013; Statham et al., 2006) or research on professional avalanche assessment expertise (e.g., Atkins, 2004; Haegeli, 2010b; Hendrikx et al., 2016; Statham et al., 2010).

Statham et al. (2018) recently introduced a Conceptual Model of Avalanche Hazard (CMAH) to describe the key elements of the avalanche hazard assessment process, which is the foundation of avalanche risk management. The authors broke avalanche hazard down into its fundamental components (avalanche problem types, location, ease of triggering and destructive size) and reorganized them in a sequential workflow that represents how professional avalanche forecasters think when assessing avalanche hazard. The CMAH provides a transparent approach characterizing the existing avalanche hazard in a way that is particularly informative for choosing risk management strategies (Atkins, 2004; Statham et al., 2010).

Managing avalanche risk requires the continuous tracking of weather, snowpack and avalanche conditions throughout the entire winter. Keeping track of changes in the seasonal snowpack is the foundation for learning and adapting to the constantly changing conditions, and handling the inherent spatial variability and uncertainty. Israelson (2015) describes the process as a series of filters. It starts with the daily hazard assessment in the morning, which produces a large-scale avalanche forecast for the entire tenure for the day, mainly incorporating data from the debrief meeting from the previous day and any overnight changes in weather and snowpack conditions. Subsequently, the guiding team goes through their entire inventory of predefined ski runs and collectively decides which runs are open or closed for skiing with guests (coded as green and red respectively) under the expected conditions. It is important to note that the scale and spatial delineation of ski runs can vary considerably from operation to operation, and there may be multiple distinct ways of skiing a run. However, ski runs are the decision units at this stage of the risk management process. The resulting large-scale, consensus-based 'run list' has established itself as a critical component in the risk management process of many commercial backcountry skiing operations. It represents the foundation for all subsequent guiding decisions during the daily skiing program by explicitly specifying the set of ski runs that have acceptable ski lines under the current conditions. In most helicopter skiing operations, helicopters serve multiple groups of skiers, each of them led by a guide. It is common practice that the guide of the first group serviced by the helicopter (known as the 'lead guide') decides what runs the groups of this helicopter ski. How exactly a particular run is skied is the responsibility of the guide of each group. During a skiing day, terrain choices are further refined and adapted using real-time snow and avalanche observations. This sequence of (1) a run list established by entire guiding team, (2) run choices made by lead guide and (3) ski line choice within run made by individual guide, highlights the hierarchical and iterative nature of the terrain selection process. At each filter level, the decisions are adjusted based on a real-time avalanche hazard assessment. While avalanche hazard is one of the most critical factors in this process, other factors such as weather and flying conditions, flight economics, skiing quality, guest preferences, and skiing abilities also play an important role influencing the selection and sequence of skied terrain (Israelson, 2015). Although the terrain selection process has been described conceptually, we do not yet understand the relative importance of and interaction among the influencing factors and the underlying rules used to make these decisions.

Identifying these decision rules directly by interviewing guides is difficult since it is well known that experts in complex decision environments have difficulties describing their tacit knowledge and explicitly articulating their decision rules as their reasoning process has become highly intuitive (Bruns, 1996; Klein, 1998). Thus, many of the existing studies in avalanche risk management are mainly descriptive and qualitatively explore factors either influencing judgement and decision-making capacities (Adams, 2005) or the development of expertise (e.g., Stewart-Patterson, 2016). Grímsdottír (2004) used surveys to analyze terrain characteristics that influence guide decision-making, but the insights produced by this research seem limited because the results lack the context of the specific decision situations. Among the studies that have examined the decision-making process quantitively, Haegeli (2010b) and Haegeli and Atkins (2010) used online surveys that include realistic, but hypothetical decision situations to capture the decision expertise of professional mountain guides. While these types of surveys offer important advantages for the quantitative analysis, the hypothetical decision scenarios are unable to accurately represent the full complexity of real-world decision situations. Most recently, Hendrikx et al. (2016) used GPS devices to passively record and examine terrain preferences of heli-ski guides at Majestic Heli-Ski in Alaska during 18 days. Their analysis primarily focused on the relationship between individual characteristics of terrain skied (incline and aspect) and avalanche hazard conditions described with hazard ratings and avalanche problems. While the study provides interesting first insights, the practical application of the results is limited by the small dataset. Moreover, this study only focused on physical terrain characteristics and the operational environment in helicopter skiing was underrepresented (other factors such as accessibility due to weather and flying conditions, flight economics, skiing quality, etc.). Examining the decision-making process of professional guides requires comprehensive, long-term operational datasets that contain information about terrain decisions and environmental conditions as well as operational constraints under a variety of different winters. Hence, existing research on professional terrain selection in mechanized skiing is limited and has so far focused on either hypothetical decision-situations or on small-scale terrain choices while neglecting the decisions that were made at the run list stage.

1.2. Objectives

In this thesis I aim to improve our quantitative understanding of how avalanche risk is managed by professional guides through large-scale terrain selection at the run list decision stage. The objectives of this research are:

- To develop a comprehensive understanding of run characteristics that drive professional terrain management decisions incorporating both terrain characteristics and operational attributes by identifying and analyzing long term patterns of terrain choices.

- To explicitly examine the relationship between acceptable skiing terrain (i.e., it being open for guiding) and avalanche hazard conditions at the run scale using historic avalanche hazard assessments and run list ratings from a commercial helicopter skiing operation.

1.3. Contributions

To address the objectives mentioned above, this thesis presents two contributions that have been formatted as stand-alone manuscripts for publication in a peer-reviewed academic journal.

- A method of deriving operation-specific ski run classes for avalanche risk management decisions in mechanized skiing (Chapter 2)

- Modelling the relationship between acceptable skiing terrain (i.e., status open) and avalanche hazard conditions (Chapter 3)

The first contribution has been submitted to Natural Hazards and Earth System Science, and at the time of writing, the manuscript was under review after having been through one round of review. The second contribution is being prepared for submission. Both contributions will be published under Creative Commons licenses that allow reproduction of the material in this thesis. The co-authors Pascal Haegeli and Patrick Mair also granted permission to reproduce the material.

Chapter 2.

A method of deriving operation-specific ski run classes for avalanche risk management decisions in mechanized skiing

A version of this chapter has been submitted for publication in Natural Hazard and Earth System Science as Sterchi, R., and Haegeli, P. "A method of deriving operation-specific ski run classes for avalanche risk management decisions in mechanized skiing". I co-led the design of this research, conducted all of the statistical analysis, and authored nearly all of the text of the manuscript. The manuscript has been reviewed by two anonymous referees and a revised version of the manuscript was submitted on Nov. 8, 2018. The manuscript, the comments of the reviewers and my responses are all accessible at https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2018-209/. *The content is distributed under the Creative Commons Attribution 4.0 License and has been reformatted to comply with SFU guidelines.*

Abstract

An in-depth understanding of the nature of the available terrain and its exposure to avalanche hazard is crucial for making informed risk management decisions when travelling in the backcountry. While the Avalanche Terrain Exposure Scale (ATES) is broadly used for providing recreationists with terrain information, this type of terrain classification has so far only seen limited adoption within the professional ski guiding community. We hypothesize that it is the generic nature and small number of terrain classes of ATES and its precursor systems that prevent them from offering meaningful assistance to professional decision makers. Working with two mechanized skiing operations in British Columbia, Canada, we present a new approach for deriving terrain classifications from daily terrain assessment records. We used a combination of self-organizing maps and hierarchical clustering to identify groups of ski runs that have been assessed similarly in the past and organized them into operation-specific ski run hierarchies. We then examined the nature of the emerging ski run hierarchies using comprehensive run characterizations from experienced guides. Our approach produces high-resolution ski run hierarchies that offer a more nuanced and meaningful perspective

on the available skiing terrain and provide new opportunities for examining professional avalanche risk management practices and developing meaningful decision aids.

2.1. Introduction

Commercial mechanized backcountry skiing is a type of downhill skiing where guided groups use helicopters or snowcats to access remote and pristine skiing terrain that would otherwise be difficult to access. In Canada, the birthplace of mechanized skiing, this sector is a substantial part of the local skiing industry, providing more than 100,000 skier days per winter (HeliCat Canada, 2016). Since its inception in the late 1960s, the Canadian mechanized skiing industry has provided roughly 3 million skier days in total (HeliCat Canada, personal communication; Walcher et al., under review). While most of the global mechanized skiing activity is taking place in Canada, it is also offered in other parts of the world including the United States, Iceland, Greenland, South America, and the Caucasus region.

Skiing untracked powder in uncontrolled mountain terrain is not without risk. Skiers are exposed to numerous types of natural hazards that can lead to injury or even death. Snow avalanches are the greatest natural hazard affecting the mechanized skiing industry in Canada (Bruns, 1996). Walcher et al. (under review) documented that between 1970 and 2016, the Canadian mechanized skiing industry experienced a total of 81 avalanche fatalities in 44 accidents involving both guides and guests. During the last two decades (1997-2016), the risk of dying in an accidentally triggered avalanche was calculated as 14.4 micromorts (number of deaths per million skier days), which represents 77% of the overall mortality in mechanized skiing in Canada due to natural hazards during that period (Walcher et al., under review).

While the risk from avalanches can never be eliminated completely, mechanized skiing operations aim to provide their guests with a high-quality skiing experience without exposing them to an unacceptable level of risk (Israelson, 2015; McClung, 2002). The primary strategy for managing the risk from avalanches when travelling in the backcountry during the winter is to limit one’s exposure by carefully choosing when and where to travel (Canadian Avalanche Association, 2016; Statham, 2008). Thus, identifying terrain that is appropriate under different types of avalanche conditions is crucial for making informed decisions when travelling in the backcountry.

In Canada, guiding teams in mechanized skiing operations select terrain for skiing by following a well-established, iterative process. This risk management process has been described as a series of filters occurring at multiple spatial and temporal scales (Israelson, 2013, 2015) that progressively eliminate skiing terrain from consideration. The first filter is the creation of the so-called "run list", which occurs during the guides' meeting each morning. During their meeting, guiding teams go through their inventory of predefined ski runs and collectively decide which runs are open or closed for skiing with guests under the expected avalanche hazard conditions. It is important to note that the scale and spatial delineation of ski runs can vary considerably from operation to operation, and there may be multiple distinct ways of skiing a run. However, ski runs are the decision units at this stage of the risk management process. The large-scale, consensus-based "run list" that emerges from the morning meeting is a critical planning tool that sets the stage for the skiing program of the day by eliminating certain runs from consideration. Over the course of a skiing day, terrain choices are further refined and adapted in response to direct field observations. While avalanche hazard is one of the most critical factors in this process, other factors such as weather and flying conditions, flight economics, skiing quality, guest preferences, and skiing abilities also affect the selection and sequencing of skied terrain (Israelson, 2015).

Bruns (1996) and later Adams (2005) describe that senior guides make their risk management decisions to a considerable part intuitively, using experience-based heuristics without necessarily reviewing every aspect of the decision situation conscientiously. While research in cognitive psychology has shown that experience-based heuristics can perform well under uncertainty (e.g., Gigerenzer & Gaissmaier, 2011), they can also lead to erroneous outcomes if not applied appropriately (e.g., McCammon, 2002). Despite the well-established, systematic approach to terrain selection, the mis-management of terrain remains among the most common errors of professional guides in the mechanized skiing industry (Guyn, 2016). To assist guides in their daily terrain selection, there have been various attempts to classify the severity of ski runs. Canadian Mountain Holidays (CMH), a large mechanized skiing provider that operates twelve lodges in the Columbia Mountains of western Canada, developed an ordinal severity rating system for their ski runs in the late 1980s (J. R. Bezzola: personal communication). Based on the expert opinion of long-time guides working at each lodge, this system assigned all ski runs into one of three increasingly severe terrain classes ranging from *Class A* (forgiving terrain that needed little investigation and could be skied safely in most conditions) to *Class B* (terrain that is moderately difficult to assess considering historical climatic conditions and that has moderate consequences in case of a mishap) and *Class C* (complex terrain with severe consequences in case of a mishap and which needed more extensive investigation before being skied) (Canadian Mountain Holidays, 1994). The vision was that the classification system would simplify the complexity of the terrain and allow guides to make appropriate terrain choices more easily. However, despite considerable efforts by CMH, the terrain classification system did not establish itself as an operational tool for making run lists. Experienced guides did not find that the rating system added value, as they perceived the classes to be too general and the system too restrictive for meaningful decision-making (J. R. Bezzola: personal communication). The three-class rating system was eventually abolished in the mid-1990s.

To provide amateur recreationists with a tangible tool for making terrain choices when planning a backcountry trip, Statham et al. (2006) developed the Avalanche Terrain Exposure Scale (ATES). Like the original system of CMH, the objective of ATES was to provide users with an overall severity assessment of linear backcountry trips into avalanche terrain that is easy to understand and communicate. The system considers eleven terrain parameters (e.g., slope angle, slope shape, terrain traps, route options, etc.) and classifies trips into three ordinal classes. *Simple* terrain is characterized by exposure to low angle or primarily forested terrain. Some forest openings may involve the runout zones of infrequent avalanches but many options to reduce or eliminate exposure may exist. *Challenging* terrain is described as being exposed to well defined avalanche paths, start zones or terrain traps. Options to reduce or eliminate exposure exist, but require careful route finding. *Complex* terrain, the most severe class, is characterized by multiple overlapping avalanche paths or large expanses of steep, open terrain with multiple avalanche start zones and terrain traps below with minimal options to reduce exposure (Statham et al., 2006). Since the initial introduction of ATES, many backcountry trips in Canada have been rated according to the system (e.g., https://www.pc.gc.ca/en/pn-np/mtn/securiteenmontagne-mountainsafety/avalanche/echelle-ratings). At the time of this writing, Avalanche Canada has mapped more than 8,000 km^2 of avalanche terrain in western Canada using the ATES mapping approach developed by Campbell and Marshall (2010), Campbell et al.

(2012), and Campbell and Gould (2013) (K. Klassen: personal communication). Today, ATES ratings are a critical component of the Canadian avalanche awareness curiculum and public avalanche safety products, such as the trip planning tool of the Avaluator V2.0 decision aid (Haegeli, 2010a) and its online implementation (https://www.avalanche.ca/planning/trip-planner). The system has also been adopted in other countries including Spain (Gavaldà et al., 2013; Martí et al., 2013), Sweden (Mårtensson et al., 2013), and Switzerland (Pielmeier et al., 2014).

Even though it has been hypothesized that many guides conceptualize the ski runs of their operation in terms of groups with a hierarchical structure (J. R. Bezzola: personal communication), the response of the mechanized skiing community to the ATES system has so far been limited. Northern Escape Heli-Skiing (NEH) initially tried to use the ATES system for classifying its ski runs but the system was found it to be far too conservative for professional use in commercial heli-skiing (Israelson, 2013). Consequently, NEH developed its own qualitative avalanche terrain severity rating system, which classifies individual ski lines according to their overall exposure to avalanche hazard on a three-class scale (Israelson, 2013).

Given the broad use of ATES among amateur recreationists and the repeated attempts to introduce similar systems in mechanized skiing operations, it is clear that terrain classifications have the potential to play an important role in backcountry avalanche risk management. But why have these efforts only had limited success in mechanized skiing operations so far? We hypothesize that the generic definitions and the small number of classes (i.e., limited resolution) of the existing systems are unable to characterize ski runs in a way that can offer meaningful insight to professional guides for their risk management decisions. But how can a more useful terrain classification system be created for mechanized skiing operations?

There has been considerable research that aims to better understand the link between terrain and avalanche hazard. Most of that research has taken a natural science perspective to relate patterns of well documented avalanche occurrences to geomorphologic parameters. This approach has linked relatively easily accessible geomorphologic parameters, such as incline or curvature, with the frequency or likelihood of avalanches (Maggioni & Gruber, 2003; Schaerer, 1977; Smith & McClung, 1997). Moreover, automated procedures based on digital elevation models have been developed to identify potential avalanche release areas as input for numerical avalanche runout modeling (Bühler et al., 2013; Maggioni & Gruber, 2003) or for mapping avalanche terrain (Delparte, 2007). While this area of research provides valuable input for land-use planning and the protection of permanent structures, it has so far only offered limited tools for backcountry risk management. Grímsdottír (2004) used questionnaires and interviews to examine the terrain selection process of professional guides. While her research highlighted individual terrain characteristics that influence the decision process of guides (e.g., terrain shape, slope size), it did not produce a tangible tool for assessing the overall severity of ski runs and for deriving terrain classes.

The objective of our study is to introduce an alternative and transferable method for deriving ski run classes that offer meaningful insight into risk management decisions in commercial mechanized skiing operations. Instead of building the classification from physical terrain characteristics, we derive the terrain classes from patterns in revealed terrain preferences reflected in past daily run list ratings. Our assumption is that ski runs that are considered open and closed for guiding under similar conditions will represent groupings that more closely relate to operational decision-making. We hypothesize that each operation has a unique, finely differentiated hierarchy within its ski runs that emerges from the available skiing terrain, the local snow climate, and the particular skiing product it offers to its clients. Furthermore, we suspect that the details of the run hierarchies might differ from year to year in response to the particular conditions of the individual winters. We will use historic run list data from two commercial mechanized backcountry skiing operations to illustrate our approach and explore these research questions in detail.

The remainder of the paper is organized as follows: Section 2 introduces the study sites, offers an overview of the dataset, and describes our two-step approach for identifying groups of ski runs and combining them into a run hierarchy. In section 3, we present the identified hierarchies of ski runs and describe the nature of the identified groups. We conclude by discussing the implications of our results for terrain management and professional decision-making in mechanized skiing.

2.2. Data and methods

Our method for developing a useful ski run classification for mechanized skiing operations applies a modern clustering approach to multi-season records of daily run list ratings that combines the advantages of an unsupervised machine learning algorithm with traditional hierarchical clustering. To better understand and describe the nature of the emerging hierarchy of ski run groups, we had a senior lead guide in each participating operation independently provide comprehensive characterizations of all their operation's runs included in our study. Since guides' terrain choices are driven by more factors than just the hazard potential, our run characterization included a wider range of operational attributes. In our final step of the analysis, we applied hierarchical clustering to the typical run list rating time series of the identified run groups for each individual season to examine how the nature of specific winters can affect the run classification. The following sections describe the various components of our analysis in more detail.

2.2.1. Study sites

We used data from two commercial helicopter-skiing companies—Northern Escape Heli-Skiing and Canadian Mountain Holidays Galena—that operate in different types of skiing terrain and snow climates and offer skiing products with a distinct focus. *Northern Escape Heli-Skiing* (NEH) is located in Terrace, British Columbia, and its operating area in the Skeena Mountains spans an area of nearly 6,000 km^2. NEH has been operating for 14 years, typically running a skiing program with multiple helicopters serving either single or multiple small groups. The elevation of the available skiing terrain ranges from 500 m to 2,000 m above sea level. While its entire tenure has 260 established ski runs, much of the skiing is focused on approximately 80 ski runs in its home drainage called Promised Land. Our study will focus exclusively on the ski runs located in Promised Land, which range in size between 0.1 km^2 and 2.8 km^2. The character of the local snow climate is maritime with storm slab avalanche problems during or immediately following storms being the primary avalanche hazard concerns and warm temperatures promoting rapid stabilization (McClung & Schaerer, 2006; Shandro & Haegeli, 2018).

Canadian Mountain Holidays Galena (CMHGL) is based out of a remote lodge in the Selkirk Mountains near Trout Lake, British Columbia, roughly 75 km southeast of Revelstoke. Its tenure area consists of approximately 1,200 km^2 of skiing terrain ranging from 850 m to 2,850 m above sea level and includes 295 established ski runs, which range in size between 0.1 km^2 and 19.1 km^2. CMHGL has been operating for 28 years, typically running a skiing program with a single helicopter that serves three or four groups of 11 skiers each. The tenure area of CMHGL is located in a transitional snow climate with a strong maritime influence (Haegeli & McClung, 2003). The two most important types of persistent weak layers in this area are crust-facet combinations due to rain-on-snow events in early season and surface hoar layers during the main winter months (Haegeli & McClung, 2003). Thus, avalanche hazard conditions with a combination of storm and persistent slab avalanche problems types are frequent (Shandro & Haegeli, 2018).

2.2.2. Identifying run groups and overall ski run hierarchy

While NEH and CMHGL both have extensive operational databases that include field observations, hazard assessments, and records of terrain choices, the primary data used in this study are daily run list ratings that describe the suitability of the ski runs for guiding guests under the existing hazard conditions. In both operations, the guiding team codes runs or ski lines as either “Open for guiding”, “Closed for guiding” or “Not discussed” every morning of the season. In addition to these standard codes, CMHGL also uses “Conditionally open for guiding” (i.e., can only be considered for skiing if a specified condition is fulfilled, which has to be determined in the field) and NEH uses “Closed for guiding for other reasons than avalanche hazard” (e.g., crevasses, open creeks, ski quality). While CMHGL does not have an explicit code for identifying runs that are closed for other reasons than avalanche hazard, it is common practice at this operation that these types of runs would not be discussed at the guides’ meeting. The complete dataset for CMHGL consists of 469,280 run list ratings for 295 ski runs from 2,029 days during 18 winter seasons from 2000 to 2017. The complete dataset for NEH consists of 32,655 ratings for 80 ski runs that were assessed on 429 days during the five winter seasons from 2013 to 2017. Hence, each of the ski runs included in our analysis is characterized by a multi-season time series of daily run list ratings.

Since large datasets with many attributes are challenging for traditional clustering techniques (Assent, 2012), we applied a two-step approach that combines the strengths and efficiency of self-organizing maps (SOM, Kohonen, 2001), an unsupervised competitive neural network clustering algorithm, with the transparency of traditional hierarchical clustering (Gonçalves et al., 2008; Vesanto & Alhoniemi, 2000). This approach circumvents the challenge of the large dataset by first using SOM to produce an analysis dataset with substantially fewer items that represent meaningful averages and are less sensitive to random variations than the run list time series included in the original data. Hierarchical clustering is subsequently applied to the reduced dataset to derive the final groups of runs (Vesanto & Alhoniemi, 2000). While it would be possible to group the runs entirely with SOM, the dendrogram of hierarchical clustering allows a more transparent evaluation of the clustering solution. Vesanto and Alhoniemi (2000) showed that for large datasets this two-level clustering approach performs well compared with direct clustering.

SOM (Kohonen, 1982, 2001) is a machine learning algorithm that is particularly adept at pattern recognition and clustering in large complex datasets (Kohonen, 2013). The method performs a nonlinear projection from the high-dimensional input data space to a smaller number of neural network nodes on a two-dimensional grid while preserving the topological relationships of the input data. SOM has been widely used as an analytical and visualization tool in exploratory and statistical data analysis in science and industrial applications (e.g., Gonçalves et al., 2008; Kaski et al., 1998; Oja et al., 2003; Pöllä et al., 2009; Radić et al., 2015; Shandro & Haegeli, 2018).

The neural network of a SOM consists of an input layer of x p-dimensional observations and an output layer of k neural nodes, each of which is characterized with a p-dimensional weight vector w representing an archetypal pattern in the input data. In our case, the input data consists of time series of daily run list ratings for each run and the weight vectors of the SOM nodes represent typical time series of how those runs were coded. Each SOM node has a position on a two-dimensional map and an initial weight vector w based on a randomly selected object from the input data. Training the network is performed for a chosen number of iterations where the entire input dataset is presented to the network repeatedly. For each input vector the node with the closest weight vector—known as the “best matching unit” (BMU)—is individually determined using a specified distance measure. The network learns (i.e., “self-organizes”) by adapting the weight vectors of the BMU and the nodes within a predefined neighborhood of the BMU to the input vector. This updating step is described by $w(t+1) = w(t) + \Theta(\mathrm{t})\alpha(t)[v(t) - w(t)]$, where *t* is the current iteration, *w* is the weight vector, *v* is the input vector, Θ is the neighborhood function that considers distance from the best matching node, and α is an iteration-dependent learning function. An essential characteristic of the SOM is that this iterative process eventually stabilizes in such a way that nodes that are similar to one another are situated close together on the map, thus preserving the topology of the input data. After the training process, individual SOM nodes represent archetypal patterns found in the original data. In our case, the patterns are characteristic time series of run list ratings for the runs included in each node. The amount of original information retained depends primarily on the size of the SOM (i.e., the number of nodes), with smaller sizes producing broader generalizations of the input datasets and larger sizes capturing increasingly fine details. Following the work of Liu et al. (2006), we selected a map size that optimizes the average distance between each input vector (quantization error), minimizes the percentage of input vectors for which the first best matching unit and second best matching unit are not neighboring nodes (topographical error), and minimizes the percentage of empty nodes on the map. Interested readers are referred to Kohonen (2001) for a more in-depth explanation of the development and details of the SOM algorithm.

To derive the final groups of runs, we applied hierarchical clustering to the characteristic run list rating time series identified by the SOM. Hierarchical clustering groups similar objects into clusters where each cluster is distinct from every other cluster, and the objects within each cluster are most similar to each other (Hastie et al., 2009). The main output of hierarchical clustering is a dendrogram, which shows the hierarchical relationship between the clusters graphically. We chose the final number of groups of runs based on an inspection of the clustering dendrogram, while balancing resolution and interpretability of the cluster solution. Finally, we arranged the identified groups into a hierarchy by ordering them according to the average percentage of days the runs were open within each group.

To ensure that we extracted meaningful patterns from our dataset, we preprocessed our input data prior to the clustering analysis using the following steps. First, we needed to make the run list ratings of the two operations consistent. While the guides at CMHGL open or close entire runs, NEH rates the individual ski lines on each run in their run list. To make the analysis comparable between the two operations, we converted the NEH ski line ratings into run-level ratings by considering a run open as soon as at least one of its ski lines was open. Second, we excluded ski runs that were closed during the entire study period (e.g., ski runs that were kept in the run list as a reminder for the guiding team that the runs are permanently closed due to wildlife concerns) since these runs would not contribute any meaningful information to our analysis. Third, we only included ski runs in our analysis that were at least occasionally used. Following the recommendations of our collaborating senior guides, we only included runs that were skied at least once a season at NEH, while we restricted our CMHGL dataset to runs that were skied at least once during the entire study period. Fourth, we restricted the dataset to ski runs that were included in the run list of all winters of the study period (2013 to 2017 at NEH; 2007 to 2017 at CMHGL) since the employed clustering algorithms are sensitive to large amounts of missing data. The final dataset for the SOM analysis consisted of 25,311 daily run list ratings from 59 ski runs on 429 days for NEH and 286,008 daily run list ratings from 227 ski runs on 1,260 days for CMHGL.

Since SOM requires input data to either be numerical or binary (i.e., 0 or 1), we had to recode our categorical run list ratings before processing. Following the approach of dummy coding routinely used for categorical data in regression analysis, we converted our original time series with five run list codes into two simplified binary time series. The first binary time series describes whether a ski run was open with 1 representing the original run list codes *“Open for guiding”* and *“Conditionally open for guiding”* (CMHGL only). The second binary time series describes whether a ski run was closed for avalanche hazard with 1 standing for *“Closed for guiding”*. This means that runs that were open for guiding were coded as 1-0 (first binary time series – second binary time series), runs that were closed for avalanche hazard were coded as 0-1, and runs that were closed for other reasons (*“Not discussed”*, *“Closed for guiding for other reasons than avalanche hazard”* (NEH only) or days with missing data) were coded as 0-0. The two binary time series of each run were then combined to produce the input data for the SOM analysis that represents the originally categorical nature of the run list data in a binary format. At the end of the training process of the SOM, the initially binary input data is represented by the weight vectors of each nodes as typical time series on a continuous scale between 0 and 1 that allows for the subsequent clustering with an appropriate similarity measure.

We performed our analysis using the R statistical software (R Core Team, 2017) and the Kohonen package (Wehrens & Buydens, 2007). We used a training length of 200 iterations, the Tanimoto similarity measure for binary data, a hexagonal topology, a circular neighborhood function, and a decreasing learning rate from 0.05 to 0.01. For the subsequent hierarchical clustering we used Ward's minimum variance method appropriate for numerical data.

2.2.3. Characterization of the identified run groups

To understand the nature of the emerging groups of ski runs, we had a senior lead guide in each operation complete a detailed terrain characterization survey for all their operation's runs included in our study. The collaborating guides had 20 and 34 years of guiding experience in mechanized skiing and guided at their operation for 5 years as the operations manager and 17 years as a lead guide respectively. The objective was to collect information on key characteristics that affect guiding teams to either open or close ski runs. While existing terrain studies have primarily focused on hazard information, we aimed for a more comprehensive assessment that included information on *Access*, *Type of Terrain*, *Skiing Experience*, *Operational Role*, *Hazard Potential*, and *Guide-ability* (see Table A1 for details on each run attribute and levels included). Each of these themes was assessed with a series of questions that asked about the presence or absence of specific features (e.g., “What type(s) of skiing terrain does this run include?”), included ordinal assessments of the magnitude or severity of features (e.g., “What is the steepness of the most serious slopes on this run?”), and qualitative evaluations of the overall perception of the nature of the terrain (e.g., “In terms of hazards, what is your sense of the overall friendliness of the terrain of this run?”). The last type of question aimed to capture the general feel for the terrain that experienced guides develop based on their overall knowledge and experience with a ski run. We deliberately chose to mainly focus on guides' comprehensive assessment of the terrain instead of elementary terrain parameters typically included in avalanche terrain studies. For example, instead of focusing on incline in degrees (e.g., Thumlert & Haegeli, 2018) or the precise location of exposure to avalanche paths like traditional terrain studies, our approach captures the general steepness of the run (e.g., gentle, moderately steep, moderately steep with pitches, sustained steep) and its exposure to overhead hazard (e.g., threatened during regular avalanche cycles, threatened during large avalanche cycles only) in a more general and qualitative perspective. This approach also allows us to gather information on more intangible ski run characteristics that go beyond pure terrain characteristics, such as the quality of the skiing experience and the guide-ability of a run. While these guides' perspectives are associated with a certain level of subjectivity, they offer a much richer and more encompassing viewpoint of the relevant standout terrain features of ski runs that ultimately drive guiding decisions. McClung (2002) highlights the importance of human perception as a critical link or filter between observations and avalanche hazard assessment.

The characterization questions were grouped into themes that represent different aspects of operational decision-making. An important operational factor in helicopter-skiing is the ease of access of landings and pickups. *Access* captures the general accessibility with respect to required flying conditions as well as particular characteristics of the pickup location(s), such as overhead hazards, which might limit accessibility of the ski run. *Type of Terrain* describes important terrain features and aims to capture the overall character of the terrain of a ski run. Examples of the descriptors used for characterizing the type of terrain include glaciated alpine terrain, open slopes at tree line, open canopy snow forest (where the crowns of individual mature trees do not overlap), and large avalanche paths from above. Mechanized skiing operators aim to provide guests with an excellent skiing product and each ski run in their tenure offers certain operational benefits for achieving that. The theme *Skiing Experience* covers information on the overall skiing experience and skiing difficulty level. *Operational Role* describes how a ski run is typically used in the ski program of the operation. While some ski runs can be used under almost all circumstances (i.e., “safe and accessible”), others are jump runs that offer important connections among other ski runs and make daily circuits work. *Hazard Potential* aims to capture the relevant hazards of a ski run and was characterized in detail by individually assessing steepness, exposure, avalanche terrain hazards (e.g., avalanche overhead hazard to the ski line(s) or unavoidable unsupported terrain shapes), and other hazards (e.g., crevasse or tree well hazard). For ski runs that were moderately steep or steeper, exposure was assessed by specifying the size of potential avalanche slopes (e.g., large avalanche slope(s) producing size 3.0 or greater). In addition, the overall friendliness of the terrain was assessed on a five-point Likert scale ranging from very friendly to very unfriendly. *Guide-ability* of a ski run describes how challenging it is to guide a group of guests safely through the terrain of that ski run (e.g., the terrain naturally leads guests to the right line or it requires detailed instructions and a close eye on the guest). This aspect of a run was assessed using a four-point Likert scale including very easy, easy, difficult, and very difficult.

The comprehensive run characterizations were summarized to describe the nature of the identified groups of runs. Specifically, we compared attribute frequencies of each group with overall attribute frequency among all ski runs of each operation. Because some groups of runs contained a relatively small numbers of runs, we focused on a more qualitative description of the nature of the groups instead of performing any statistical tests to compare groups.

2.2.4. Seasonal variability in run groups

To examine how the specific nature of individual winters might affect the grouping of ski runs, we applied hierarchical clustering for a second time. This time, we focused on individual seasons and clustered the representative time series of the previously identified groups to combine groups of ski runs with similar run list rating patterns within that season. We chose the number of seasonal clusters based on an inspection of the clustering dendrogram using Ward's minimum variance method.

2.3. Results

2.3.1. Operational terrain classes at NEH

Run groups and overall ski run hierarchy

For NEH, our analysis identified six groups of ski runs that exhibited distinct patterns in their run list ratings over the entire period 2013 to 2017 (Figure 2.1a). After training several SOMs with varying number of nodes, we selected a robust SOM solution with 6x3 nodes that optimized the quantization and topographical errors. Based on the visualization of the node dissimilarities in the clustering dendrogram, we chose a final solution that consisted of six groups of ski runs.

Figure 2.1a shows the NEH time series of run list ratings of consecutive winters (December 1 to March 31) grouped into the six identified groups. The time series strips of each group consist of colour-coded rows representing the run list ratings of the individual runs included in that group, with taller strips representing groups with more runs. Days when ski runs were open are shown in green, days when they were closed due to avalanche hazard are shown in red, and days when they were not discussed at the guides' meeting or were closed due to non-avalanche hazard related reasons are shown in black. Days with no run list data at all (e.g., prior to operating season, days when operation was shut down due to inclement weather conditions) are shown in grey. A visual inspection of Figure 2.1a confirms the grouping of the runs as one can see considerable consistency in the run list rating patterns within groups. At the same time, one can see individual days when certain ski runs were coded differently than the rest of their group.

The groups of ski runs are arranged hierarchically according to the average percentage of days the runs in the group were open for skiing with guests over the five seasons. The group of runs shown at the very top was open for skiing with guests the most often with an average of 97% of the days during the study period (seasonal values ranging between 94% and >99%, Table B1). These runs were closed due to avalanche hazard on only 1% of the days and either not discussed or closed due to other reasons than avalanche hazard on 2% of the days. In contrast, the lowest group in the ski run hierarchy includes fourteen ski runs that were, on average, only open on 29% of the days during the study period (seasonal values ranging between 18% and 35%, Table B1). These runs were closed due to avalanche hazard on 61% of the days of a season and either closed due to other reasons than avalanche hazards or not discussed at all on 10% of the days.

Run group characterization

Based on the run characterization provided by our experienced guide contact, the skiing terrain of NEH generally offers a variety of skiing at all three elevation bands (Table 1). The majority of the 59 ski runs includes non-glaciated alpine terrain and many comprised open slopes at tree line or glades. However, the terrain at NEH also includes ski runs that go through open canopy snow forests below tree line. A fifth of all the ski runs include large avalanches paths formed from above. The majority of the ski runs were characterized as gentle or moderately steep. While sustained steep ski runs with exposure to large avalanches slopes capable of producing Size 3.0 avalanches exist, approximately half of the ski runs included in our study do not involve exposure to avalanches slopes.

Figure 2.1 Identified ski run hierarchy with groups of similarly managed ski runs at NEH with (a) typical time series of run list ratings for the winter seasons 2013 to 2017 and (b) inter-seasonal variation within the hierarchy.

The time series strips of each group consist of color-coded rows representing the run list ratings of the individual runs included in that group. Taller strips therefore represent groups with larger numbers of runs. Days when ski runs were open are shown in green, days when they were closed due to avalanche hazard are shown in red, and days when they were not discussed or closed due to non-avalanche hazard related reasons are shown in black. Days with no run list data at all (e.g., prior to operating season, days when operation was shut down due to inclement weather conditions) are shown in grey. Panel (b) shows the identified within-season clusters (blue boxes) with multi-season ski run classes faded.

Group 1, which consists of eight ski runs that are most frequently open, is characterized by mostly gentle terrain with ski lines that have no exposure or only limited exposure to avalanche slopes (Table 2.1). Much of the ski terrain consists of open slopes at tree line or open canopy snow forest below tree line as well a few non-glaciated and glaciated alpine runs (Figure 2.2). The ski runs of this group provide easy skiing and generally a good skiing experience. Overall, the majority of the ski runs were characterized as safe and accessible under most conditions and many were identified as high efficiency production runs. At the same time, one of the ski runs included in this group was flagged as only rarely being used because it provides a poor skiing experience for guests.

Figure 2.2 Examples of Group 1 ski runs at NEH.
Photo: NEH. Reproduced with permission.

Group 2 is made up of nine gentle ski runs with no exposure to avalanche slopes on the ski lines. Another main feature of this group is that the terrain mainly consists of open slopes or glades at tree line (Figure 2.3). These runs are almost always accessible. While they provide easy skiing, the overall skiing experience was characterized as fair.

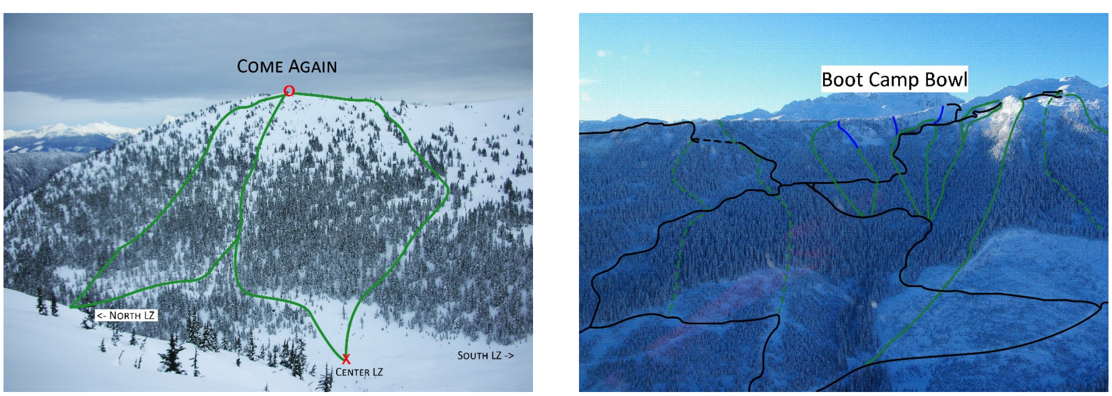


Figure 2.3 Examples of Group 2 ski runs at NEH.
Photo: NEH. Reproduced with permission.

Group 3 consists of only two runs that are always accessible and provide fair and good skiing through snow forest, glades, and a large avalanche path formed from above (Figure 2.4). One ski run is moderately steep with short steep pitches and the ski line is exposed to multiple smaller avalanche slopes, while the other ski run is gentle with no exposure to avalanche slopes. Skiing is moderately challenging or challenging and guide-ability was characterized as difficult on one run and easy on the other.

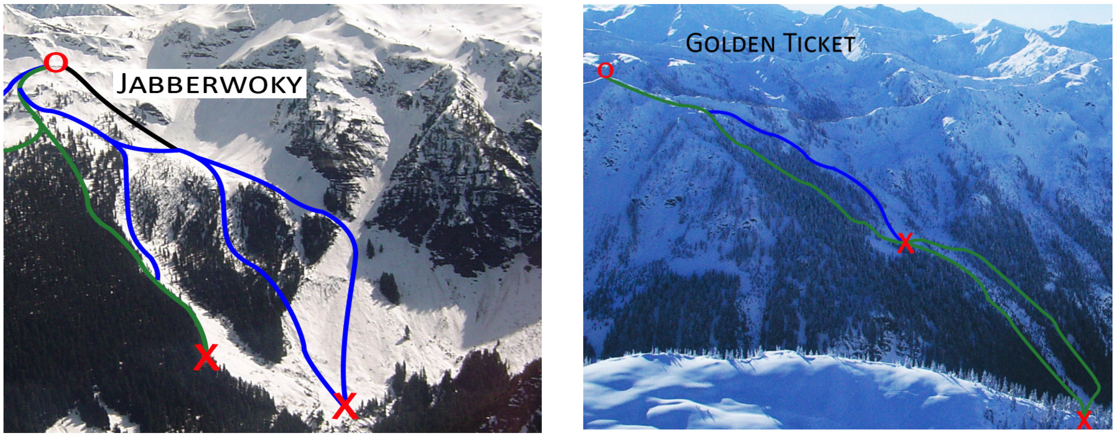


Figure 2.4 Examples of Group 3 ski runs at NEH.
Photo: NEH. Reproduced with permission.

While most of the ski runs of the first three groups are below or around tree line, the next three groups predominantly consist of alpine terrain. Group 4 consists of thirteen ski runs. The main characteristic of this group is gentle, non-glaciated or glaciated alpine terrain or open slopes at tree line where most ski lines do not cross any avalanche slopes (Figure 2.5).

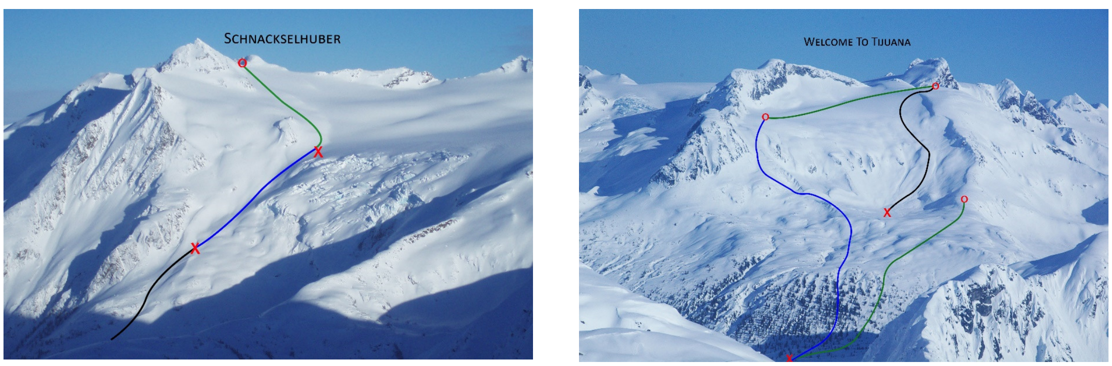
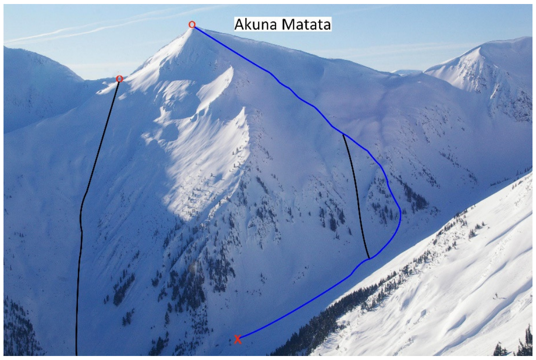


Figure 2.5 Examples of Group 4 ski runs at NEH.
Photo: NEH. Reproduced with permission.

These friendly or very friendly ski runs are often accessible and provide generally good skiing experience with easy or moderately challenging skiing. Some of the ski runs in this group can be exposed to overhead avalanche hazards during regular avalanches cycles (i.e., avalanche cycles producing avalanches up to Size 3.0).

All thirteen ski runs of Group 5 are located in the alpine and many also include skiing on glaciers or through open slopes at tree line (Figure 2.6). Most of the ski runs are moderately steep or steeper and include travelling through smaller or larger avalanche slopes. Almost half of the ski lines can be directly affected by overhead hazard during regular avalanches cycles, which makes this group exhibit the highest prevalence of that particular hazard. While the majority of the runs included in this group can be accessed by helicopter under most conditions, many pickup locations are threatened by overhead avalanche hazard during large avalanche cycles (producing avalanches of Size 3.5 or greater) and some of the pickups are even threatened during regular avalanche cycles. Many of the pickups are also exposed to the persistent presence of triggers for overhead hazards (e.g., ice fall or cornices). While skiing on these runs was mainly characterized as moderately challenging, they offer very good or even “life-changing” skiing experiences for guests. This group of runs is critical for the operation as many of the runs are high-efficiency production runs, and numerous runs are used as a destination in a daily skiing program or are perceived as providing a skiing experience that defines the operation.



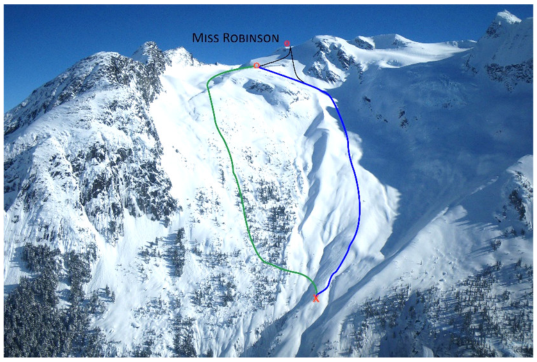


Figure 2.6 Examples of Group 5 ski runs at NEH.
Photo: NEH. Reproduced with permission.

Group 6 mainly includes moderately challenging or challenging alpine ski runs that are rarely skied but can play an important operation role under special circumstances and runs that are only considered under “bomb-proof” conditions (Figure 2.7). Most of these fourteen ski runs have moderately steep or steeper slopes that can produce avalanches of Size 3.0 or greater. Many pickup locations are regularly exposed to overhead avalanche hazard. However, ski runs in this group provide good or very good skiing experiences for guests.

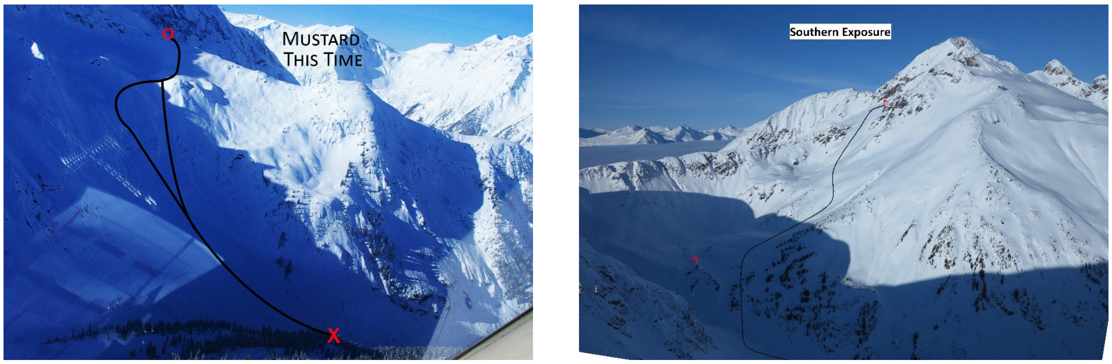


Figure 2.7 Examples of Group 6 ski runs at NEH.
Photo: NEH. Reproduced with permission.

Inter-seasonal variations

The seasonal clustering of the long-term terrain groups discussed above revealed that adjacent groups of runs in the ski run hierarchy would sometimes be combined as they were coded very similarly during some of the seasons Figure 2.1b, seasonal groups indicated with black boxes). While the identified long-term ski run hierarchy consists of six groups, the number of seasonal groups ranges from four to six with an average of five groups per season. This additional seasonal grouping was only observed among the first three groups where most ski runs are at tree line or below. Groups 1 and 2 were combined for three out of the five seasons (2013, 2016, and 2017). Similarly, Groups 2 and 3 were coded very similarly during the seasons 2013, 2015, and 2016. On the other hand, Groups 4, 5, and 6 had more distinct run list rating patterns during all five seasons. These three groups, which mainly consist of alpine ski runs, were never clustered together.

2.3.2. Operational terrain classes at CMHGL

Run groups and overall ski run hierarchy

For CMHGL, our analysis identified seven groups of ski runs that were coded similarly over the entire study period from 2007 to 2017 (Figure 2.8a). In this case, a SOM solution with 6x5 nodes optimized the quantization and topographical errors and the resulting 30 archetype patterns were subsequently used as input for the hierarchical clustering. Based on the visualization of the node dissimilarities in the clustering dendrogram we chose a final solution with seven clusters.

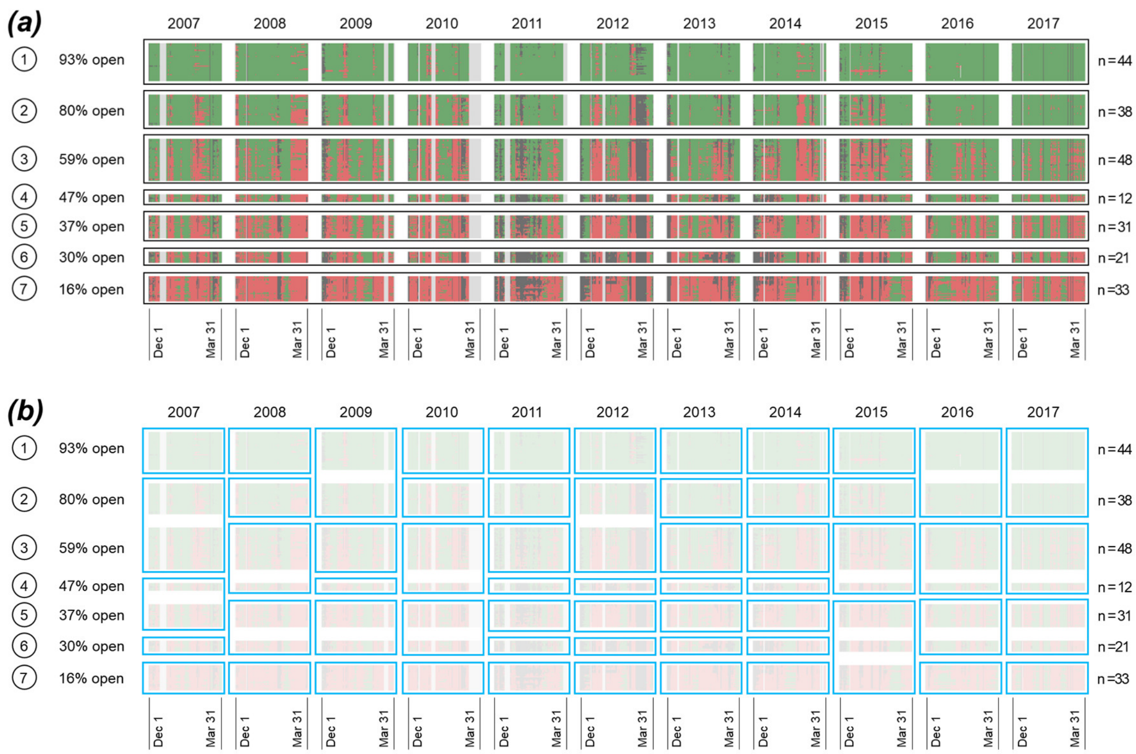


Figure 2.8 Identified ski run hierarchy with groups of similarly managed ski runs at CMHGL with (a) typical time series of run list ratings for the winter seasons 2007 to 2017 and (b) inter-seasonal variation within the hierarchy.

The time series strips of each group consist of color-coded rows representing the run list ratings of the individual runs included in that group. Taller strips therefore represent groups with larger numbers of runs. Days when ski runs were open are shown in green, days when they were closed due to avalanche hazard are shown in red, and days when they were not discussed or closed due to non-avalanche hazard related reasons are shown in black. Days with no run list data at all (e.g., prior to operating season, days when operation was shut down due to inclement weather conditions) are shown in grey. Panel (b) shows the identified within-season clusters (blue boxes) with multi-season ski run classes faded.

Table 2.1 Characteristics of the identified terrain groups at NEH and CMHGL (percentages that are greater than the basic distribution across all groups at an operation are highlighted with bold font and shaded in grey).

Attribute and levels		Group at NEH							Group at CMHGL							
		All	1	2	3	4	5	6	All	1	2	3	4	5	6	7
	Number of ski runs	59	8	9	2	13	13	14	227	44	38	48	12	31	21	33
Access																
Required flying conditions																
Run is almost always accessible		28	**38**	**56**	**100**	17	15	14	28	**64**	**58**	23	8	3	-	-
Run is often accessible		60	**63**	44	-	**67**	**85**	50	22	20	**26**	**35**	**25**	19	10	9
Conditions must line up		10	-	-	-	8	-	**36**	31	14	16	**38**	**42**	**48**	**57**	27
Conditions must be perfect		2	-	-	-	**8**	-	-	19	2	-	4	**25**	**29**	**33**	**64**
Particular pickup features																
Overhead hazard, regular avalanche cycles		9	-	-	-	-	**15**	**21**	20	7	-	**21**	**50**	16	**43**	**39**
Overhead hazard, large avalanche cycles only		47	13	22	**50**	42	**69**	**64**	53	25	**63**	**54**	42	**77**	52	**61**
Common trigger for overhead hazard		10	-	-	-	-	**38**	7	-	-	-	-	-	-	-	-
Type of terrain[a]																
Extreme alpine faces		2	-	-	-	-	**8**	-	2	-	-	-	-	-	-	**12**
Glaciated alpine		26	25	-	-	**50**	**38**	14	11	2	3	2	8	**19**	**19**	**33**
Non-glaciated alpine		66	38	-	-	**75**	**100**	**93**	7	7	3	**8**	**17**	6	5	**12**
Open slopes at tree line		41	**50**	**67**	**50**	**50**	**46**	7	68	39	39	65	67	**97**	**100**	**97**
Glades		38	25	**89**	**100**	33	31	14	17	7	**50**	17	8	10	14	3
Open canopy snow forest		17	**38**	**44**	**100**	-	-	7	29	**66**	**58**	21	-	3	10	3
Dense forest		2	-	**11**	-	-	-	-	1	**7**	-	-	-	-	-	-
Cut blocks		3	**13**	**11**	-	-	-	-	3	**9**	**5**	-	-	-	**5**	-
Large avalanche path formed from above		21	-	11	**50**	8	**38**	**29**	56	9	32	**69**	**67**	**81**	**81**	**82**
Planar slopes		9	-	**11**	-	-	**15**	**14**	3	-	-	-	-	**10**	-	**12**

Table 2.1 Continued.

		Group at NEH							Group at CMHGL							
	All	1	2	3	4	5	6	All	1	2	3	4	5	6	7
Attribute and levels — Number of ski runs	59	8	9	2	13	13	14	227	44	38	48	12	31	21	33
Skiing experience															
Skiing difficulty															
Easy	33	**63**	**56**	-	**58**	15	-	16	**34**	13	**23**	**25**	6	-	3
Moderate	50	38	33	50	42	**69**	**57**	71	66	**76**	58	67	**87**	**95**	61
Challenging	17	-	11	**50**	-	15	**43**	13	-	11	**19**	8	6	5	**36**
Overall guest experience															
Poor (Happy to move on)	7	**13**	**22**	-	-	-	7	4	**16**	-	4	-	-	-	-
Fair (Not bad skiing)	21	13	**44**	**50**	17	15	14	17	**25**	**21**	**21**	**25**	6	**19**	3
Good (A good product)	41	**75**	33	**50**	**67**	8	36	37	**43**	**42**	31	**58**	**48**	24	24
Very good (This is why guests come back for more)	26	-	-	-	17	**62**	**36**	33	16	32	**38**	8	**35**	**52**	**42**
Exceptional (Life changing mountain experience)	5	-	-	-	-	**15**	**7**	9	-	5	6	8	**10**	5	**30**
Operational role															
Safe and accessible under almost all conditions	41	**88**	**78**	**100**	**58**	8	-	6	**30**	-	-	-	-	-	-
Bread and butter (high efficiency production run)	33	**38**	33	**50**	25	**54**	14	19	**59**	**37**	6	-	-	-	-
Key jump run (makes a circuit work)	28	**38**	**44**	**50**	**42**	23	-	5	**9**	5	4	-	3	**10**	-
Regular lunch run	9	**25**	-	-	8	**15**	-	4	**14**	3	2	-	-	-	-
Time management run (e.g., used during fuel run of helicopter)	5	-	**22**	-	-	**8**	-	-	-	-	-	-	-	-	-
Destination run (objective of a circuit)	12	-	-	-	**17**	**31**	7	6	-	-	**10**	**17**	-	**14**	**9**
Signature run (defining the operation)	7	-	-	-	-	**23**	7	1	**2**	**3**	-	-	-	-	-
Open season run (only considered under bomb-proof conditions)	10	-	-	-	-	8	**36**	2	-	-	-	-	**3**	-	**9**
Rarely skied (but important under special circumstances)	24	13	-	-	17	23	**57**	2	-	-	-	-	-	-	**12**
Not preferred run (considered when lacking reasonable skiing)	10	-	**22**	-	8	-	**21**	4	**14**	-	2	-	-	**5**	-

Table 2.1 Continued.

Attribute and levels		Group at NEH							Group at CMHGL							
	All	1	2	3	4	5	6	All	1	2	3	4	5	6	7
Number of ski runs	59	8	9	2	13	13	14	227	44	38	48	12	31	21	33
Hazard potential															
Steepness															
Gentle	47	**75**	**100**	**50**	**75**	15	-	2	**11**	-	-	-	-	-	-
Moderate	28	25	-	-	25	**46**	**36**	11	**20**	**18**	10	8	6	5	-
Moderate with steep pitches	14	-	-	**50**	-	**23**	**29**	43	**52**	**63**	**52**	**67**	23	33	12
Sustained steep	12	-	-	-	-	**15**	**36**	44	16	18	38	25	**71**	**62**	**88**
Exposure to avalanche slopes on the ski line(s)															
None	47	**75**	**100**	**50**	**75**	15	-	1	**5**	-	-	-	-	-	-
Single small slopes, can produce Size ≤ 2.5 avalanches	12	**13**	-	-	**17**	**23**	7	5	**7**	5	**8**	**17**	-	5	-
Multiple small slopes, can produce Size ≤ 2.5 avalanches	19	13	-	**50**	-	**31**	**36**	44	**82**	**79**	44	**50**	13	10	-
Large slope(s), can produce Size ≥ 3.0 avalanches	22	-	-	-	8	**31**	**57**	50	7	16	48	33	**87**	**86**	**100**
Avalanche terrain hazards[b]															
Overhead hazard, regular avalanche cycles	16	-	-	-	**17**	**46**	7	24	9	5	**29**	**33**	**29**	**48**	**36**
Overhead hazard, large avalanche cycles only	10	**13**	**22**	-	**25**	-	-	22	14	21	15	**33**	19	**38**	**30**
Common trigger for overhead hazard	3	-	-	-	**8**	**8**	-	1	-	**3**	-	-	-	**5**	**3**
Unavoidable unsupported terrain shapes	7	-	-	-	**17**	**8**	7	2	-	-	2	-	**3**	-	**9**
High consequence terrain	3	-	-	-	-	**8**	**7**	2	-	-	2	-	**3**	-	**9**
Other hazards[b]															
Crevasse hazard, isolated	9	-	-	-	8	**23**	7	4	-	3	2	**8**	3	**5**	**9**
Crevasse hazard, widespread and/or unavoidable	2	-	-	-	-	-	**7**	2	-	-	2	-	-	-	**12**
Cornices directly affecting the ski line(s)	12	-	-	-	-	**31**	**21**	5	-	-	4	-	**16**	**14**	**6**
Tree well hazard	9	-	**22**	**50**	8	-	7	4	**16**	-	2	-	-	-	-
Open creeks, vent holes etc.	3	**13**	-	-	-	**8**	-	3	-	3	**6**	-	3	-	**6**

Table 2.1 Continued.

Attribute and levels		Group at NEH							Group at CMHGL							
		All	1	2	3	4	5	6	All	1	2	3	4	5	6	7
	Number of ski runs	59	8	9	2	13	13	14	227	44	38	48	12	31	21	33
Hazard potential (continued)																
Overall friendliness																
Very friendly		34	**88**	**44**	-	**58**	15	-	6	**25**	3	2	-	-	-	-
Friendly		19	13	11	**50**	**42**	8	14	21	**61**	**32**	13	8	3	5	-
Neutral		26	-	**44**	**50**	-	**46**	**29**	19	9	**34**	19	**58**	**23**	-	6
Unfriendly		16	-	-	-	-	**23**	**43**	43	5	32	**65**	33	**55**	**81**	**45**
Very unfriendly		5	-	-	-	-	**8**	**14**	11	-	-	2	-	**19**	10	**48**
Guide-ability																
Very easy		39	**50**	11	-	**50**	38	**50**	5	**7**	3	4	-	**13**	5	-
Easy		37	**50**	33	**50**	**42**	**46**	21	42	32	39	33	**50**	**45**	**52**	**61**
Difficult		22	-	**56**	**50**	8	15	**29**	52	**59**	**58**	**63**	50	35	43	39
Very difficult		-	-	-	-	-	-	-	1	**2**	-	-	-	**6**	-	-

[a] Only the ten most prominent types of terrain in both operations are shown.

[b] Only the five most prominent avalanche terrain hazards resp. other hazards in both operations are shown.

At the top of CMHGL's ski run hierarchy is Group 1, which includes 44 ski runs that were almost always open. Over the entire study period, these ski runs were open for skiing with guests on 93% of the days (seasonal values ranging between 86% and 98%, Table B2). They were closed due to avalanche hazard on only 3% of the days and either not discussed or closed due to other reasons than avalanche hazard on 4% of the days. At the other end of spectrum, the lowest group in the identified ski run hierarchy consists of 33 ski runs that were only open on 16% of the days (seasonal values ranging between 5% and 32%). These runs were closed due to avalanche hazard on 67% of the days and not discussed at all on 17% of the days.

Group characterization

The overall character of the ski terrain at CMHGL is dominated by steep tree skiing. While some runs start in the alpine, the vast majority of the 227 ski runs involves skiing through open slopes at tree line or open canopy snow forest below tree line. More than half of all the ski runs involve skiing through large avalanche paths formed from above. Most of the ski runs were characterized as either moderately steep but with steep pitches or as sustained steep. Many runs involve skiing with exposure to multiple small slopes capable of producing up to Size 2.5 avalanches or even to large slopes that can produce avalanches of Size 3.0 or greater.

The ski runs in the first three groups at CMHGL are predominantly located at tree line or below. The ski terrain of the 44 ski runs in Group 1 is characterized mainly as snow forest with open canopy, dense forest, or cut blocks (Figure 2.9). However, a few runs contain open slopes at tree line and both non-glaciated or glaciated sections in the alpine. Most of the ski runs are moderately steep, but half of them include steep pitches. Most of these ski runs involve exposure to multiple small avalanche slopes that can produce avalanches up to Size 2.5. Many ski runs in Group 1 provide good skiing experience and most them are almost always accessible. Overall, the terrain in this group is predominantly characterized as friendly and the ski runs are either high-efficiency production runs or runs that are safe and accessible under most conditions.

Group 2 includes 38 almost always accessible ski runs where the terrain is similar to the runs included in Group 1—open canopy snow forests and cut blocks at and below tree line—but also features more glades and more large avalanche paths formed from above (Figure 2.10). Most of the ski runs are moderately steep but include steep pitches with exposure to multiple small avalanche slopes that can produce avalanches up to Size 2.5. The friendliness of the ski runs in this group ranges from friendly to unfriendly, but most are perceived in the middle as neither friendly nor unfriendly. The ski runs in Group 2 generally provide good skiing experience and their operational roles are mainly high-efficiency production runs.

Figure 2.9 Examples of Group 1 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

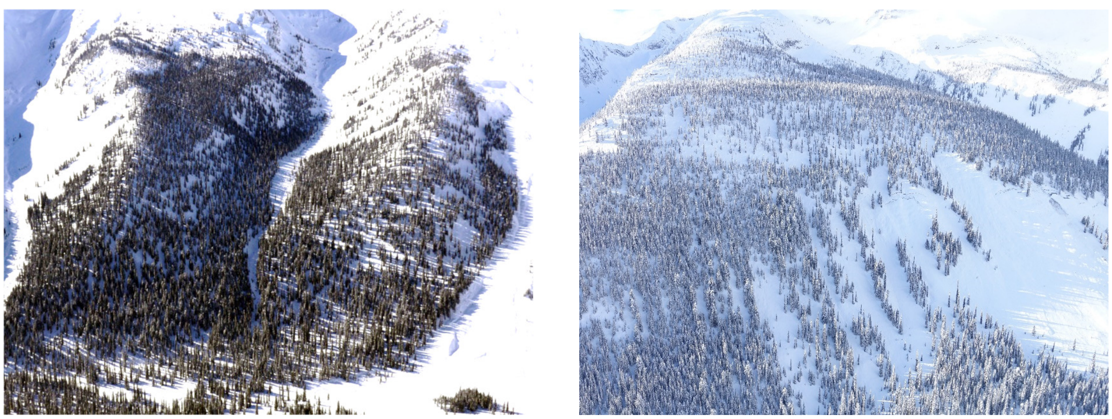


Figure 2.10 Examples of Group 2 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

Group 3, the biggest group in the CMHGL ski run hierarchy, consists of 48 ski runs that mainly have steep pitches or are sustained steep on open slopes at tree line (Figure 2.11). Skiing involves exposure either to multiple small or even large avalanche slopes on the ski lines and a third of the ski runs includes exposure to overhead hazard during regular avalanche cycles. Moreover, Group 3 is the first group with a substantial proportion of runs that require skiing through avalanche paths formed from above. While the runs included in this group cover the full range of perceived friendliness, most of them are perceived as being unfriendly. The ski runs of this group are considerably less accessible than the runs of the previous groups and approximately one fifth of the pickup locations can be exposed to overhead hazard during regular avalanche cycles. However, many of these ski runs provide very good skiing experiences.

Figure 2.11 Examples of Group 3 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

Group 4 consists of twelve ski runs that offer similar terrain as Group 3. However, these ski runs are less accessible than the runs of Group 3, and half of the pickup locations can be exposed to overhead hazard during regular avalanche cycles (Figure 2.12). The ski runs are predominantly moderately steep but include steep pitches and multiple smaller avalanche slopes.

Figure 2.12 Examples of Group 4 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

In addition to open slopes at tree line and many large avalanche paths, some of these ski runs include non-glaciated or glaciated alpine terrain with isolated crevasse hazard. Overall, the friendliness of these ski runs is predominantly perceived as neutral. Most of these ski runs provide a good skiing experience and are mainly used as a destination of a daily skiing circuit.

The three groups at the bottom of CMHGL's ski run hierarchy all consist of ski runs at tree line or above that also contain substantial glaciated sections. The ski runs of these three groups are predominantly sustained steep and skiers are mainly exposed to large slopes capable of producing avalanche of Size 3.0 or greater. In Group 5, the vast majority of the 31 ski runs are sustained steep and include large avalanche slopes (Figure 2.13). Almost all these ski runs include open slopes at tree line, large avalanche paths, and some glaciated alpine terrain. Many of the ski lines on these runs are exposed to overhead avalanche hazard during regular avalanches cycles and some have the potential of being hit by cornices from above. Most of these ski runs are perceived as unfriendly, but they provide good skiing. Generally, accessing these ski runs requires flight conditions to line up or even be perfect. However, only some pickup locations are exposed to overhead hazard during regular avalanche cycles.

Figure 2.13 Examples of Group 5 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

Group 6 includes 21 ski runs that are mainly sustained steep with exposure to large avalanche slopes on the ski lines (Figure 2.14). Their terrain consists of open slopes at tree line, many large avalanche paths, and some glaciated alpine terrain. Most prominently, overhead hazard during regular avalanches cycles is a concern for almost half of the ski runs in this group. In addition, some of the ski runs have overhead cornices directly affecting the ski lines. This group of ski runs is perceived as unfriendly, but it provides very good skiing. Just like in Group 5, flight conditions need to line up or even be perfect for accessing these runs, but many of the pickup locations in Group 6 are also exposed to overhead hazard.

Figure 2.14 Examples of Group 6 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

Group 7 offers the most severe, least accessible, but also some of the best skiing terrain within the tenure of CMHGL (Figure 2.14). The 33 ski runs in this group are predominantly sustained steep and all of them involve skiing on slopes that can produce large avalanches of Size 3.0 or greater. Flying conditions must be perfect to consider the runs of this group and many of the pickup locations are threatened by avalanches during regular avalanche cycles. Besides skiing on open slopes at tree line and through large avalanche paths, both non-glaciated and glaciated alpine terrain, this is the only group of runs that includes extreme alpine faces. The most frequently mentioned hazards in this group are unavoidable and unsupported terrain shapes, high consequence terrain when caught in an avalanche, and crevasse hazard (especially widespread and/or unavoidable). Overall, the ski runs in this group are characterized as very unfriendly. From an operational perspective, these ski runs represent destinations of a daily skiing program or are only considered when “conditions are bomb-proof”. Even though many of these ski runs provide very good or even exceptional skiing, these runs are only rarely skied.

Figure 2.15 Examples of Group 7 ski runs at CMHGL.
Photo: CMHGL. Reproduced with permission.

Inter-seasonal variations

The cluster analysis based on the typical seasonal time series shows that in most seasons several groups of runs were coded similarly (Figure 2.8b, seasonal groups indicated with black boxes). On average, the seasonal ski run hierarchy consists of five groups but ranges from only four to all seven groups that were identified over the entire period. While the seasonal clustering at NEH only revealed seasonal groupings at the top of the ski run hierarchy, the analysis at CMHGL showed seasonal groupings at all levels. Groups 1 and 2 were grouped together in three of eleven seasons (2009, 2016, and 2017). Groups 2 and 3 had very similar seasonal run list coding patterns only in 2007 and 2012. On the other hand, Groups 3 and 4 showed strong similarities in how they are coded and were grouped together in five seasons (2008, 2010, 2015, 2016, and 2017). These two groups of ski runs have similar characteristics in terms of skiing terrain and hazard potential on the ski run, but they differ in accessibility as the pickup locations in Group 4 are characterized as being more exposed to overhead avalanche hazards. The step from Group 4 to Group 5 emerges as a strong transition in the ski run hierarchy at CMHGL as these two groups were only combined once (2007). Nearly all the ski runs in Group 5 consist of sustained steep ski runs at tree line or in glaciated alpine with exposure to large avalanche slopes that can produce size 3.0 avalanches or greater. Groups 5 and 6 have very similar run list coding patterns and were grouped together in six of the eleven seasons (2008, 2009, 2010, 2015, 2016, and 2017). They offer very similar skiing terrain, but the pickup locations of Group 6 are characterized as being more exposed to overhead avalanche hazard. The step between Group 6 and Group 7 in the CMHGL ski run hierarchy marks a second significant transition as they were consistently coded differently and only grouped together once (2015). Group 7 is the only group that contains ski runs that were either characterized as extreme alpine faces or have widespread/or unavoidable crevasses.

2.4. Discussion

2.4.1. Customized terrain classes and ski run hierarchy

We identified distinct groups of ski runs based on run list ratings (i.e., revealed terrain preferences) that represent the avalanche risk management expertise of the local guiding teams. In comparison to existing terrain classification systems (e.g., ATES) that divide terrain into a small number of universal classes, our analysis of run list ratings identifies high-resolution ski run hierarchies that offer a more detailed terrain description and reflect the variety and relative characteristics of available local terrain in a more meaningful way. The local nature of the ski run hierarchy is illustrated by the fact that the characteristics of the most frequently open groups of runs differ greatly between the two operations included in this study. At NEH, this group is predominantly characterized by gentle terrain with no exposure to avalanche slopes and includes ski runs in all elevation bands. At CMHGL, the most frequently open group mainly consists of ski runs below tree line that include steep pitches and exposure to multiple small slopes capable of producing avalanches up to Size 2.5. We interpret this difference to reflect variations in the available terrain and operational practices at the two participating operations.

The terrain characteristics associated with the emerging ski run hierarchies generally agree with our existing understanding of what determines the severity of avalanche terrain (see, e.g., McClung & Schaerer, 2006; Statham et al., 2006). Both steepness and size of the avalanche slopes skied emerged as strong drivers behind the observed terrain groups at both operations. The identified ski run hierarchies are also generally consistent with the nature of the terrain classes described in the ATES system (Statham et al., 2006). The ski runs that were less frequently open were generally characterized as having more unavoidable unsupported terrain shapes, included more convoluted terrain, had more open planar slopes capable of producing large avalanches, and were characterized more frequently as having high consequence terrain. Ski runs with large avalanche paths formed from above or overhead hazard during regular avalanche cycles were also generally associated with groups that are less frequently open.

However, our analysis also revealed some notable differences that, at first glance, may seem inconsistent with the established understanding of avalanche terrain severity. At NEH, the most obvious example is that the group of most frequently open ski runs contains runs that include glacier travel. In the ATES system, the presence of glaciated terrain automatically puts ski runs into the most severe terrain class (Statham et al., 2006). Another example at NEH is Group 5, which includes a few runs without any avalanche related hazards on the ski line itself. However, these runs are often closed because the pickup locations can be affected by overhead avalanche hazard during regular avalanches cycles. At CMHGL, a noteworthy exception is Group 1, which contains seven ski runs below tree line that are sustained steep and have multiple slopes that can produce avalanches up to size 2.5. While the physical terrain characteristics of these runs would not necessarily suggest that they belong into the group of runs that are open most often, the reason for their classification is the fact that they are actively maintained by the guiding team. Guides intentionally choose to ski these runs on a regular basis to destroy any potential weak layers before they are buried and become a risk management problem (R. Atkins, personal communication). This risk management practice allows CMHGL to have these runs open more often than their physical terrain characteristics would suggest and to ski steeper terrain than on unmanaged ski runs under similar hazard conditions.

These observations clearly demonstrate the ability of our approach to capture the nuanced terrain selection and risk management expertise of guides and turn them into insightful ski run hierarchies within local contexts. The groups of similar types of ski runs reflect terrain severities at individual mechanized skiing operations in relation to the available terrain, local snow and avalanche climate, and operational practices. Characterizing the identified groups with hazard considerations beyond the ones that just affect the ski lines (e.g., exposure of the pickup locations to overhead avalanche hazard) offers a more comprehensive description of their severity. This makes the derived ski run hierarchy more meaningful for operational use and the development of useful decision aids.

2.4.2. Seasonal variations in long-term operational ski run hierarchies

Our analysis of seasonal variation in ski run hierarchies highlights the necessity of long-term records for studying patterns in avalanche terrain selection in a meaningful way. While the overall structure of the ski run hierarchies was consistent throughout the entire study period, our within-season ski run group clustering revealed considerable season to season variabilities due to the specific meteorological character of a winter or particular sequences of weather events.

At NEH, the observed seasonal variations illustrate the influence of the particular seasonal weather on ski run choices. While the first three groups of the ski run hierarchy at NEH are usually coded similarly, the ski runs in Group 2 were open on fewer days than average during the 2014 and 2015 winters (79% resp. 61% compared to 86%). Many regions in western Canada reported record low snowpack heights for the 2014 winter, and the warmer-than-usual 2015 winter was characterized by below average snowfall and well above average rainfall (SFU Avalanche Research Program, 2018). As a result, the lower elevation ski runs of Group 2 were not discussed or were closed for other reasons than avalanche hazards (e.g., marginal snowpack, increased skiing hazards for the guests) more than a third of the days during the 2015 season. At the same time, the alpine ski runs of Groups 5 and 6 were open more days than usual due the longer fair-weather periods during that season and favorable avalanche conditions in the alpine.

At CMHGL, Groups 1 and 2 are usually coded differently, but they were managed more similarly during the winter seasons of 2009, 2016, and 2017. In 2009, the similarity is due to a major avalanche cycle that occurred in early January when most of the ski runs in both groups were closed for a few days. This cycle was due to the combination of a persistent weak layer buried early in December and one of the season’s largest snowfalls. Many avalanches during this cycle ran to valley bottoms and, in some cases, beyond historical runout zones (SFU Avalanche Research Program, 2018). In 2016 and 2017, the similarity between the two groups was due to Group 2 ski runs being open considerably more often than normal because the forested and gladed terrain of Groups 1 and 2 ski runs was particularly well suited for the conditions of these two seasons. The 2016 season started unseasonably warm with freezing levels reaching up to 2,300 m in December. The subsequent clear and stable conditions in early January produced a persistent weak interface in the snowpack that dominated the nature of avalanche hazard during that winter. The 2017 winter started with some of the season’s coldest temperatures, unsettled conditions, and continued snowfall, forming a mid-December interface that would remain a major feature of the snowpack for the rest of the season. The conditions during these two winters clearly favoured the use of Group 1 and 2 ski runs, which were consistently open throughout the season, while the runs of other groups were closed as soon as the early season interfaces were buried.

2.4.3. Additional factors affecting ski run hierarchies

In addition to offering insight on how avalanche hazard characteristics affect run list ratings, our analysis also highlights how non-avalanche hazard related factors affect ski run choices. At NEH, for example, the ski run “Evil Twin Sister”, was assigned to Group 5, which is open only about half of the time. While most ski runs in this group involve skiing through substantially severe avalanche terrain that is also exposed to overhead hazard, “Evil Twin Sister” is a gentle ski run with no exposure to avalanche hazard. The reason for this unexpected grouping is likely the fact that “Evil Twin Sister” only provides a fair skiing experience and might therefore be discussed less frequently than other ski runs of similar terrain severity that offer better skiing experiences. In general, however, the quality of the skiing experience tends to correlate well with the ski run hierarchies that emerged at both participating operations. While the more severe ski runs at each operation are only rarely open, they are often described as offering exceptional skiing experience for guests.

Our results at CMHGL show that the flying conditions required for accessing runs is also an important consideration during the run list rating process. Overall, accessibility strongly decreases throughout the ski run hierarchy at CMHGL, and pickup locations that are threatened from above during regular avalanche cycles are a common concern in the run groups lower on the ski run hierarchy. Since our NEH analysis only included runs from their core operating area, this pattern did not emerge to a similar degree for NEH. However, it is typical that the runs located in drainages away from their core operating area are only discussed when the expected flying conditions allow guides to access these places in the first place (C. Israelson, personal communication). These examples demonstrate that patterns in revealed terrain choices are the result of complex interactions between avalanche hazard factors and other operational considerations. While some of these patterns reflect natural collinearities (e.g., severity of avalanche terrain and ease of access), it is critical to consider non-avalanche related factors when interpreting patterns in revealed terrain choices and using the extracted knowledge for developing operational avalanche risk management tools and decision aids.

2.4.4. Limitations

While our analysis offers valuable insight about the ski run hierarchy at the two participating operations, we acknowledge that our characterizations of the identified groups of ski runs were only based on the perspective of a single experienced guide at each location. Since our characterizations not only included assessments of measurable physical characteristics, but also more intangible aspects and subjective assessments that integrate a wide variety of factors and personal experiences, it is possible that these perspectives might vary among guides. However, the opening or closing of ski runs during the daily guides' meeting is a consensus-based group decision, and we believe that the opinions expressed by senior guides with extensive terrain experience under a wide variety of conditions likely carry more weight than the perspective of more junior guides. We therefore believe that the senior guides' assessments offer a valid general characterization of the terrain that is sufficient for the present analysis.

2.5. Conclusions

We used multi-season datasets of daily run list ratings at two commercial mechanized backcountry skiing operations to identify groups of similarly treated ski runs and arrange them into operation-specific ski run hierarchies that reflect the local terrain expertise and avalanche risk management practices in the context of the available terrain and local snow and avalanche climate conditions. To characterize the revealed ski run classes in detail, we had a senior lead guide at each operation describe the nature of each of the ski runs included in the study with respect to access, type of terrain, skiing experience, operational role, hazard potential, and guide-ability. While earlier studies exploring the terrain management expertise of mountain guides at the run scale were confined to hypothetical decision situations (Grímsdottír, 2004; Haegeli, 2010b) we present a flexible approach for identifying patterns in actual risk management decisions. To our knowledge, this is the first time that large operational backcountry skiing datasets have been used to identify patterns in professional terrain selection and formally extract the operational avalanche risk management expertise at the run scale.

The results of our study offer numerous contributions for future backcountry avalanche risk management research and development projects. Since a meaningful representation of terrain is critical for properly linking backcountry terrain decisions to avalanche hazard and weather conditions, the operation-specific ski run classes identified in our study provide an exciting opportunity for exploring this link. Our method of identifying ski run classes aims to overcome some of the challenges that have prevented the adoption of terrain classification systems in mechanized skiing operations in the past. While the categories of existing avalanche terrain classification system have been too broad and generic for providing meaningful assistance to professional guides, our method of identifying ski run classes aims to overcome these challenges by identifying a larger number of operation-specific terrain classes organized in ski run hierarchies that offers a much more nuanced and applied perspective of the terrain.

Even though some of the identified ski run classes might need to be further split to properly account for special risk mitigation practices (e.g., deliberate frequent skiing to manage formation of persistent weak layers), correlating avalanche conditions to the identified ski run classes has the potential to offer useful insight for the development of evidence-based decision aids that can assist guiding teams during their morning meetings. Since the patterns identified by our analysis reflect actual risk management practices that have been used at participating operations for many years, the ski run hierarchies developed through our approach are more closely linked to the risk management decisions that the classification aims to support than are existing terrain classification systems. Furthermore, the reflective nature of our approach and the fact that the emerging classification is grounded in past local risk management decisions has the potential to increase guides' acceptance and trust in the developed risk management decision aids.

While revealed terrain preference data from GPS tracking units (e.g., Hendrikx et al., 2016; Thumlert & Haegeli, 2018) offer promising avenues for learning about professional avalanche risk management expertise at spatial scales below the run level, it is important to remember that terrain decisions in mechanized skiing operations are made in stages (Israelson, 2013, 2015). Since small-scale terrain choices are only made within runs that were previously considered open for guiding, the patterns captured in the operation-specific ski run hierarchies presented in this study offer critical context for the meaningful analyses of GPS data. Our study also highlights that having long-term datasets is critical for identifying meaningful patterns as the particularities of individual winters can affect observed choices considerably. Finally, our study reiterates that it is difficult to relate terrain choices to physical terrain characteristics alone (Haegeli &

Atkins, 2016). Examples of important other factors that emerged from our study include exposure of pickup locations to overhead hazard, accessibility of ski runs, previous skiing on runs, and the type and quality of the guest skiing experience. To identify insightful patterns and analytically isolate the effect of avalanche hazard, it is critical for future research to examine revealed terrain preference data within the full array of influencing factors and operational constraints.

2.6. Acknowledgments

We would like to thank Canadian Mountain Holidays Galena and Northern Escape Heli Skiing for their willingness to participate in this study. Especially, we would like to thank Clair Israelson and Roger Atkins for their contribution to this work by taking the time and characterizing the ski runs in their tenures. The NSERC Industrial Research Chair in Avalanche Risk Management at Simon Fraser University is financially supported by Canadian Pacific Railway, HeliCat Canada, Mike Wiegele Helicopter Skiing, and the Canadian Avalanche Association. The research program receives additional support from Avalanche Canada and the Avalanche Canada Foundation. Reto Sterchi was also supported by SFU’s Big Data Initiative KEY and a Mitacs Accelerate fellowship in partnership with HeliCat Canada.

Chapter 3.

Exploring the relationship between avalanche hazard and large-scale terrain choices at a helicopter skiing operation - Insight from run list ratings

This chapter presents the content of a manuscript in preparation for submission to a peer-reviewed journal, co-authored with Pascal Haegeli and Patrick Mair. As the primary author of this manuscript, I co-led the design of this research with Pascal Haegeli and was responsible for the majority of the data analysis and writing. Patrick Mair provided guidance on the statistical analysis.

Abstract

While guides in mechanized skiing operations use a well-established terrain selection process to limit their exposure to avalanche hazard and keep the residual risk at an acceptable level, the relationship between the open/closed status of runs and environmental factors is complex and has so far only received limited attention from research. Using a large data set of over 25,000 operational run list codes from a collaborating mechanized skiing operation, we applied a general linear mixed effects model to explore the relationship between acceptable skiing terrain (i.e., status open) and avalanche hazard conditions. Our results show that the magnitude of the effect of avalanche hazard on run list codes depends on the type of terrain that is being assessed by the guiding team. Ski runs in severe alpine terrain with steep lines through large avalanche slopes are much more susceptible to increases in avalanche hazard than less severe terrain. However, our results also highlight the strong effects of recent skiing on the run coding and thus the importance of prior first-hand experience. Expressing these relationships numerically provides an important step towards the development of meaningful decision aids, which can assist commercial operations to manage their avalanche risk more effectively and efficiently.

3.1. Introduction

Snow avalanches are the most significant hazard affecting daily operations in mechanized skiing in Canada (Bruns, 1996). Walcher et al. (under review) report that between 1997 and 2016 avalanches accounted for 77% of the overall natural hazard mortality in mechanized skiing in Canada. Operations manage this risk by continuously assessing the local avalanche hazard conditions throughout the winter and carefully choosing appropriate terrain and travel procedures to limit their exposure to avalanche hazard and keep the residual risk at an acceptable level while still providing a high-quality skiing experience.

In Canada, mechanized skiing operations select terrain for skiing by following a well-established, iterative process. This risk management process has been described as a series of filters occurring at multiple spatial and temporal scales (Israelson, 2013, 2015) that progressively eliminate skiing terrain from consideration. The daily process starts with a hazard assessment in the morning, which results in a large-scale avalanche forecast for the entire tenure. The first filter of eliminating terrain is the creation of the so-called “run list”, which occurs during the guides’ meeting each morning. During their meeting, guiding teams go through their inventory of predefined ski runs and collectively decide which runs are open or closed for skiing with guests under the expected avalanche hazard conditions. It is important to note that the scale and spatial delineation of ski runs can vary considerably from operation to operation, and there may be multiple distinct ways of skiing a run. However, ski runs are the decision units at this stage of the risk management process. The large-scale, consensus-based “run list” that emerges from the morning meeting is a critical planning tool that sets the stage for the skiing program of the day by eliminating certain runs from consideration. Over the course of a skiing day, terrain choices are further refined and adapted in response to direct field observations. In most helicopter skiing operations, helicopters serve multiple groups of skiers, each of them led by a guide. It is common practice that the guide of the first group serviced by the helicopter (known as the ‘lead guide’) decides what runs the groups of this helicopter ski (second filter). How exactly a particular run is skied is the responsibility of the guide of each group (third filter). This sequence of (1) run list established by entire guiding team, (2) run choice made by lead guide and (3) ski line choice within run made by individual guide, highlights the hierarchical and iterative nature of the terrain selection process. At each filter level, the decisions are adjusted based on an up-to-date avalanche hazard assessment. While avalanche hazard is one of the most critical factors in this process, other factors such as weather and flying conditions, flight economics, skiing quality, guest preferences and skiing abilities also affect the selection and sequencing of skied terrain (Israelson, 2015). This terrain selection process is repeated every day and over the course of the season, a guiding team constantly updates their terrain choices in response to the observed changes in avalanche hazard conditions.

While the steps of the terrain selection process are well defined and easy to describe, the relationship between environmental factors and the open/closed status of runs is complex and has so far only received limited attention from research. Grímsdottír (2004) and Haegeli (2010b) identified critical terrain and avalanche hazard factors contributing to the terrain decisions at the run scale but did not examine the relationship between avalanche hazard conditions and run list codings. While Hendrikx et al. (2016) and Thumlert and Haegeli (2018) studied the association between small-scale terrain choices and avalanche conditions by analyzing patterns in GPS tracks, they did not consider the hierarchical and temporal context that the run list (or similar earlier large-scale terrain choices) sets for the smaller-scale terrain choices.

The objective of our study is to address this knowledge gap by explicitly examining the relationship between acceptable skiing terrain (i.e., it being open or closed for guiding) and avalanche hazard conditions at the run scale using historic avalanche hazard assessments and run list ratings from a commercial helicopter skiing operation. Focusing our analysis on examining existing professional terrain management practices allows us to tap into the tacit risk management expertise of guiding teams and extract the information on relevant patterns in a way that facilitates learning from the past and developing decision support tools that can aid the terrain selection process in a professional context in a meaningful way.

3.2. Methods

3.2.1. Study site

For this study, we collaborated with Northern Escape Heli Skiing (NEH), a commercial helicopter skiing company based out of Terrace, BC, Canada (Figure 3.1). NEH's operating tenure is in the Skeena Mountains and spans an area of nearly 6,000 km^2. The skiing terrain ranges from 500 m to 2000 m above sea level covering all three elevation bands (alpine, treeline and below treeline). While their entire tenure has 260 established ski runs, much of their skiing is focused on approximately 60 runs in their home drainage, which is the focus of our study. The character of the local snow climate is maritime with storm slab avalanche problems during or immediately following storms being the primary avalanche hazard concerns (McClung & Schaerer, 2006; Shandro & Haegeli, 2018).

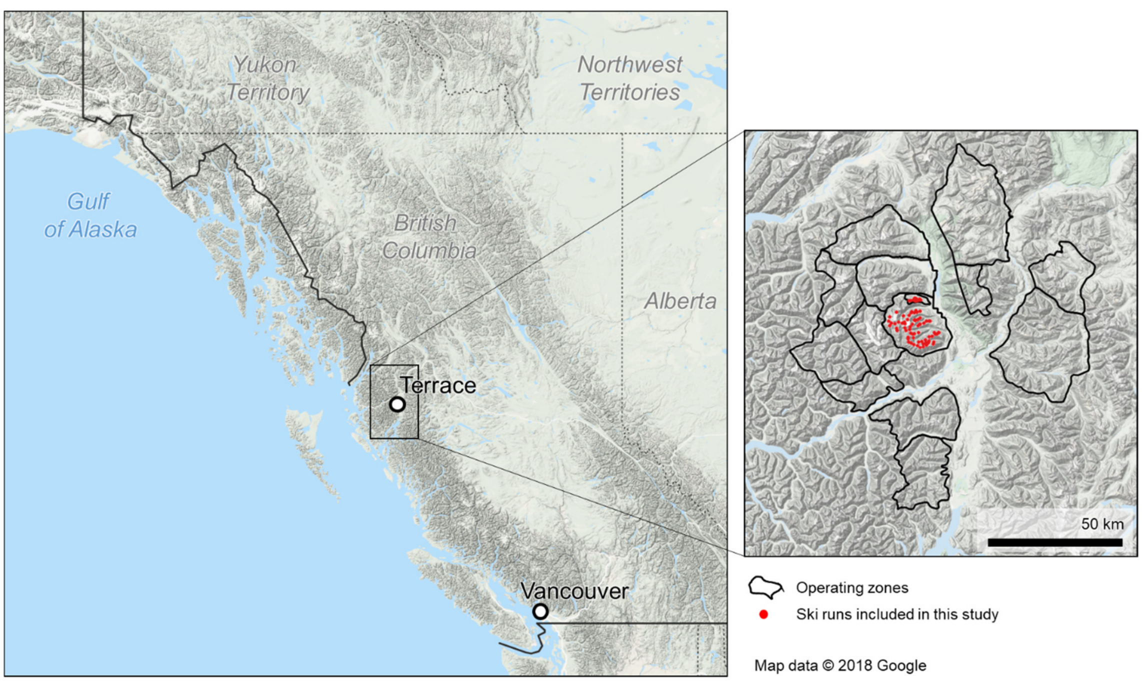


Figure 3.1 Geographical overview of the study site with location of the tenure region and the ski runs for one of the operating zones included in this study.

3.2.2. Data set

The primary dataset used in this study consists of daily run list and avalanche hazard information for the six winter seasons 2012/13 to 2017/18 (517 operational days between December 1 and March 31 of each season). The run list dataset consists of 26,488 individual run ratings in total, one for every run on each of the 517 operational days. At NEH, the guiding team codes runs as either “Open for guiding” (i.e., the run is safe to ski with guests), “Closed for guiding due to avalanche hazard” (i.e., any member of the guiding team is not comfortable with taking guests onto that run), “Closed for guiding for other reasons than avalanche hazard” (e.g. other mountain hazards such as crevasses, open creeks, ski quality) or “Not discussed” (i.e., ski runs in zones not considered are automatically closed for skiing that day).

NEH’s avalanche hazard assessment process follows the Conceptual Model of Avalanche Hazard (CMAH, Statham et al., 2018), which provides a framework that structures the process around the identification and characterization of avalanche problem. Avalanche problems represent actual operational concerns about potential avalanches that can be described in terms of the type of avalanche problem, the location in the terrain where the problem can be found, the likelihood of associated avalanches, and their destructive size. The concept of avalanche problem type plays a central role in the CMAH as it represents the idea that from a risk management perspective, there are distinct types of avalanches that emerge from specific snowpack structures and weather events (Statham et al., 2018). For example, a *Wind Slab Avalanche Problem* presents a different pattern of avalanche release than a *Deep Persistent Slab Avalanche Problem*. *Wind Slab Avalanche Problems* typically form cohesive slabs of wind-deposited and broken snow-particles that are created on lee-ward (downwind) slopes or in cross-winded areas where the winds blow across the terrain. Wind slabs are often limited in size and tend to stabilize within one or two days, but the instability may persist longer in cold temperatures. On the other hand, *Deep persistent slabs* form when a persistent weak layer becomes deeply buried under a thick slab of snow. Its susceptibility is highly dependent on how deeply buried the weak layer is. Remote triggering from shallow or weak spots in the snowpack is common and makes this avalanche problem type particularly challenging. Typically, such instabilities persist for extended periods of time. They are highly unpredictable and destructive; essentially not survivable. Overall, Statham et al. (2018) describe eight distinct types of avalanches problems (*Deep*

Persistent Slab Avalanche Problem, Persistent Slab Avalanche Problem, *Storm Slab Avalanche Problem*, *Wind Slab Avalanche Problem*, *Dry Loose Avalanche Problem*, *Wet Loose Avalanche Problem*, *Wet Slab Avalanche Problem*, *Cornice Avalanche Problem*) that differ in their development, avalanche activity patterns, how they are best recognized and assessed in the field, and what risk management strategies are most effective for managing them.

After the guides have identified the types of their avalanche problems, they describe their locations in the terrain in terms of elevation bands (alpine, treeline and below treeline) and aspect ranges. The likelihood of avalanches includes both the sensitivity to triggers and the spatial distribution and is expressed on an ordinal scale using the qualitative terms 'unlikely,' 'possible,' 'likely,' 'very likely' and 'almost certain' (Statham et al., 2018). Destructive size is assessed according to the Canadian avalanche size classification (Canadian Avalanche Association, 2014) on a scale ranging from 1.0 (relatively harmless for people) to 5.0 (largest snow avalanche known for a given path, which could destroy a village or a large forest area of approximately 40 hectares). Guides express their uncertainty in hazard assessments by specifying ranges of likelihood and size for each avalanche problem (minimum, typical, and maximum for both parameters). The hazard assessments for each elevation band are concluded by summarizing the overall hazard level that emerges from the combined avalanche problems with a single hazard rating on an ordinal scale from 1 (Low) to 5 (Extreme, Statham et al., 2010).

To describe the general nature of the ski runs included in this study, we employed the ski run classification developed by Sterchi and Haegeli (under review; Chapter 2). In comparison to existing terrain classification systems with small numbers of universal terrain classes (e.g., ATES; Statham et al., 2006), Sterchi and Haegeli's approach identifies high-resolution, operation-specific ski run hierarchies based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences). Sterchi and Haegeli first identified groups of ski runs by clustering similarly coded ski runs over the course of several winter seasons. Subsequently, they arranged the identified groups into a hierarchy that ranges from runs that are almost always open and runs that are only open when conditions are favourable. To better understand the nature of the revealed ski run classes, the authors had a senior lead guide at each participating operation provide a comprehensive but structured description of their ski runs with respect to access, type of terrain, skiing experience, operational role, hazard potential, and guide-ability. Since this ski run classification is based on past operational risk management decisions, it reflects the local terrain expertise and avalanche risk management practices in the context of the available terrain and local snow and avalanche climate conditions (Sterchi & Haegeli, under review).

Sterchi and Haegeli (under review; Chapter 2) identified six distinct ski run classes at NEH. To illustrate the nature of the skiing terrain included in this study, Figure 3.2 shows the average seasonal percentage of run code ‘open’ for each ski run grouped into the six classes. While the severity of terrain generally increases from Class 1 to Class 6, the groupings also reflect other run characteristics like accessibility, quality of skiing experience and operational practices.

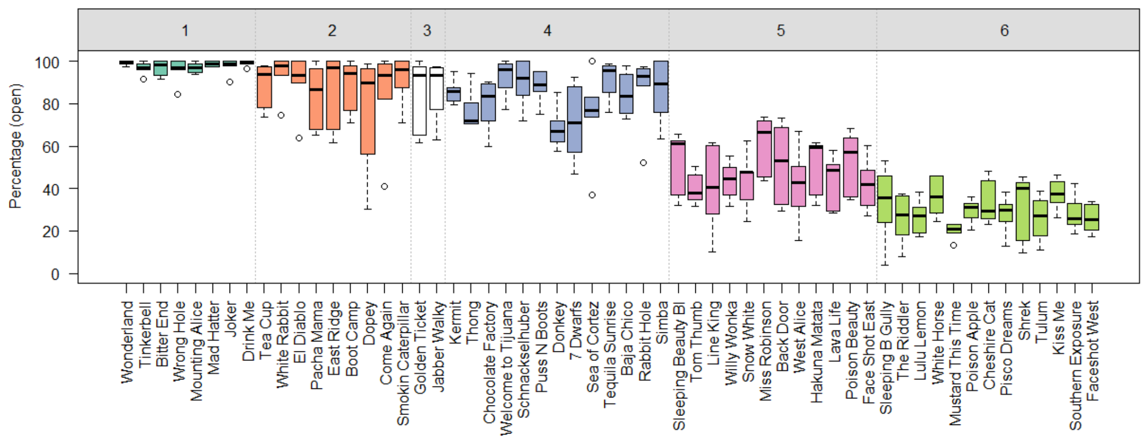


Figure 3.2 **Average seasonal percentage of run code ‘open’ for the 57 ski runs during the six seasons 2012/13 to 2017/18 with the six identified classes of similarly managed ski runs (Sterchi & Haegeli, under review). Due to the small group size and their outlier characteristics, the two runs of Class 3 were not included in the present analysis.**

The first three classes generally consist of easily accessible and mostly gentle ski runs with no or only limited exposure to avalanche slopes. Most of the skiing is through open slopes at tree line, open canopy snow forest below tree line, or non-glaciated or glaciated alpine. The main difference between the first two classes is that the runs of Class 1 provide a better skiing experience. Since Class 1 runs are more attractive, they are typically skied more often, guides have a better handle on the local conditions, and hence the runs are coded open more consistently. The two runs included in Class 3 are of similar general character, but they are located at lower elevations, which makes them more susceptible to rising freezing levels. Due to the small group size and their outlier characteristics, we excluded them from the present analysis. While most of the ski runs of the first three groups are at tree line and below, Class 4 to 6 predominantly consist of alpine terrain. Class 4 consists of ski runs in gentle alpine terrain or open slopes at tree line where most ski lines do not cross any avalanche slopes. These ski runs are often accessible and provide generally a good skiing experience with easy or moderately challenging skiing. However, some of the ski runs can be exposed to overhead avalanche hazards during regular avalanche cycles. The ski runs included in Class 5 are also located in the alpine but are substantially steeper and cross avalanche slopes more frequently than the runs of Class 4. Furthermore, almost half of the ski runs in Class 5 can be directly affected by overhead hazard during regular avalanches cycles and many pickup locations are threatened by overhead avalanche hazard during large avalanche cycles. While skiing on these runs was characterized as moderately challenging, they offer very good or even “life-changing” skiing experiences for guests. Class 6, the highest group in the NEH ski run hierarchy, mainly consists of runs in the most serious alpine terrain skied at NEH. The runs are rarely skied but can play an important operational role when conditions are appropriate. Most of these runs have moderately steep or steeper slopes that can produce avalanches of Size 3.0 or bigger and many pickup locations are exposed to overhead avalanche hazard during regular avalanche cycles. However, they provide good or very good skiing experiences for the guests.

3.2.3. Statistical analysis

Since our dataset consists of run list codes that were repeatedly recorded for the same runs over the course of several winters, traditional regression models that require observations to be independent from each other are inappropriate for our analysis (Long, 2012). Mixed effects models are an extension of traditional regression models that allow for heterogeneity, nested data, temporal or spatial correlation in longitudinal and/or clustered datasets by relaxing some of the necessary assumptions (Bolker et al., 2009; Harrison et al., 2018; Zuur et al., 2009). To overcome the issue of repeated measures and nested data, mixed effects models include both fixed and random effects in the regression equation. The fixed effects, which are equivalent to the normal intercept and slope estimates in traditional regression models, capture the relationship between the predictor and response variables for the entire dataset. While traditional regression models assign the remaining unexplained variance in the data (i.e., randomness) entirely to the global error term, mixed effect models represent the portions from the unexplained variance that originate from groupings within the dataset in random effects. Thus, random effects can highlight how groups within the dataset deviate from the overall pattern described by the fixed effects. Consistent with fixed effects, random intercepts and slopes can be estimated. While random intercepts explain how the average conditions within groups deviate from the average conditions across the entire dataset, random slopes capture differences in the relationship between the predictor and response variables. The overall response of a particular grouping to the predictor variables can therefore be described as the linear combination of the overall fixed effects and the grouping-specific random effects.

To examine the acceptability of runs (i.e., being open or closed) under different hazard conditions, we regressed their daily run list codes against the hazard situation with the runs' terrain characteristics, their past use and their run list codes of the previous day as covariates (Figure 3.3).

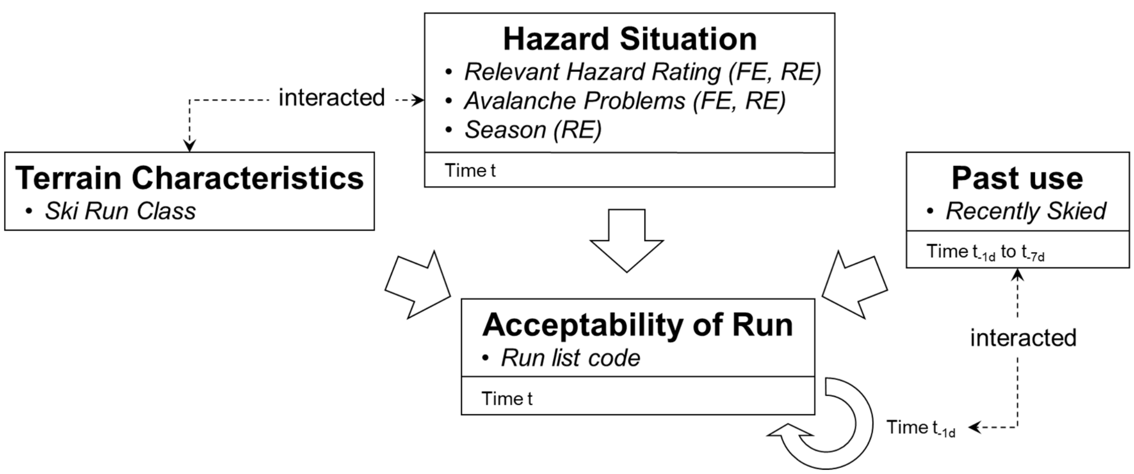


Figure 3.3 Illustration of the model.
The model included variables describing the hazard situation, the terrain characteristics of a ski run, and its past use to examine their relationships with the acceptability of a run (e.g., it being coded "open"). To account for the iterative character of the terrain assessment process in mechanized skiing the model also included the run list code of the previous day. In addition to the fixed effects (FE), we included random effects (RE) for hazard rating and avalanche problems potentially highlighting effects on the run-level that go beyond the effect on the terrain class. Similarly, seasonal random effects were included in the model to account for the character of each winter season.

We recoded the categorical run list ratings before fitting the regression model. Run list codes indicating that a run was open (i.e., “Open for guiding”) were recoded to 1 whereas run list codes indicating that a run was closed because of avalanche concerns (i.e., “Closed for guiding due to avalanche hazard”) were coded as 0. Run list codes indicating that a run was not considered for any other reasons (i.e., “Closed for guiding for other reasons than avalanche hazard”, “Not discussed”) were excluded from the analysis. The simplified run list codes allowed us to focus our analysis on the effect of avalanche hazard on open and closed status of runs.

In its basic form, the logistic model uses the logistic function to model the relationship between a binary dependent variable (e.g., 1 and 0, true and false, present and absent, open and closed) and one or more predictors x_i (Cox, 1958). In such a model, the probability of item k to be of value "1" can be expressed with

$$Prob\ (value_k = "1") = \frac{1}{1+e^{-\left(\beta_0 + \sum_{i=1}^{j} \beta_i f_i(x_{ik})\right)}}.$$

In this equation, β_0 is the intercept, β_i are the regression parameter estimates associated with the functional forms $f_i()$ (e.g., transformations such as coding a categorical variable into dichotomous variables) of the predictors x_i included in the model. The subscript k indicates that probability calculation for item k depends on its particular characteristics as described by the predictor values x_{ik}. The linear combination of the predictors multiplied with the parameter estimates β_i in the exponent in the denominator represents the log-odds (the logarithm of the odds) of the value labelled “1”. The components of the equation can be interpreted as follows: The intercept β_0 represents the log-odds when all predictors are zero. A parameter estimate of β_1 = 1 means that increasing x_{1k} by 1 increases the log-odds by 1 or multiplies the odds by a factor of e^1. This is referred to as the “effect” of the predictor x_{k1}. Similarly, a parameter estimate of β_2 = 2 means that increasing x_{2k} by 1 increases the log-odds by 2 or multiplies the odds by a factor of e^2. Thus, the effect of x_{2k} on the log-odds is twice as great as the effect of x_{1k}.

Avalanche hazard conditions were represented in the model with the *Relevant hazard rating* of the day and the *Types of avalanche problems* present. Since ski runs can cross several elevation bands (e.g., a ski run can start in the alpine, include skiing at treeline and have its pickup location below treeline), multiple avalanche hazard ratings might apply. To circumvent this issue in our analysis, we derived a *Relevant hazard rating* of the day for each run by taking the highest hazard rating of the elevation bands crossed by the run. *Types of avalanche problem present* was implemented in the model as eight binary covariates (1: present; 0: absent) each representing one of the eight avalanche problems specified by the CMAH. Because the avalanche problems are also assessed for each elevation band separately, we derived relevant daily avalanche problem values for each run similarly to the relevant hazard rating described above. We only included avalanche problems that were characterized with a maximum destructive size of at least Size 2.0 in our analysis dataset, because avalanches of Size 1.0 to 1.5 are considered relatively harmless to people (McClung & Schaerer, 2006). Because of the small number of cases, we also excluded avalanche problems where the maximum likelihood was assessed lower than “unlikely”. To allow our model to account for the possibility that the effect of avalanche hazard on the acceptability of a run being open might differ among terrain types, we interacted the *Relevant hazard rating* and all eight binary variables for *Types of avalanche problem present* with *Ski Run Class*.

To account for the iterative character of the terrain assessment process in mechanized skiing, we included two variables in our model that represent critical temporal influences on run list codes. *Skied in the previous seven days* represents past use, which offers both first-hand skiing experience and direct weather, snowpack and avalanche observations for a run. *Run code of the previous day* was included to account for the direct influence of previous run lists on subsequent days. To acknowledge possible correlations between *Skied in the previous seven days* and *Run code of the previous day* (i.e., a run needs to be open to be skied) we also added the interaction between these two variables to our model.

Since our dataset consists of repeated ratings of the same runs (i.e., panel structure), we included random by-run intercepts and slopes for hazard and avalanche problems. This allows the model to capture the run-specific effect of hazard and avalanche problems goes beyond the terrain class specific effect. We also included a random by-season intercepts to account for the unique character of each winter in the model.

We performed the model estimation in a Bayesian framework using the statistical software R (R Core Team, 2017) and the package *rstanarm* (Stan Development Team, 2016). We estimated the model with 2500 warmup and 2500 sampling iterations for four separate sampling chains with default priors. Model convergence was inspected based on the potential scale reduction factor (Gelman & Rubin, 1992), which compares the estimated between- and within-chain variances between multiple Markov chains for each model parameter. Large differences between these variances indicate that a model did not converge while values close to 1.0 indicate good convergence. The Markov chains exhibit some degree of autocorrelation, where a lower autocorrelation indicates more independent sampling of the posterior. The approximate number of independent draws with the same accuracy as the sample of correlated draws is referred to as the effective sample size (ESS). We consider an ESS of greater than 1000 as indication of independent sampling of the posterior.

To eliminate the potentially undesirable impact a variable might have due purely to its scale, *Relevant hazard rating* was included in the model as a numeric variable scaled to range between 0 and 1. While *Ski Run Class* was included as a dummy-coded categorical variable with Class 1 as the reference class, all other predictors were represented as binary variables. We explored different model combinations including models where the avalanche problems of concern were included as categorical variables including combinations of different avalanche problems. Only parameter estimates with 95% credible intervals different from 0 were considered significant and odds ratios (OR) are used to describe the effects of predictors. In binomial regression models, OR for individual effects can directly be derived by applying an exponential function to the regression coefficients. An OR > 1 means that the odds of a run being open are higher relative to the base level of that predictor.

Since we included both ski run class-specific intercepts and ski run class-specific slopes for hazard ratings, interpreting the effect of avalanche hazard on run list ratings directly from the parameter estimates is not straightforward. To simplify the interpretation of the combined effect, we calculated OR for each terrain class and hazard rating based on the regression coefficients. We present this effect in two tables showing (a) the odds ratios of ski run classes being open with increasing avalanche hazard relative to themselves at Low hazard and (b) the odds ratios of ski run classes being open with increasing avalanche hazard relative to terrain Class 1. Both tables are normalized relative to the OR of ski run class 1 with Low hazard.

To further illustrate our results and make their interpretation mode tangible, we calculated the probabilities of runs of different ski run classes being open under different hazard conditions and various operational settings. We present the following three operational scenarios: (a) ski runs were neither open previously nor skied recently, (b) ski runs were not open the day before but recently skied, and (c) runs were open the day before and recently skied. We then plotted the probabilities for each ski run class as a whole and included the 50%, 80% and 95% probability intervals based on the averages of 50 draws from the posterior distribution of the individuals runs from each ski run class. Along with the probability curves, average daily percentages of open runs per ski run class are plotted where observations for this scenario existed in the dataset.

3.3. Results and Discussion

The following sections present and discuss the results of our study with specific focus on the relationship between avalanche hazard rating and the presence of avalanche problems and run list codes. Moreover, we discuss the influence that run codes of the previous day as well as recent skiing have on the probability of a run being open. We then discuss our observations of by-run and by-season random effects and end with a discussion of the limitations of our study.

The sampling chains of our model converged successfully as indicated with both the potential scale reduction factor (values of 1.0) and for effective sample size (values > 1000) for all parameter estimates. Since the variable *Ski Run Class* was dummy coded in our model, the main effects for the variables that were interacted with *Ski Run Class* represent the effect for the *Ski Run Class 1*. The effects for the other classes need to be derived by adding the main effect with the ski run class-specific interaction effect.

The strongly positive main effect intercept indicates that there is a strong base tendency (i.e., with low avalanche hazard) for the runs of Class 1 to be open (Table 3.1). The intercept-ski run class interaction effects for all the other classes are significantly negative (Table 3.2).

3.3.1. Effect of hazard rating and terrain type

As expected, the probability of a run being open decreases substantially with increasing hazard for all types of terrain as illustrated by the negative main effect for hazard rating (Table 3.1) and the mainly negative interaction effects hazard rating and ski run class (Table 3.2).

However, the fact that the interaction effects of the different ski run classes differ significantly from each other highlights that the magnitude of this effect strongly depends on the type of terrain being assessed by the guiding team. This pattern is also visible in Figure 3.4, which shows the probabilities of runs of different ski run classes being open for different hazard ratings illustrated for situations when storm slab avalanches are a concern.

Table 3.1 Main effects: Diagnostics and posterior summary statistics of the estimated parameters from the mixed-effects logistic regression model. ESS is the effective sample size for each parameter. Significant parameter estimates are indicated in bold. Not significant (ns) OR omitted.

Parameter	Value	ESS	Mean	SD	2.5%	97.5%	OR
Intercept	-	2185	**5.50**	0.80	3.97	7.09	**247.15**
Relevant hazard rating	Extreme	2198	**-6.59**	1.12	-8.79	-4.40	**0.001**
Deep persistent slab	Present	2516	0.72	0.69	-0.54	2.12	ns
Persistent slab	Present	2956	0.1	0.45	-0.77	0.98	ns
Storm slab	Present	2353	0.24	0.45	-0.66	1.13	ns
Wind slab	Present	2558	-0.13	0.49	-1.05	0.84	ns
Cornice	Present	4240	1.31	1.06	-0.68	3.47	ns
Loose wet avalanche	Present	3212	0.66	0.86	-0.94	2.45	ns
Loose dry avalanche	Present	10000	-1.14	1.95	-4.90	2.66	ns
Wet slab	Present	4365	**-1.60**	0.64	-2.82	-0.32	**0.21**
Run code previous day:	Open	10000	**2.99**	0.06	2.87	3.11	**19.89**
Skied in previous week	Skied	10000	**3.44**	0.42	2.64	4.29	**31.19**

Combining the group-specific intercept (showing the base tendency of each group) and the group-specific slope estimate (determining how strongly the run list coding of a group of runs are affected by increasing hazard) provides a more comprehensive picture. While the odds of runs being open decrease with increasing avalanche hazard ratings in all ski runs classes, the magnitude of the decrease varies substantially (Table 3.3). The odds of ski runs in Class 1 being open decreases by 1000 times as avalanche hazard goes from *Low* to *Extreme*. In comparison, ski runs in Class 2 are only 20 times less likely to be open with the same increase in avalanche hazard. This means that despite the lower overall tendency of runs included in this class to be open, the run list ratings of these runs are less affected by danger ratings.

Table 3.2 Interaction effects: Diagnostics and posterior summary statistics of the estimated parameters from the mixed-effects logistic regression model. ESS is the effective sample size for each parameter. Significant parameter estimates and odds ratios (OR) indicated in bold. Not significant (ns) OR omitted.

Parameter	ESS	Mean	SD	2.5%	97.5%	OR
Intercept						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	2428	**-3.68**	0.78	-5.25	-2.17	**0.03**
Ski run class 4	2440	**-2.46**	0.78	-4.00	-0.96	**0.09**
Ski run class 5	2434	**-3.13**	0.76	-4.64	-1.68	**0.04**
Ski run class 6	2363	**-4.70**	0.75	-6.18	-3.25	**0.01**
Relevant hazard rating						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	2475	**3.57**	1.28	1.09	6.07	**35.52**
Ski run class 4	2336	0.74	1.22	-1.60	3.12	ns
Ski run class 5	2368	**-3.07**	1.22	-5.46	-0.66	**0.05**
Ski run class 6	2435	-2.24	1.25	-4.71	0.15	ns
Deep persistent slab						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	3711	0.60	0.82	-1.06	2.18	ns
Ski run class 4	2541	-0.69	0.73	-2.18	0.69	ns
Ski run class 5	2805	**-2.33**	0.75	-3.86	-0.94	**0.10**
Ski run class 6	3508	**-2.66**	0.82	-4.33	-1.17	**0.07**
Persistent slab						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	3283	0.36	0.52	-0.64	1.37	ns
Ski run class 4	3111	-0.43	0.48	-1.38	0.5	ns
Ski run class 5	3035	-0.82	0.47	-1.74	0.09	ns
Ski run class 6	3106	**-1.19**	0.48	-2.15	-0.26	**0.30**
Storm slab						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	2954	0.38	0.52	-0.64	1.39	ns
Ski run class 4	2533	-0.25	0.47	-1.19	0.69	ns
Ski run class 5	2453	-0.44	0.47	-1.37	0.5	ns
Ski run class 6	2504	-0.56	0.47	-1.5	0.36	ns
Wind slab						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	3026	0.25	0.56	-0.86	1.35	ns
Ski run class 4	2708	0.17	0.52	-0.84	1.20	ns
Ski run class 5	2676	0.41	0.51	-0.58	1.39	ns
Ski run class 6	2637	0.4	0.51	-0.6	1.38	ns

Table 3.2 Continued.

Parameter	ESS	Mean	SD	2.5%	97.5%	OR
Cornice						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	10000	1.99	1.77	-1.2	5.77	ns
Ski run class 4	4411	-0.51	1.12	-2.76	1.65	ns
Ski run class 5	4320	-1.09	1.08	-3.26	0.97	ns
Ski run class 6	4249	-0.09	1.07	-2.26	1.94	ns
Loose wet avalanches						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	3507	-0.94	0.92	-2.81	0.82	ns
Ski run class 4	3519	-0.54	0.94	-2.43	1.24	ns
Ski run class 5	3345	**-1.77**	0.90	-3.61	-0.08	**0.17**
Ski run class 6	3471	-1.31	0.93	-3.21	0.43	ns
Loose dry avalanches						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	10000	0.83	2.20	-3.32	5.20	ns
Ski run class 4	10000	-2.00	2.10	-6.18	2.14	ns
*Ski run class 5**	-	-	-	-	-	
*Ski run class 6**	-	-	-	-	-	
Wet slab						
Ski run class 1 (reference level)		0				1.00
Ski run class 2	5640	0.26	0.80	-1.32	1.81	ns
Ski run class 4	5361	1.46	0.79	-0.10	2.99	ns
Ski run class 5	10000	0.96	1.10	-1.28	3.02	ns
Ski run class 6	10000	-0.93	2.00	-5.21	2.55	ns
Run code previous day						
Not skied in previous week (reference level)		0				1.00
Skied in previous week	10000	-0.37	0.68	-1.67	1.04	ns

* There are no cases in the dataset, where Loose Dry Avalanche Problems were specified for ski runs in classes 5 or 6.

Since many of these ski runs are located at or below tree line, we suspect that the observed pattern reflects that many of these runs offer safe skiing options through trees, even when avalanche hazard is elevated. The alpine terrain classes are much more strongly affected by changes in danger ratings as evident by the large negative slope estimates. The odds of ski runs in Classes 4 to be open decrease by 300 times with increasing hazard from *Low* to *Extreme*. The odds of ski runs in Classes 5 and 6 to be open decrease even by more than 1000 times. These alpine ski runs are substantially steeper. Moreover, many of the ski runs or the pickup locations can be affected by overhead hazard.

Table 3.3 Odds ratios of each ski run classes being open with increasing avalanche hazard relative to Low avalanche hazard.

	Ski run class				
Hazard	**Class 1**	**Class 2**	**Class 4**	**Class 5**	**Class 6**
Low	1.000	1.000	1.000	1.000	1.000
Moderate	0.020	0.049	0.024	0.009	0.011
Considerable	0.010	0.059	0.014	0.002	0.003
High	0.005	0.072	0.009	<0.001	0.001
Extreme	0.001	0.049	0.003	<0.001	<0.001

Another way of looking at the relationship between the odds of runs being open, ski run class and hazard rating is to examine the odds of runs in a specific class being open at a specific avalanche hazard relative to Class 1 (Table 3.4). This perspective highlights the relative importance of the various ski run classes at different hazard ratings.

Table 3.4 Odds ratios of ski run classes being open with increasing avalanche hazard relative to ski run class 1.

	Ski run class				
Hazard	**Class 1**	**Class 2**	**Class 4**	**Class 5**	**Class 6**
Low	1.000	0.025	0.085	0.044	0.009
Moderate	1.000	0.062	0.103	0.020	0.005
Considerable	1.000	0.150	0.124	0.009	0.003
High	1.000	0.367	0.149	0.004	0.002
Extreme	1.000	0.896	0.179	0.002	0.001

For instance, the odds of runs in Class 2 being open relative to Class 1 increases with increasing avalanche hazard rating. This pattern emerges from the fact that the odds of being open decrease more quickly in Class 1 than in Class 2 (Table 3.3). A similar pattern can be observed between ski run Classes 4 and 5. Runs of Class 4 is approximately 12 times less likely to be open at *Low* hazard conditions than ski runs of Class 1. Similarly, ski runs in Class 5 are approximately 22 times less likely to be open at *Low* hazard conditions than Class 1. However, the ski runs of Class 5 are closed much more quickly as avalanche increases. The relative odds for ski runs in Class 4 being open are more than 5 times smaller for *Extreme* avalanche hazard, the relative odds for ski runs in Class 5 are 500 times smaller. Ski runs in Class 6 are more than 100 times less likely to be open with *Low* hazard and 1000 times with *Extreme* avalanche hazard.

As expected, our results confirm that the probability of a run being open decreases with increasing hazard. However, they also highlight that the effect of avalanche hazard on run list codes depends heavily on the type of terrain that is being assessed. Gentle and frequently skied terrain in all elevation bands with no or only minor exposure to avalanches slopes is much less affected by avalanche hazard. Severe alpine terrain with exposure to either multiple smaller or even large avalanche slopes on the ski runs or exposure to overhead hazard is much more affected by an increase in avalanche hazard. Such overhead hazard often not only exists while skiing but can also threaten the pickup locations. These results highlight the potential to examine the nuanced terrain selection expertise of professional guides numerically using hazard assessments based on the CMAH and revealed ski run classes.

3.3.2. Effect of avalanche problems and terrain type

Our results show that only certain avalanche problem types have an effect on run list codes and that their effect differs between ski run classes. The presence of Deep persistent slab avalanche problems exhibits a negative effect on ski runs Classes 5 and 6. This means that these runs in severe alpine terrain are much less likely to be open during times when deep persistent slab avalanche problems are a concern (OR=0.10 and OR=0.07, respectively, Table 3.1). We observed a similar trend for Persistent slab avalanche problems. In this case, however, only ski runs of Class 6 showed a significant decrease in the likelihood of being open (OR=0.30). The presence of Wet slab avalanche problems has a negative effect on the likelihood of runs being open on all ski run classes (main effect OR=0.21, Table 3.1). We observed a negative effect of Loose wet avalanches on the severe runs in Class 5 (OR=0.17).

Compared to the avalanche hazard rating, the effect of the different avalanche problem types is smaller. While a hazard rating reflects the likelihood and size of avalanches in general and affects the run coding more globally, the avalanche problem type can modulate this effect for the specific avalanche situation. For instance, while widespread storm slabs did not have a significant effect on the likelihood of ski runs of different classes being open, the presence of deep persistent slabs significantly affects the run coding for ski runs with severe alpine terrain with generally steeper or larger avalanche slopes. Similarly, our results only showed a significant effect of Loose wet avalanches on run list coding of severe alpine terrain. While these avalanches are typically confined to surface layers and therefore often small, the can gain size and speed. As such, terrain with severe consequences in case of someone being caught (e.g., being carried into obstacles or over cliffs) seems to be more cautiously assessed.

3.3.3. Effect of run code of the previous day and recent skiing on a run

Whether a run was open the previous day and whether it was skied within the previous seven days have both a significant influence on it being open on any given day (Table 3.1). Compared to a run that had not been skied during the previous seven days and was closed the day before, being open the day before increases a run's odds of being open by 26 times. The effect of having recently skied the run is even larger, as it increases the odds of a run that was closed the day before to be open by 28 times (Figure 3.4b).

Our results illustrate the strong effect of the run list from the previous day as terrain choices evolve over the course of a season. Terrain choices in mechanized skiing operations are made in stages and are constantly adjusted based on the conditions on the day before incorporating the incremental daily changes (Israelson, 2013, 2015). Moreover, the strong effect of previous skiing supports the often-expressed importance by guides of experiencing the conditions and having recent first-hand field observations. This effect is even more important than being open the previous day. As the season progresses, runs that have been skied before and where the guiding team has recent observations about the specific conditions on that run are opened more quickly than comparable runs where such recent experiences are lacking.

Together, these effects underline the necessity for analyzing professional terrain choices in their temporal context. While revealed terrain preference data from GPS tracking units (e.g., Hendrikx et al., 2016; Thumlert & Haegeli, 2018) offer promising avenues for learning about professional avalanche risk management expertise at spatial scales below the run level, it is important to remember that terrain decisions in mechanized skiing operations are made in inter-related stages (Israelson, 2013, 2015).

Small-scale terrain choices are only made within runs that were previously considered open for guiding and skiing these runs yields important field observations on the snow and hazard conditions.

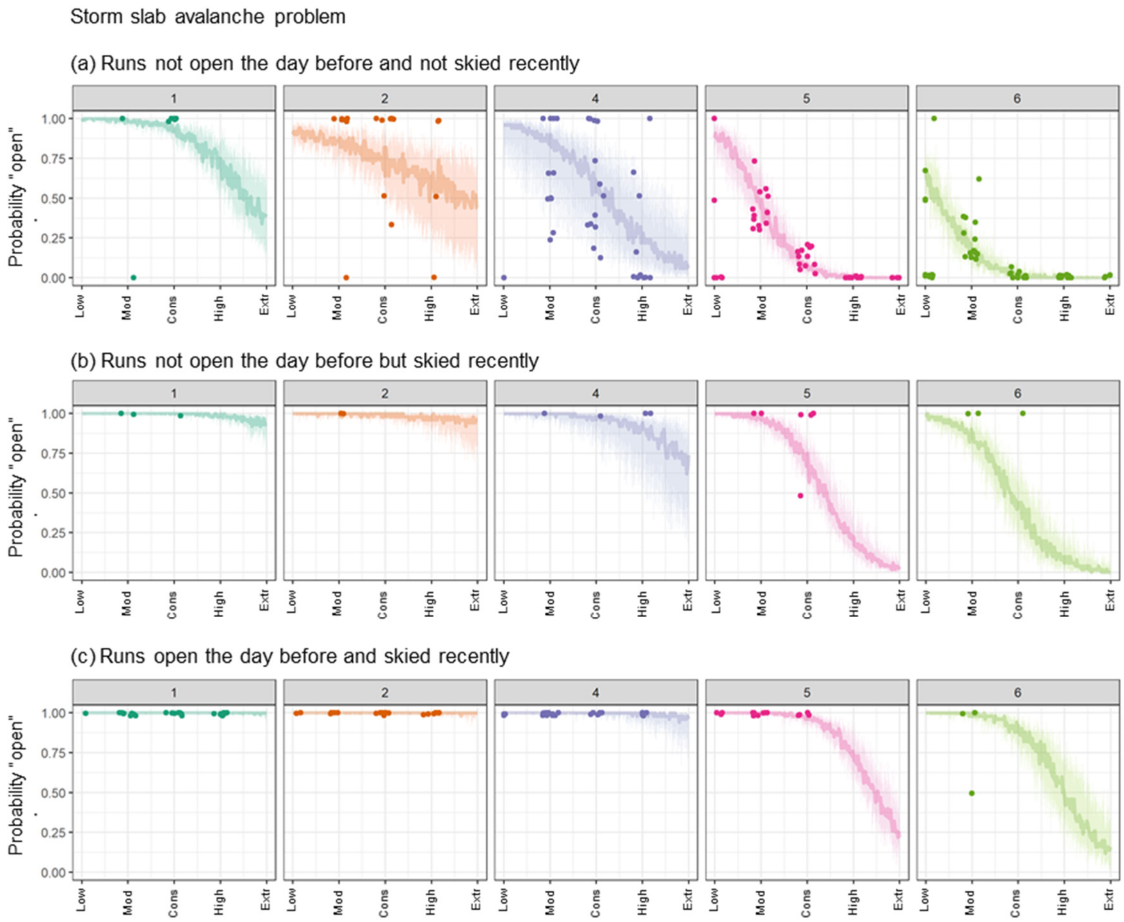


Figure 3.4 **Probabilities of ski runs being open for Storm slab avalanche problems with (a) a scenario where ski runs were neither open previously nor skied recently, (b) a scenario where runs were not open the day before but recently skied, and (c) a scenario where runs were open the day before and recently skied.**

The visualizations include probability intervals of 50%, 80% and 95% for each ski run class as a whole based on 50 draws from the posterior distribution. Average daily percentages of open runs per ski run class are plotted as points where observations for this scenario exist in the dataset.

3.3.4. Random effects on run level

While random effects on the run level were highly significant in preliminary models that did not include ski run class as a covariate, they were mostly insignificant in our final model that included ski run class as covariate (Figure 3.6). Thus, the type of terrain captures most of this variation and supports the suitability of ski run classes for analyzing professional terrain choices in avalanche terrain.

However, the random effects still provide useful insight into factors affecting run list choices of individual ski runs. For instance, the run “Sea of Cortez” (Class 4) is significantly less open than the rest of this group of ski runs when *Deep Persistent Slab Avalanches* are a concern. We suspect that this difference might be caused by the fact that a more severely exposed line of this ski run can be affected by large overhead avalanche hazard. Similarly, the ski run “Pacha Mama” (Class 2) is significantly less open with under conditions with higher hazard than the rest of the group. While the least severe ski line at treeline on this run only has minor exposure to avalanche hazard, more severe sections of the run are also exposed to overhead hazard. In both cases, we suspect that such a configuration might also affect the decision to close run sections that have no exposure to avalanche hazard. The ski run “Shrek” (Class 6) exhibits another interesting pattern. While it has a negative random intercept indicating that it is significantly less open than the rest of its class, it is significantly more open when *Deep Persistent Slab Avalanches* or *Persistent Slab Avalanches* are a concern, or with increased avalanche hazard. A detailed look at the characteristics of “Shrek” provides some insight into the reason behind this pattern. “Shrek” offers moderately steep skiing through glades and snow forest with an open canopy. While skiers are only exposed to smaller avalanche slopes, the run contains tree well hazard and was characterized as unfriendly and not preferred by the guiding team.

Based on this characterization, we suspect that “Shrek” is a unfavoured run that is generally closed but opened when operationally needed (i.e., when challenging hazard conditions restrict other skiing options). This highlights that professional terrain choices in mechanized skiing are influenced by factors beyond the avalanche hazard, and a meaningful interpretation of the observed pattern requires a more comprehensive description of the terrain that takes these factors into account Sterchi and Haegeli (under review, Chapter 2).

3.3.5. Seasonal differences

The random effects for season reflect differences in the general propensity of runs being open in each season. For instance, runs were coded open less than half as often during the low snowpack winter of 2014 compared to other seasons (Figure 3.5).

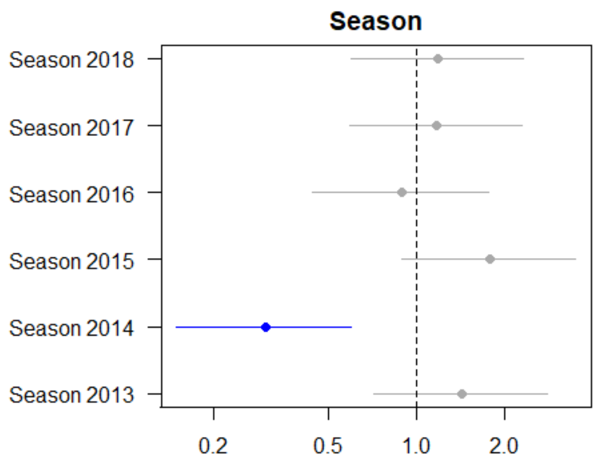


Figure 3.5 By-season random effects.

This highlights that having long-term datasets is critical for identifying meaningful patterns in risk management practices as the particularities of individual winters can affect observed choices considerably. Our results also highlight the necessity to account for these effects when analyzing professional terrain choices. Mixed effects models including random effects are an adequate statistical tool for analyzing terrain choices since they can properly account for the repeated measure nature (i.e., panel structure) of the dataset.

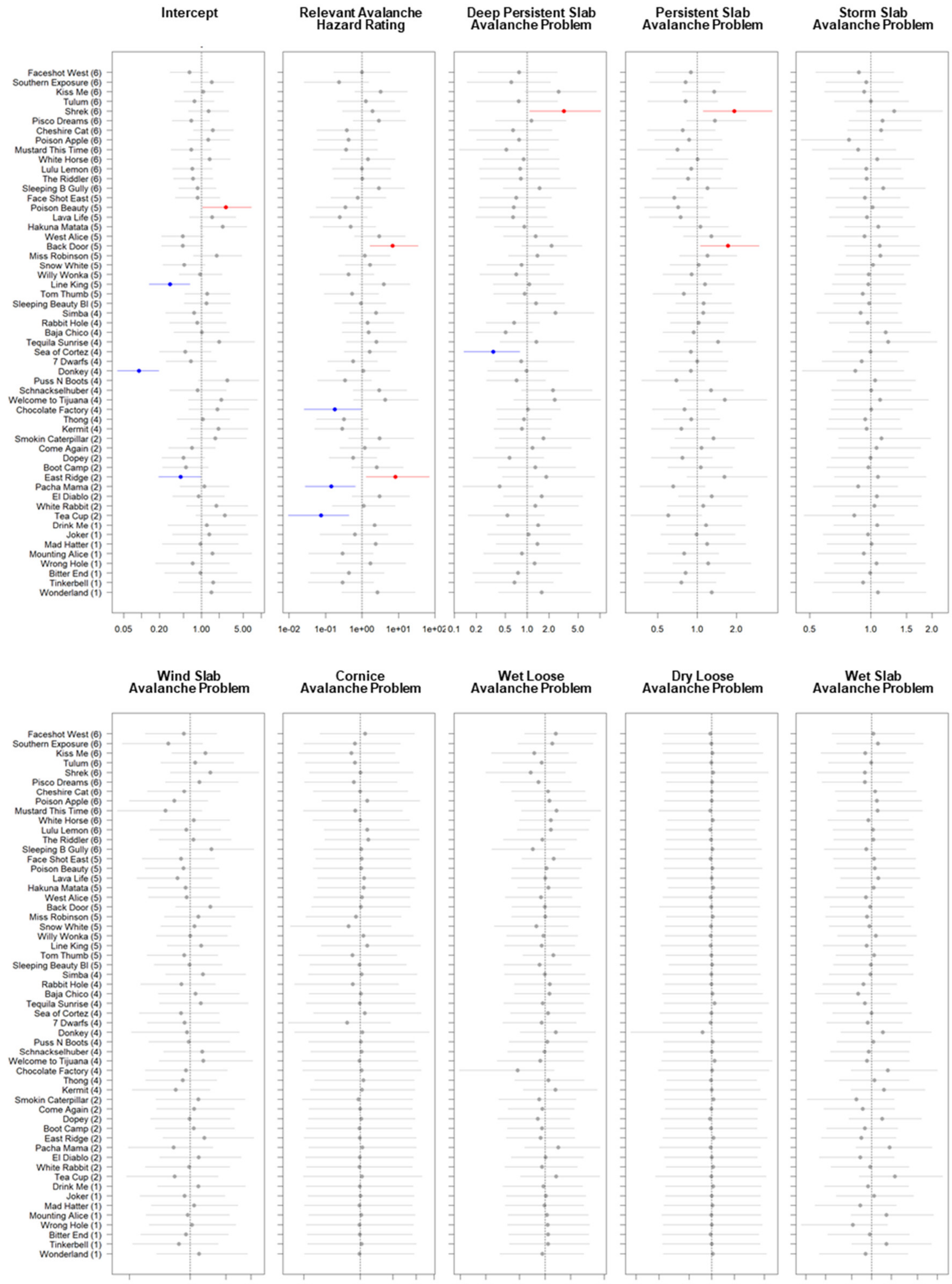


Figure 3.6 By-run random effects.

3.3.6. Limitations and future challenges

While the results presented on situation-specific acceptability of runs are encouraging, the following limitation prevent the current model from being directly used as a decision support tool. A primary limitation of the present model relates to the relatively crude representation of avalanche hazard, which only included the maximum relevant avalanche hazard and the presence/absence of avalanche problem types. The full characterization of avalanche hazard according to the conceptual model of avalanche hazard (Statham et al., 2018) is much more comprehensive, and we suspect that a more complete integration would result in additional insight. For example, including the likelihood of avalanches and destructive size parameters of the existing avalanche problems in the run list model has the potential to extract more detailed information about the relationship between avalanche hazard and run characteristics. However, taking this research to this level will require an operational dataset that is substantially larger than the dataset used in the present study.

3.4. Conclusions

Using a large, multi-seasonal dataset of operational run list choices in mechanized skiing, we applied a general linear mixed effects model to explore the relationship between avalanche hazard conditions and acceptable skiing terrain numerically for the first time. Mixed effects models including random effects are an adequate statistical tool for analyzing terrain choices since they can properly account for the repeated measure nature (i.e., panel structure) of the dataset. Our model included an avalanche hazard rating and whether eight avalanche problem types were present as predictors and the terrain class of the run, whether it was skied in the previous seven days and how it was rated on the previous day as covariates. The model included by-run and by-season random effects.

Our results highlight that the effect of avalanche hazard on run list codes depends heavily on the type of terrain that is being assessed. While the run list ratings of the gentlest terrain are only marginally affected by hazard ratings, severe alpine terrain is especially susceptible to increasing avalanche hazard. Compared to the effect of the avalanche hazard rating, the effects of the different avalanche problem types on the run list codes are smaller but represent critical adjustments. Our results also highlight the strong effect of recent skiing and thus experiencing the conditions and having recent first-hand field observations. This result reflects the fact that guides reopen runs they have recently skied more quickly than other comparable runs. The strong effect of the run code of the previous day highlights that terrain choices in mechanized skiing are evolving over the course of a season and underline the necessity for analyzing professional terrain choices in their temporal context.

While our results primarily confirm expectations, we believe this study provides a valuable step towards describing the terrain selection process at mechanized skiing operations numerically in a meaningful way. Based on the present results, we feel that a more comprehensive integration of the characteristics of the individual avalanche problem types as specified in the conceptual model of avalanche hazard (i.e., likelihood of avalanches and destructive size) has promise to produce more refined models that relate relevant parts of the hazard assessments more closely to terrain characteristics of individual runs. The results of this research will create the necessary foundation for the development of meaningful decision aids for guiding teams and provide important context for the analysis of small-scale terrain choices.

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Chapter 4.

Conclusions

This thesis first presented a new method for deriving ski run classifications from daily terrain assessment records (Chapter 2) and subsequently explored the relationship between avalanche hazard conditions and acceptable skiing terrain (Chapter 3). The following section summarizes the results of these two studies and discusses their implications.

The presented approach to derive ski run classification uses multi-season datasets of daily run list ratings at mechanized backcountry skiing operations to identify groups of similarly treated ski runs and arrange them into operation-specific ski run hierarchies. The resulting high-resolution ski run hierarchies reflect the local terrain expertise and avalanche risk management practices that have developed at an operation in the context of the available terrain and local snow and avalanche climate conditions. To our knowledge, this is the first time that such patterns in professional terrain selection have been identified and that the operational avalanche risk management expertise at the run scale has been formally extracted.

The relationship between avalanche hazard conditions and acceptable skiing terrain was explored numerically using a large, multi-seasonal dataset of operational run list choices in mechanized skiing by applying a general linear mixed effects model. This model included an avalanche hazard rating and whether eight avalanche problem types were present as predictors and the terrain class of the run, whether it was skied in the previous seven days and how it was rated on the previous day as covariates. The results show that the magnitude of the effect of avalanche hazard on run list codes depends on the type of terrain that is being assessed by the guiding team, and thus link the identified ski run hierarchies identified in the first study to avalanche hazard.

The results of these studies offer numerous contributions for future backcountry avalanche risk management research and development projects. Since a meaningful representation of terrain is critical for properly linking backcountry terrain decisions to avalanche hazard and weather conditions, the operation-specific ski run classes identified in this thesis provide an exciting opportunity for exploring this link. The presented method of identifying ski run classes aims to overcome some of the challenges that have prevented the adoption of terrain classification systems in mechanized skiing operations in the past by identifying a larger number of operation-specific terrain classes organized in ski run hierarchies that offers a much more nuanced and applied perspective of the terrain and provides a more meaningful assistance to professional guides. Since the identified ski run hierarchies reflect actual risk management practices that have been used at participating operations for many years, they are more closely linked to the risk management decisions that the classification aims to support than existing terrain classification systems. Furthermore, the fact that the emerging classification is grounded in past local risk management decisions has the potential to increase guides' acceptance and trust in the developed risk management decision aids. The characteristics of the identified ski run classes also reiterate that it is difficult to relate terrain choices to physical terrain characteristics alone (Haegeli and Atkins, 2016). Examples of important other factors that emerged from this study include exposure of pickup locations to overhead hazard, accessibility of ski runs, previous skiing on runs, and the type and quality of the guest skiing experience. To identify insightful patterns and analytically isolate the effect of avalanche hazard, it is critical for future research to examine revealed terrain preference data within the full array of influencing factors and operational constraints.

Correlating avalanche conditions to the identified ski run classes has the potential to offer useful insight for the development of evidence-based decision aids that can assist guiding teams during their morning meetings. We believe this study provides a valuable step towards describing the terrain selection process at mechanized skiing operations numerically in a meaningful way. While avalanche hazard certainly drives terrain choices, our approach accounts for the fact that terrain choices in mechanized skiing are evolving over the course of a season, and our results underline the necessity for analyzing professional terrain choices in their temporal context. Future models that incorporate the characteristics of the individual avalanche problem types as specified in the conceptual model of avalanche hazard (i.e., likelihood of avalanches and destructive size) will allow to develop more refined models that relate these relevant parts of the hazard assessments more closely to terrain characteristics of individual runs. The results of such research will create the necessary foundation for the development of meaningful decision aids for guiding teams and provide important context for the analysis of small-scale terrain choices. While revealed terrain preference data from GPS tracking units (e.g., Hendrikx et al., 2016; Thumlert and Haegeli, 2017) offer promising avenues for learning about professional avalanche risk management expertise at spatial scales below the run level, it is important to remember that terrain decisions in mechanized skiing operations are made in stages (Israelson, 2013, 2015). Since small-scale terrain choices are only made within runs that were previously considered open for guiding, the patterns captured in the operation-specific ski run hierarchies presented in this thesis offer critical context for the meaningful analyses of GPS data.

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Appendix A.

Qualitative run characterization

Table A1: Qualitative run characterization with attribute names and levels.

Attribute name	Question	Levels
Access		
Required flying conditions	How do you generally feel about the accessibility of this run when the cluster of runs is accessible?	1. I can always get to this run. 2. It is often possible to make this work. 3. Conditions need to line up to make this work. 4. Flying conditions need to be perfect to consider this run
Particular pickup features	What other access feature of the pickup(s) of this run stand out?	1. Avalanche overhead hazard during regular cycles. 2. Avalanche overhead hazard during large cycles. 3. Common presence of triggers for overhead avalanche hazards
Type of Terrain		
Type of terrain	What type(s) of skiing terrain does this run include?	1. Glaciated terrain 2. Non-glaciated alpine terrain 3. Extreme alpine terrain (faces) 4. Open slopes at tree line or below tree line 5. Glades at tree line or below tree line 6. Open canopy/snow forest (individual tree crowns do not overlap) 7. Burnt forest 8. Cut blocks 9. Large avalanche path formed from above 10. Dense forest 11. Open planar slopes 12. Highly featured/convoluted terrain
Skiing Experience		
Skiing difficulty	What is the difficulty level of this run when conditions are good?	1. Easy 2. Moderate 3. Challenging
Overall guest experience	When the conditions on this run are good, what is your opinion of the overall skiing experience that his run offers?	1. Poor (Happy to move on) 2. Fair (Not bad skiing) 3. Good (A good product) 4. Very good (This is why guests come back for more) 5. Exceptional (Life changing mountain experience)

Table A1: Continued.

Attribute name	Question	Levels
Operational role(s)		
Operational role(s)	What particular operational role(s) does this run have in your program?	1. Safe and accessible under almost all conditions run 2. Signature run (defines your operation) 3. Destination run (objective of a circuit) 4. Bread and butter run (high efficiency production run) 5. Key jump run (might not have good skiing, but makes a circuit work) 6. Time management run (can be used to keep busy for a while, e.g., during fuel run) 7. Regular lunch run 8. Not preferred run (only considered if running out of options for reasonable skiing) 9. Open season run (only considered under bombproof conditions) 10. Rarely visited, but important under special circumstance
Hazard Potential		
Steepness	What is the steepness of the most serious slopes on this run?	1. Gentle (no significant avalanche slopes on ski lines) 2. Moderately steep (concerned about avalanches under specific condition) 3. Moderate with steep pitches (always concerned about avalanches) 4. Sustained steep (always concerned about avalanches)
Exposure to avalanche slopes on the ski line(s)	If moderately steep or steep, what is the exposure to avalanche slopes on this run?	1. A single smaller avalanche slope capable of producing Size 1.5-2.5 2. Multiple smaller avalanche slopes capable of producing Size 1.5-2.5 3. Large avalanche slopes producing Size 3.0 or larger
Avalanche related terrain hazards	What avalanche related terrain hazards stand out on this run?	1. Avalanche overhead hazard during regular cycles (Size 3.0 or smaller) 2. Avalanche overhead hazard during large events only (Size 3.5 or larger) 3. Common presence of triggers for overhead avalanche hazard (e.g., ice fall, cornice) 4. Unavoidable unsupported terrain shapes 5. Lack of surface roughness 6. Frequent performers that retain hazard and wait for human triggering 7. Frequent natural avalanche which stabilize the slope 8. High consequence terrain when caught

Table A1: Continued.

Attribute name	Question	Levels
Hazard Potential (continued)		
Other hazards	What other hazards stand out on this run?	1. Crevasse hazard, isolated 2. Crevasse hazard, widespread and/or unavoidable 3. Cornices directly affecting the ski line(s) 4. Tree well hazard 5. Open creeks, vent holes, rock crevasses 6. Particularly large tree bombs 7. Potentially particularly challenging for rescues and/or finding a lost skier
Overall friendliness	In terms of hazards, what is your sense of the overall friendliness of the terrain on this run?	1. Very friendly 2. Friendly 3. Neutral 4. Unfriendly 5. Very unfriendly
Guide-ability		
Guide-ability	What is your opinion of the guide-ability of this run?	1. Very easy (i.e., the terrain naturally leads guests to the right line) 2. Easy 3. Difficult 4. Very difficult (i.e., requires detailed instructions and a close eye on the guest)

Appendix B.

Average seasonal and overall percentages of run list ratings

Table B2: Average seasonal and overall percentages of run list ratings for the six groups of similarly managed ski runs at NEH.

Group	n	Run list rating	2013	2014	2015	2016	2017	Overall
1	8	open	97%	97%	94%	98%	>99%	97%
		closed due to avalanche hazard	<1%	3%	<1%	<1%	<1%	1%
		other hazards / not discussed	2%	0%	5%	1%	0%	2%
2	9	open	95%	79%	61%	91%	>99%	86%
		closed due to avalanche hazard	1%	21%	3%	5%	<1%	6%
		other hazards / not discussed	4%	0%	36%	4%	0%	9%
3	2	open	98%	90%	69%	97%	63%	84%
		closed due to avalanche hazard	0%	10%	<1%	0%	1%	2%
		other hazards / not discussed	2%	0%	30%	3%	36%	15%
4	13	open	87%	80%	79%	74%	85%	81%
		closed due to avalanche hazard	10%	20%	5%	14%	12%	12%
		other hazards / not discussed	3%	0%	16%	12%	3%	7%
5	13	open	56%	28%	61%	53%	36%	47%
		closed due to avalanche hazard	42%	71%	30%	39%	64%	49%
		other hazards / not discussed	2%	1%	9%	8%	0%	4%
6	14	open	31%	18%	35%	33%	25%	29%
		closed due to avalanche hazard	67%	82%	36%	50%	70%	61%
		other hazards / not discussed	2%	<1%	29%	17%	5%	10%

Table B3: Average seasonal and overall percentages of run list ratings for the seven groups of similarly managed ski runs at CMHGL.

Group	n	Run list rating	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Overall
1	44	open	95%	95%	91%	90%	97%	86%	96%	92%	92%	98%	95%	93%
		closed due to avalanche hazard	3%	4%	5%	7%	<1%	6%	<1%	4%	5%	<1%	<1%	3%
		other hazards / not discussed	2%	1%	4%	3%	3%	8%	3%	4%	3%	1%	5%	4%
2	38	open	81%	77%	82%	67%	85%	59%	86%	76%	77%	94%	93%	80%
		closed due to avalanche hazard	15%	20%	13%	27%	6%	20%	5%	17%	14%	3%	2%	13%
		other hazards / not discussed	4%	3%	5%	6%	9%	21%	9%	7%	9%	3%	5%	7%
3	48	open	67%	56%	62%	48%	62%	40%	65%	50%	52%	78%	74%	59%
		closed due to avalanche hazard	27%	39%	31%	41%	18%	35%	23%	39%	35%	18%	20%	30%
		other hazards / not discussed	6%	5%	7%	11%	20%	25%	12%	11%	13%	4%	6%	11%
4	12	open	55%	43%	52%	42%	49%	27%	47%	32%	44%	70%	60%	47%
		closed due to avalanche hazard	33%	49%	37%	45%	10%	25%	29%	35%	35%	21%	33%	32%
		other hazards / not discussed	12%	8%	11%	13%	41%	48%	24%	33%	21%	9%	7%	21%
5	31	open	45%	29%	37%	28%	35%	22%	40%	25%	36%	60%	46%	37%
		closed due to avalanche hazard	48%	64%	56%	60%	35%	50%	48%	61%	51%	35%	49%	51%
		other hazards / not discussed	7%	7%	7%	12%	30%	28%	12%	14%	13%	5%	5%	13%
6	21	open	35%	22%	33%	21%	29%	18%	30%	17%	29%	57%	38%	30%
		closed due to avalanche hazard	48%	67%	52%	63%	16%	29%	39%	44%	46%	31%	53%	44%
		other hazards / not discussed	17%	11%	15%	16%	55%	53%	31%	39%	25%	12%	9%	26%
7	33	open	18%	10%	17%	5%	10%	9%	15%	10%	21%	32%	26%	16%
		closed due to avalanche hazard	70%	81%	73%	81%	50%	53%	70%	71%	62%	62%	68%	67%
		other hazards / not discussed	12%	9%	10%	14%	40%	38%	15%	19%	17%	6%	6%	17%