The demand side of climate services for real-time snow management in Alpine ski resorts: Some empirical insights and implications for climate services development

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A R T I C L E I N F O

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Limit conjoint analysis

A B S T R A C T

Whilst there has been significant effort to stimulate the supply side of the market for climate services, the demand side still receives less attention. For this reason, this paper presents empirical data on prospective demand for (sub-)seasonal climate services addressing daily operational decision-making in ski resorts, particularly in the field of snow management. Based on theoretical considerations about what determines the market size for climate services and responses from two surveys among Alpine ski resorts, we address questions about (i) the potential to optimise snow management by increasing the ability to anticipate weather and snow conditions, (ii) ski resorts' interest in (sub-)seasonal climate services and (iii) their willingness to pay. Our survey results reveal several aspects with a positive impact on the theoretical demand for (sub-)seasonal climate services in the field of ski resorts' snow management. This includes high saving potential in some ski resorts from perfect or improved knowledge of upcoming meteorological conditions, widespread experience in the use of forecasts and snow management tools, and a noticeable portion of actors willing to consider uncertain information in decision-making to some extent. Nevertheless, the willingness to pay for (sub-)seasonal climate services seems somewhat limited. Recommendations for service providers include demonstrating clearly where and how even uncertain information can add value to decision-making, careful weighing of the costs of provision of each service component against added value for customers, and a flexible and modular product design.

Practical implications

The provision of climate services (CS) has long been very supply-driven, with little attention paid to the demand side. Meanwhile, there is a strong understanding that tailoring services to the actual needs of users by means of co-creation is important to increase chances of actual service uptake. There are, however, additional demand-side aspects besides user needs that are of particular relevance for service provision but have not yet received proper attention. This includes insights into potential market size or users' willingness and ability to pay for a particular service. These aspects are of particular importance for the development of viable business models and long-term maintenance of service provision.

We introduce some theoretical considerations about what defines the market size for (sub-)seasonal CS, including three determinants of demand: (i) the weather or climate sensitivity of the sector or activity, (ii) the benefits arising from better knowledge about upcoming weather and climatic conditions, in other words, the ability to react, and (iii) the degree of risk aversion towards the use of somewhat uncertain forecasts. Based on these considerations and drawing on responses from two surveys among Alpine ski resorts, we present empirical data that helps with assessing the prospective demand for (sub-)seasonal CS addressing daily operational decision-making in the field of snow management. Questions addressed include the potential to optimise snow management by increasing ski resorts' ability to anticipate weather and snow conditions, ski resorts' interest in (sub-)seasonal CS and their risk attitudes towards the use of forecasts that exhibit some uncertainty, as well as ski resorts' preferences

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towards service design and their willingness to pay for (sub-)seasonal CS. The latter is investigated for a concrete service prototype, developed by means of a co-creation process within an EU-funded research project: the PROSNOW® service. It provides seamless forecasts on meteorological variables and snow conditions on slopes for the next hours to several months ahead, considering different snow production configurations and snow management choices.

The empirical data from the two surveys reveals and confirms several aspects with a positive impact on the theoretical demand for (sub-)seasonal CS in the field of ski resorts' snow management:

- Some ski resorts show considerable saving potential from perfect or improved knowledge of upcoming weather and snow conditions in the field of snow management.
- There is already widespread experience in the use of forecasts as well as snow management tools.
- Risk attitudes towards potentially false forecasts are quite diverse, but a noticeable portion of actors are to some extent willing to take uncertain information into account when making decisions.

Nevertheless, the willingness to pay for (sub-)seasonal CS seems somewhat limited. Potential reasons include the great number of freely available weather forecasting products and that broad practical evidence of the profitability and added value of these new types of services is currently lacking .

Several practical implications and lessons for the development and provision of (sub-)seasonal CS in the field of snow management – and beyond – can be learnt from the empirical data presented in the article. (i) For the actual uptake and success of (sub-)seasonal CS, it seems crucial to clearly demonstrate the added value over currently used – and often freely available – weather forecasting products. This may also increase the willingness to pay. (ii) It is important to demonstrate where, and how, even uncertain information can add value in decision-making . Fully exploiting uncertain information may require training and capacity building, which could be part of the service offer. (iii) Since the willingness to pay seems somewhat limited, providers of (sub-)seasonal CS need to carefully weigh the costs of provision of each single service component against added value for customers in order to design commercially viable packages. (iv) A flexible and modular product design, resulting in different price categories, could help to account for differences in customers' product preferences as well as willingness and ability to pay.

1. Introduction

The European Union has set out a strategy to greatly improve the availability of climate services (CS) and help European researchers to take a leading role in the field (Street, 2016; Street et al., 2015). This strategy also clearly states that it wants to help to promote a market for such services. Climate services, defined by the World Meteorological Organization providing "*climate information to help individuals and organizations make climate smart decisions*" (WMO, n.d.), encompass a wide variety of time scales, including in particular long-term climate change impacts at multi-decadal time scale for various greenhouse gas concentration scenarios, and shorter-term predictions at the seasonal scale, used for various applications (Bruno Soares et al., 2018; Buontempo et al., 2018). The European Commission issued several calls to help develop such services both by the Horizon 2020 and the Copernicus programme and continues to do so also under the Green Deal calls. So whilst there is significant effort to stimulate the supply side of this (yet to be much more developed) market and some research has also been carried out to assess the value of CS (see e.g. Anderson et al., 2015; Perrels, 2020; Soares et al., 2018; Tall et al., 2018), to our knowledge, the demand side of this market still receives less attention, albeit growing (Damm et al., 2020; Jacobs and Street, 2020; Tart et al., 2020; Visscher et al., 2020); hence, this paper aims to present some empirical data on prospective demand for (sub-)seasonal CS that have been

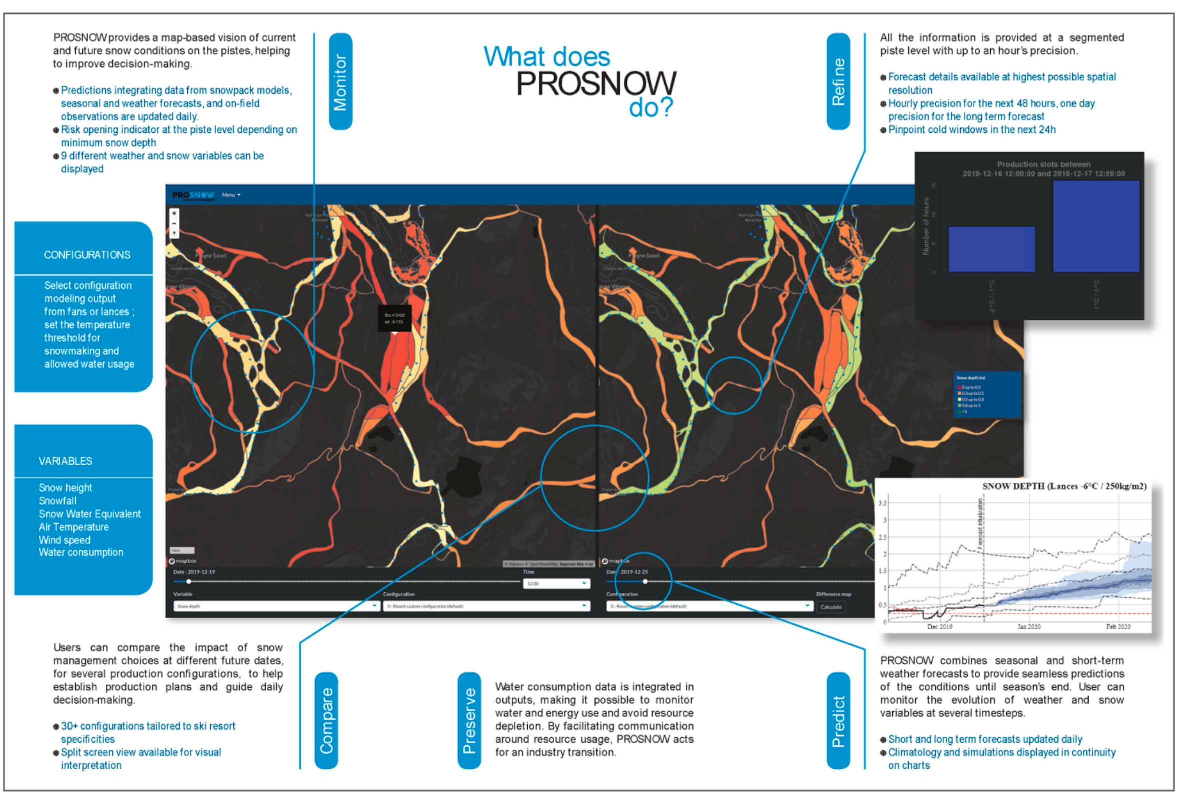

Fig. 1. PROSNOW®'s web-based user interface.

collected in ski resorts throughout the Alpine arc. Among others, we asked for the willingness to pay (WTP) for a very specific (sub-)seasonal CS that helps to better manage the sector's climate risks, especially arising from poor natural snow conditions, a problem that is well known to be deteriorating because of rising temperatures and other elements associated with climate change (cf. Hock et al., in press) and also significantly jeopardises economic wellbeing in rural areas that make their living from snow-based winter tourism (see e.g. Prettenthaler and Formayer, 2011; Steiger et al., 2017; Steiger and Scott, 2020).

We start with some theoretical thoughts about what defines the market size for (sub-)seasonal CS, including considerations about the general interplay between the market economy and weather or climate, benefits from improved knowledge about future meteorological conditions, and the role of uncertainty together with decision-makers' risk aversion. Based on these theoretical considerations, we present some empirical insights to help with assessing the prospective demand for CS tailored to daily operational decision-making in ski resorts, particularly in the field of snow management. Drawing on responses from two surveys among Alpine ski resorts carried out within the PROSNOW project (www.prosnow.org) (Köberl et al., 2019; Köberl and Damm, 2020), we address the following questions: Is there substantial optimisation potential in the field of snow management in increasing ski resorts' capacity to anticipate weather and snow conditions? Is there interest from ski resorts in (sub-)seasonal CS and does the degree of prevailing risk aversion allow for actual use of somewhat uncertain information in operational snow management decision-making? Is there enough WTP by potential end-users to develop and maintain the provision of such services in the long term?

Some of these questions, including end-users' WTP, are investigated by using the example of a concrete (sub-)seasonal CS prototype service: PROSNOW®. Developed within the eponym H2020 project PROSNOW (Morin, 2020; Morin et al., 2018), PROSNOW® represents a meteorological prediction and snow management system for ski resorts that aims to provide improved anticipation capabilities at various time-scales, spanning from a few days to the seasonal scale of several months. Besides predictions of meteorological variables, it offers forecasts on snow conditions on slopes for several snow production configurations and different snow management choices. The system was co-developed by scientists working on mountain meteorology, climate, and snow cover modelling, programmers, engineers, social scientists, economists, providers of high tech solutions for snow monitoring and management and an ensemble of nine representative pilot ski resorts in the Alps. Fig. 1 provides an overview of the functionalities of PROSNOW®'s web-based user interface and a showcase access can be found at http://showcase.prosnow.org/.

The paper is structured as follows: Section 2 outlines our theoretical considerations about what determines the demand and market size for (sub-)seasonal CS. Section 3 describes the data and methods used for the empirical part, including some notes on the research area, the data collection process, design and structure of the surveys, data processing and data analyses. The main results are presented in section 3. Section 4 discusses their implications and summarises the main conclusions.

2. Theoretical considerations

Any attempt to empirically determine the market size for (sub-)seasonal CS will have to start with some theoretical considerations of the general interplay between the market economy and weather or climate, as the "statistics of weather". What could be determining factors of demand for CS in a market economy? Needless to say, price is one of them; the lower the price, the higher the quantity demanded of most products and services. This trivial fact is only of little help here, however, and we will ignore it for a while. If a product or service is completely useless, it might even be offered free of costs and still not trigger any demand. We are seeking more general phenomena that explain why a CS might meet a demand. The most general fact, that we need to consider first, is that weather per se can also be treated as a commodity. Even though such a claim may sound paradoxical for non-economists, anybody who turns on his or her heating during winter-time is, at that very moment, purchasing a service that is delivered free of cost by the weather during warmer periods of the year; thus, the fluctuation of heating energy demand is, by and large, directly connected to the fluctuation of outside temperature and this is why this fluctuation of outside temperature is traded as a commodity – termed a weather derivative – on markets such as the Chicago Mercantile Exchange. Such a derivative can be a perfect product to hedge the economic risks of having purchased too much or too little energy in the past. So when we ask ourselves in which economic sectors we would expect an important demand for CS, it is very likely to be found in those sectors, whose production or consumption processes are strongly weather or climate dependent. There is no doubt that energy, agriculture, tourism and outdoor recreation, but also resale are such sectors, and we find numerous efforts to quantify this dependency or the associated economic risk (e.g. Bertrand and Parnaudeau, 2019; Bird et al., 2016; Damm et al., 2017; Dell et al., 2014; Hart and de Dear, 2004; Lazo et al., 2011; Prettenthaler et al., 2016; Štulec et al., 2019; Toeglhofer et al., 2012). To put it another way: some sectors should be more inclined to buy CS than others because weather per se plays a service-like role in their economic process, and if the specific weather element or a close substitute can be traded, it would be bought.

We have to consider a second influencing variable, though: since a CS is by definition not a service that can deliver this or that weather at a particular time but can only, at best, tell how weather will be at a particular time (or time span) in a particular location of interest, the market for weather (or climate) and for CS are not the same. Suppose you sent two robot ships to the Caribbean last week and lost connection with them. They could be destroyed if a hurricane arose in the region in the following days. If you had no means of altering their route, you might still buy some expensive weather forecast for the region for curiosity reasons, but in economic terms, it would not make sense; buying this service would not alter the actions you could take and the losses you incur. This little example illustrates that only if there is some potential benefit from perfect knowledge of upcoming meteorological conditions will a sector's general dependence on weather or climate result in demand for (sub-)seasonal CS by that sector's individual actors. Prettenthaler et al. (2015) have shown by a simple model how this benefit of perfect knowledge can be measured in the hospitality industry. Whether you can do something about your future economic success, given you have perfect weather information, can depend on many things: the technology, the time lag between decision and operation and so forth, but also on external socio-economic or governance factors like labour market regulation. Suppose you are a ski lift operator not allowed to lay off workers within the season and you could learn from a (sub-)seasonal CS as soon as early December whether all the snow will melt away in January and whether you will have any for the rest of the season. Would you buy this CS? Maybe yes, out of personal curiosity, but certainly not to save wage costs. Some further examples for determinants of demand: are there free substitution goods for a new CS? What are the additional benefits over existing services? What is the level of professionalisation in your company? Can you afford any new purchases at all?

For many factors that we have mentioned so far and that should have a positive impact on the demand, the Alpine ski industry seems to be a perfect match for high demand: (i) it is weather-sensitive, (ii) we would expect saving potential from perfect knowledge, particularly in the field of snow management, (iii) and there seems to be a high level of professionalisation in many ski resorts, given the challenges the sector has already had to overcome in the past (starting in mid-20th century with the high risk efforts to build this kind of infrastructure in an environment with previously no technical infrastructure, a permanently strong trigger to develop new technologies, first to withstand all kinds of natural hazards and recently the high customer demands towards quality and snow reliability in a changing climate, increasing competitive pressure, etc.). Let us now turn, though, to one determinant of demand for CS that we also expect to be high in the ski industry but, by hypothesis, should have a negative impact on the resulting demand for (sub-)seasonal CS: risk aversion.

Risk aversion and its hypothetical influence on the demand for CS is an interesting topic for two reasons: first, no (sub-)seasonal CS of any quality and for any time slice will be able to provide perfect forecasting information. This is why even a high saving potential from perfect knowledge is no guarantee of a high WTP for a particular (sub-)seasonal CS. Some stakes are too high to take any risk; thus, very high risk aversion might lead to zero demand for a (sub-)seasonal CS.

Secondly, particularly in the ski industry and the (sub-)seasonal CS that we investigate in this paper, the risk aversion will vary from resort to resort, will probably change in the future and is also (indirectly) measurable by some objective variable, such as total annual water availability for snow production. Risk aversion is directly paid for by water consumption. Consider an operator who absolutely wishes to avoid using some potentially false prediction telling how much snow to produce in the early days of November such that the resort can open on December 1st. All this operator can do is start producing snow on November 1st, using all feasible time slots even though conditions might still be rather warm and snow production inefficient. In other words: with enough water to do so, the operator can "afford" their risk aversion. With shrinking water resources, however, we would expect the risk aversion to potentially false predictions to shrink because another risk becomes prevalent: the risk of having used up all water too early and not being able to open the resort.

These theoretical thoughts will guide our way in generating empirical insights about the potential demand for (sub-)seasonal CS in the field of ski resorts' snow management.

3. Material and methods

3.1. Research area & data collection

The Alps host more than one-third of the world's total and 80% of the world's major[1] ski resorts, with the Alpine countries France, Austria, Switzerland and Italy leading the European ranking in terms of skier visits (cf. Vanat, 2020). The empirical data presented in this paper result from two different surveys conducted among Alpine ski resorts in the course of the PROSNOW project:

- **Survey A –** Online survey among representatives of Alpine ski resorts in France, Austria, Switzerland and Italy. The survey was open to participation for nine weeks, from the end of March to the end of May 2019. Survey invitations were spread via various channels: (i) emails to ski resort and ropeway operators, (ii) promotional articles in newsletters of national ropeway associations and the PROSNOW project newsletter, (iii) tweets on the PROSNOW project's Twitter account, and (iv) flyers at the Interalpin fair in Innsbruck in May 2019.
- **Survey B –** Survey among the nine PROSNOW pilot ski resorts in spring 2020, after their real-time testing of PROSNOW® in the winter season 2019/20. The PROSNOW pilot ski resorts included Arosa-Lenzerheide (CH), Obergurgl, Seefeld (AT), Garmisch/Zugspitze (DE), La Plagne, Les Saisies (FR), Colfosco, San Vigilio, and Livigno (IT). One of the main aims was to gain insights into the pilot ski resorts' WTP for a service like PROSNOW®, using some kind of choice experiment that is able to provide meaningful estimates even in the case of small sample sizes (see section 3.2.2). The questionnaire was sent to the contact persons at the pilot ski resorts as a completable PDF form, with project members offering telephone support in case of any ambiguities or questions. Note that due to the COVID-19 lockdown in spring 2020, contact persons of two pilot ski resorts were not reachable for survey participation.

[1] "Major" refers to ski resorts with more than one million skier visits per winter season.

Table 1
Attributes and levels considered in the limit conjoint analysis.

Attribute	Level	Description
Number of SRUs [a)]	1	Forecasts are provided for 1 point or 1 SRU [a)] in the ski resort
	5	Forecasts are provided for 5 points or 5 SRUs [a)] in the ski resort
	> 100	Forecasts are provided for a few hundred SRUs [a)] in the ski resort
Type of support	no	No additional training or consulting
	training	Training at the beginning of the season on how to use and interpret the indicators provided by the service
	consulting	Continuous consulting based on the forecasts throughout the season
Forecasting horizon	4 days	The forecasting horizon includes the next 4 days
	10 days	The forecasting horizon includes the next 10 days
	season	The forecasting horizon includes all days until season end
Price	€5,500 €7,500 €9,500	Prices per season (excl. the one-off payment for initial set-up)

[a)] **S**ki resort **R**eference **U**nit: a particular slope segment, within which the snowpack is considered homogeneous. The total number of SRUs for an average ski resort typically ranges between several tens and a few hundred. Experiences from the real-time testing, however, showed that there are often 4–5 critical SRUs snow managers focus on when deciding on the strategies for the upcoming hours and days.

Both surveys were available in English, French, German and Italian. The data and insights presented in this paper cover selected parts of the two surveys. The full English versions of the questionnaires are provided in the Supplementary Materials.

3.2. Survey design and structures

3.2.1. Survey A

Survey A was implemented in LimeSurvey (Limesurvey Gmbh, n.d.) and consisted of 19 questions, grouped into four topics: (i) the characteristics of the ski resort and the respondent(s), (ii) the ski resort's snow management, including products and services currently in use as well as risk attitudes and the handling of forecasting uncertainties, (iii) the composition of the ski resort's operating costs, and (iv) the expected utility of a service like PROSNOW®.

3.2.2. Survey B

Survey B aimed at evaluating the developed PROSNOW® service among the pilot ski resorts after the real-time testing season 2019/20 and gaining insights into the ski resorts' WTP for such a service. The survey consisted of 13 questions – some of them with similarities to survey A – and was structured into five thematic blocks. Amongst others, these blocks covered (i) the pilot ski resorts' testing intensity of PROSNOW®, (ii) the evaluation of PROSNOW®, (iii) the resource and cost-saving potential expected under perfect knowledge, and (iv) a limit conjoint analysis (Voeth and Hahn, 1998) to assess the pilot ski resorts' WTP.

Conjoint analysis is a family of marketing research techniques widely applied by academics and practitioners (see e.g. Breidert et al., 2017). It aims to measure individuals' preferences regarding selected product characteristics (attributes) by systematically varying different realisations of the product's attributes in an experimental design. Several product profiles, consisting of realisations of the product's attributes, are presented to the respondents, who are asked to order them according to their preferences. Based on this order, relative contributions of the different attribute levels to the overall preferences – termed part-worth utilities – can be derived. Using the product's price as one of the systematically varied attributes allows inferences on the respondent's WTP. The limit conjoint analysis is a traditional conjoint analysis but expanded by a selection decision. That is, respondents are also asked to divide the rated or ranked product profiles into "worth buying" and "not worth buying". The main reasons for choosing this type of conjoint analysis within survey B included its ability to provide meaningful estimates even in the case of small sample sizes and the possibility of analysing each respondent individually (cf. Backhaus et al., 2007).

The limit conjoint analysis conducted within survey B focused on attributes of particular relevance and interest for a potential market launch of PROSNOW®. This included preferences about (i) spatial coverage and detail of the forecasts, (ii) different forms of support, (iii) the time period covered by the forecasts, and (iv) the price. For each of the four attributes, three different realisations or levels were considered (see Table 1). All other characteristics of the final PROSNOW® service (e.g. the provided variables and indicators, daily updates of the forecasts, etc.), which had resulted from an intensive co-design and co-development process (cf. Morin, 2020; Morin et al., 2018), were treated as fixed components of each product profile.

We applied the full-profile method in presenting the product profiles to the participating pilot ski resorts; in other words, each presented profile included all attributes considered within the conjoint analysis. To avoid a temporal or cognitive overload of the survey participants, we did not decide on a full design including all 81 profiles but a symmetrical fractional factorial design with nine representative profiles that modelled the main effects. Moreover, we chose a non-metric assessment procedure; that is to say, we asked pilot ski resorts to rank the nine presented profiles in an unambiguous order according to their preferences. Compared to a metric scaled rating exercise, the ranking procedure forces respondents to compare the profiles more carefully and to express their preferences more clearly (cf. Backhaus et al., 2007).

3.3. Data processing and analyses

We used the open-source software R (R Core Team, 2020) for processing, analysing and displaying the data collected by the two surveys. Apart from the limit conjoint analysis, most data analyses were of a descriptive nature.

3.3.1. Survey A

During the nine weeks for which survey A was open to participation, we recorded 78 visits to the survey's pre-page with general information. Representatives from 50 ski resorts actually started the survey. Excluding those respondents who did not move beyond the first question block about the characteristics of the ski resort and respondents, the survey sample used for the subsequent analyses consisted of representatives from 44 different ski resorts. Due to (i) the presence of conditional questions, (ii) the skipping of single questions, and (iii) premature survey termination, the actual number of responses to a particular question partly deviated from 44. Prior to analysis, we adjusted or excluded contradictory or invalid responses:

- One respondent, who stated they used charged-for weather forecasts, but simultaneously indicated a price of €0, was regrouped to the users of free weather forecasts for the analyses.
- One response on the distribution of operating costs was excluded from the analyses since the provided figures did not sum to the required 100%.

3.3.2. Survey B

Seven out of nine PROSNOW pilot ski resorts participated in survey B. One pilot ski resort – consisting of several operating companies – provided two separate completed forms. The subsequent analyses on survey B are thus based on eight (partly) completed questionnaires from seven different pilot ski resorts. For the analysis of the conjoint experiment, we closely followed the example of Backhaus et al. (2007). That is, we applied the traditional approach of estimating the part-worth utilities using ordinary least squares (OLS) regression, with the respondent's total utility of a particular profile as the dependent variable and attribute levels (or dummy variables for attribute levels) as the independent variables. Assuming a linear relationship between price levels and resulting utility, we used a vector model for estimating the part-worth utilities of the price attribute. For the other three attributes (*number of SRUs*, *type of support*, *forecast horizon*), we applied the part-worth model. The estimated part-worth utilities were used (i) to analyse the relative importance of the different attributes and (ii) to derive the pilot ski resorts' WTP for their preferred product profiles.

4. Results

4.1. Characteristics of the ski resorts and the respondents

Almost one-third of the 44 ski resorts that participated in survey A are located in France. Austria and Switzerland each account for 25% and Italy for 18% of the considered ski resorts. In terms of ski resort size, the survey covered quite a broad range. The smallest responding ski resort offers 1 km, the biggest 306 km of ski slopes (see Table 2). Ski resorts located in France tend to rank among the larger ones covered by the survey, those located in Italy among the smaller ones. Compared to the total population of ski resorts in the four considered countries (Skiresort Service International GmbH, 2019), medium to large facilities are overrepresented in the sample. PROSNOW pilot ski resorts that participated in survey B also represent medium to large size areas (see Table 2).

At least 55 people were involved in answering survey A[2]. 51 of them provided details about their position within the ski resort by choosing between three pre-defined categories. The majority of involved respondents ranked among the group "*CEO, owner or operating manager*" (63%), followed by "*snow or slope manager*" (29%) and "*technical manager or technician*" (8%). Involved respondents showed between 0.5 and 47 years of work experience in their current position, with the middle 50% ranging from 4 to 16 years. Choosing between the categories "*a lot*", "*somewhat*" and "*not at all*", most involved respondents (96%) stated they used weather or climate information "*a lot*" in their daily work, with the remaining 4% (i.e. two respondents) making "*somewhat*" use of it. Thus, the overwhelming majority of respondents seemed to be well experienced in the use of weather or climate information and its critical relevance for ski resorts operations.

Survey B was completed by people in high technical or management positions (four "*CEOs, owners or operating managers*", three "*snow or slope managers*" and one "*Technical manager or technician*") with long experience in their current position and good knowledge of the ski resort. The great majority of respondents had been in the resort for more than 12 years and had worked in their current position for more than 7 years. Note that the self-assessed intensity of testing PROSNOW® in the season 2019/20 varied noticeably between pilot ski resorts. On a five-tier scale from "*very low*" to "*very high*", all testing intensities apart from "*very high*" were represented. Reasons for (very) low testing intensities particularly included resort-specific delays in the availability of the fully operative web-based user-interface. As the degree of testing intensity might affect ski resorts' WTP, we discuss potential impacts on our results in sections 4.6 and 5.

4.2. Composition of operating costs

The response behaviour of survey A participants supported the hypothesis that operating costs and their composition represent a sensitive issue for ski resorts. Although only asking for relative shares and no

[2] There was room to list up to four different people – or more precisely their positions and years of experience – involved in answering the survey.

Table 2
Summary statistics of the ski resorts' size – measured in slope-km – for the samples of survey A and B and the population of ski resorts in France, Italy, Austria and Switzerland.

	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
Sample of survey A (n = 44)						
Total sample	1.0	20.0	34.5	67.2	88.5	306.0
France	*12.0*	*41.8*	*82.5*	*103.1*	*137.5*	*300.0*
Italy	*6.0*	*17.1*	*21.0*	*29.4*	*26.3*	*100.0*
Austria	*13.0*	*30.0*	*41.5*	*69.8*	*72.0*	*205.0*
Switzerland	*1.0*	*19.0*	*20.0*	*46.3*	*42.5*	*306.0*
Sample of survey B (n = 8)						
Total sample	34.0	52.0	115.5	117.6	153.8	225.0
Total population (n = 1269)						
Total sample	0.1	1.0	6.8	22.4	23.0	600.0
France	*0.2*	*3.0*	*12.0*	*40.4*	*38.0*	*600.0*
Italy	*0.1*	*3.6*	*9.2*	*20.9*	*21.0*	*322.0*
Austria	*0.1*	*0.8*	*4.0*	*16.0*	*16.0*	*306.0*
Switzerland	*0.1*	*0.9*	*4.6*	*18.7*	*20.3*	*412.0*

Data sources: Survey A; Survey B; Skiresort Service International GmbH (2019).

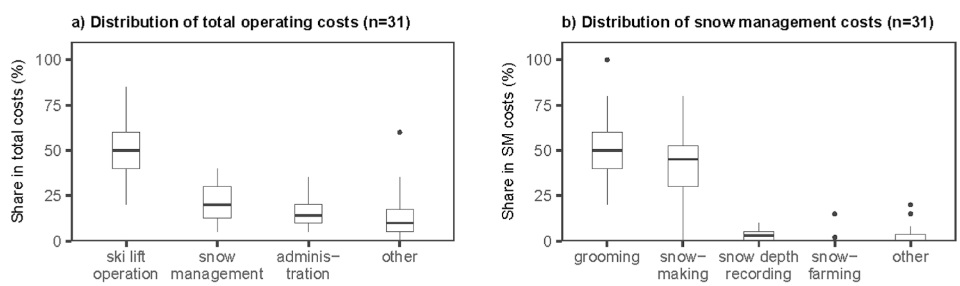

Fig. 2. Distribution of the ski resorts' (a) total annual operating costs and (b) annual snow management (SM) operating costs over different cost categories.

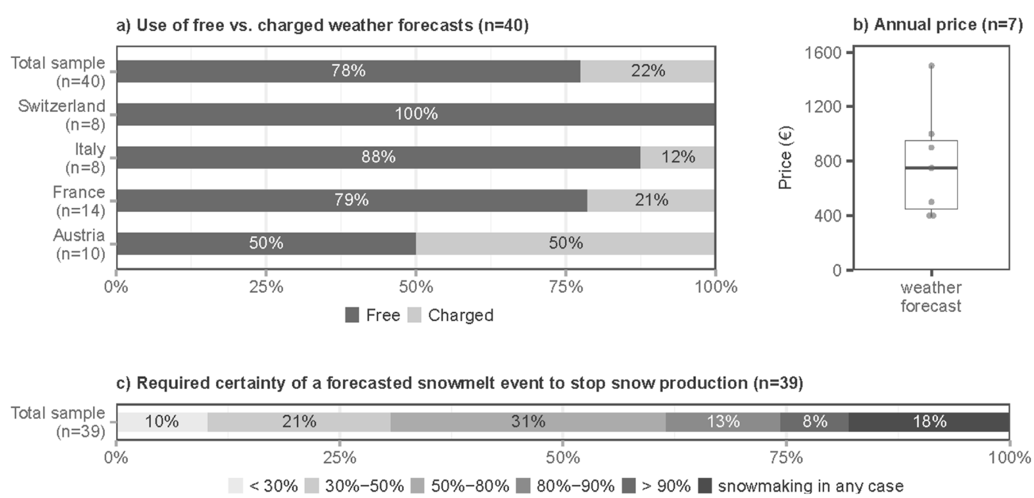

Fig. 3. Responses from ski resorts that participated in survey A: (a) use of free vs. charged-for weather forecasts for planning technical snow production, (b) annual price in the case of charged-for products, and (c) required certainty of a forecasted snowmelt event to stop snow production in the base-layer production phase. Note: any deviations from 100% are due to rounding differences.

absolute numbers to minimise the risk of substantial drop out of participants, the corresponding thematic block showed the highest drop-out rate within survey A, with nine participating ski resorts leaving the questionnaire at this point. Fig. 2.a illustrates the share of different cost categories in total annual operating costs for the remaining responding ski resorts. For most of them (27 out of 31), the category "*ski-lift operation*" accounts for the largest part of operating costs, ranging from 20% to 85% of total costs. The category "*snow management*", accounting for 5% to 40% of total operating costs, typically makes up the second largest part (for 22 of the responding areas), but may also rank first (1), third (7) or fourth (1). "*Administrative costs*", which represent the third-largest cost category for 21 of the 31 responding ski resorts, range from 5% to 35% of total operating costs. Summing up, the shares of the single categories in total operating costs can vary noticeably from ski resort to ski resort.

Taking a closer look at the composition of the category "*snow management*" reveals the dominant role of "*grooming*" and "*snowmaking*" costs (see Fig. 2.b). For 15 out of the 31 responding ski resorts, "*grooming*" makes up the largest share of total snow management operating costs, whereas for another ten ski resorts, "*snowmaking*" represents the dominant cost component. In the remaining six areas, both "*grooming*" and "*snowmaking*" rank equal first among the components of snow management operating costs. With one of the responding ski resorts still relying on natural snow only, cost shares for snowmaking range between 0% and 80%, whereas grooming accounts for 20% to 100% of total snow management costs. The remaining cost categories "*snow depth recording*", "*snow farming*" and "*other*" are almost negligible.

The share of snowmaking costs within total operating costs ranges from 0% to 24%, with the mean at 9% and the third quartile at 14%. No particular relationship was found between the ski resort's size and the share of snowmaking costs within total operating costs.

4.3. Snow management: strategies, products and services in use

At 91%, the great majority of the 44 ski resorts covered by survey A makes use of weather forecasts for planning their technical snow production. The only exceptions are four rather small-scale ski resorts with 1, 5, 15 and 20 km of ski slopes, respectively. One of these ski resorts noted that it still relies solely on natural snow. Most (78%) of the 40 ski resorts that make use of weather forecasts draw on freely available products (see Fig. 3.a). Note that this also holds true for the pilot ski resorts responding to survey B: for five out of eight resorts, the products used are free of charge. In cases where charged-for weather forecasting products are used, annual costs of the responding ski resorts of survey A range from €400 to €1,500 (see Fig. 3.b), whereas pilot ski resorts drawing on fee-based forecasts indicated costs of €2,000 and €3,250 per season.

Results from survey A suggest that the spread of charged-for products is linked to the country of ski resort location. Whereas 50% of responding Austrian resorts are using charged-for products, no single responding Swiss resort is drawing on fee-based forecasting services (see Fig. 3.a). One reason might be differences in the extent of detailed high-quality forecasts offered for free by the respective national weather services.

Most respondents to survey A rated the importance of the weather forecasts used for snow management highly. On a five-tier scale from "*not very important*" to "*very important*", 59% of the ski resorts using weather forecasts to plan their technical snow production assessed the importance of weather forecasts for their snow management with the highest score; another 33% assigned the second-highest score. Only two respondents considered the weather forecasts used "*not very important*" for snow management in their ski resort. Both represented rather small-scaled ski resorts with 13 and 30 km of ski slope, respectively.

For many ski resorts, base-layer snowmaking prior to season start represents a crucial phase that determines whether the scheduled opening date can be met. Hence, there is particular pressure to exploit those timeframes that allow for snow production, and a common strategy is to produce snow whenever possible (Hanzer et al., 2020; Spandre et al., 2016; Steiger and Mayer, 2008). To gain some insights into risk attitudes, snowmaking strategies and the handling of forecasting uncertainties, participants indicating use of weather forecasts for planning technical snow production were asked how certain forecasted subsequent snowmelt would need to be for them to leave perfect snowmaking conditions in the next 24 h unexploited within the period of pre-seasonal base-layer creation. In detail, participants were requested to envision the following situation: it is late fall, around the date that the ski resort normally starts producing snow. The weather forecast is for perfect conditions for snowmaking for the next 24 h that would allow the ski resort's technical snow production to run at full capacity. For the subsequent days, however, there is the chance of weather conditions that would melt all the snow produced in these next 24 h.

Respondents were asked, at what forecast chance of these subsequent unfavourable weather conditions they would not use the next 24 h for snowmaking. They were offered five predefined ranges of percentage values, indicating the probability of occurrence of weather conditions that would melt all the snow produced in the preceding 24 h (see Fig. 3.c). In addition, respondents could also decide on the option of using the next 24 h for snowmaking in any case.

Seven out of 39 responding ski resorts (i.e. 18%) stated that they would use the next 24 h for snowmaking in any case (see Fig. 3.c). Another three respondents (i.e. 8%) would only refrain from snowmaking if the chance of a total melt of the produced snow was 90% or higher, five respondents (i.e. 13%) if the certainty for snow melting was 80% to 90%. Thus, almost 40% of the asked ski resorts either required quite high certainties of the forecasted snow melting (80% and more) or were completely unwilling to leave potential snowmaking time unexploited in the phase of base-layer production.

At the opposite end of the scale, four respondents (i.e. 10%) stated that a melting-risk of less than 30% would suffice to decide against snowmaking within the next 24 h and another eight (i.e. 21%) would refrain from snowmaking in the case of a melting chance between 30% and 50%. Given the expected risk aversion regarding late season opening, it is somewhat surprising that about 30% would decide against snowmaking in the case of a melting risk of below 50%. Apart from any misinterpretations of the question, one likely reason could be very limited water resources and the corresponding necessity to avoid any risk of waste.

Table 3
Comments at the end of the survey with a reference to reliability. Additional columns show the respective respondent's rating of PROSNOW®'s importance for snow management (1 = not very important; 5 = very important) and their interest in a service like PROSNOW®.

Comments related to reliability	Importance	Interested
"Everything depends on the reliability that PROSNOW® can guarantee. […]"	5	somewhat
"[…] the tool must be really reliable – interest will come with its reliability."	3	somewhat
"I do not know if we will take the risk of modifying our productions on the basis of a seasonal forecast, but if this proves to be reliable, it will allow us to refine our volumes produced. […]"	4	very
"Forecasts farther than 5 days in the future are unreliable and useless, even with showing information about uncertainties."	1	not at all
"The challenge will be to use a prediction tool – based on statistics and historical data – to decide in November to produce less or more technical snow. What if it turns out that the prediction was wrong – close the slopes?!? […]"	4	very

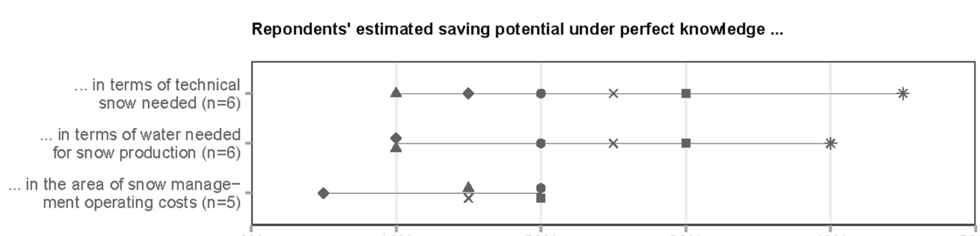

Fig. 4. Average seasonal saving potential expected by the respondents if they had perfect knowledge about the upcoming season's weather and snow conditions. Identical symbols refer to one and the same respondent.

Besides weather forecasts, the great majority (84%) of the 44 ski resorts responding to survey A indicated drawing on further snow management tools, including products and services for snow depth recording (55%), grooming management (55%) and snowmaking (66%). With respect to snowmaking, automatically operated systems – used by 50% of the responding ski resorts – are more common than manually operated ones (23%).

Asked about the benefits of the snow management tools and services used, seven out of 25 responding ski resorts referred to efficiency improvements and optimal use of resources. Improved planning represented another benefit that was mentioned six times. One respondent, who uses manually operated snowmaking, own records and experience, noted: "*[…] However, in snowy winters less technical snow would need to be produced if it was known in December how much snow was going to come in January, February, March …*".

4.4. Saving potential from perfect knowledge

One important aspect in assessing the relevance and potential market of products and services aiming to improve ski resorts' capacity to anticipate upcoming meteorological and snow conditions is the theoretical saving potential under perfect knowledge in the area of snow management. The higher the theoretical saving potential, the higher the need to increase the capacity to anticipate.

If they had perfect knowledge about the upcoming season's weather and snow conditions, pilot ski resorts responding to survey B would expect benefits, facilitations and savings in the areas of snowmaking and grooming, particularly in terms of facilitations in staff planning and savings in water, energy and machine hours. Respondents' estimates of the average seasonal saving potentials under perfect knowledge, compared to the current situation, ranged from 10% to 45% in terms of reduced amounts of technical snow needed and from 10% to 40% in terms of less water needed for producing this reduced amount of technical snow (see Fig. 4). Expected average seasonal savings in the area of snow management operating costs ranged from 5% to 20%. Note, however, that the respondent who indicated the highest expected saving potentials in terms of snow and water amounts (45% and 40%) expressed the expected cost savings in absolute instead of percentage terms, indicating an average seasonal saving potential of €50,000.

4.5. Interest in a forecasting service like PROSNOW®

Expert judgments of the pilot ski resorts suggest that the "uncertainty surcharge" due to imperfect knowledge about upcoming weather and snow conditions can account for significant proportions of total snow production and related water consumption and also of total snow management operating costs (see Fig. 4). Based on this result, we would also expect some interest in a forecasting service like PROSNOW® among the broader sample of ski resorts from survey A; and indeed, the responding ski resorts show quite high basic interest in a (sub-)seasonal service like PROSNOW® that aims at improving capacity to anticipate upcoming meteorological and snow conditions. On a three-tier scale, 41% (n = 32) stated they were very interested, another 47% somewhat interested. One respondent noted that the interest in the service would depend greatly on its reliability. The importance of reliability was also emphasised in some respondents' comments at the end of the survey (see Table 3). Only four of the responding ski resorts indicated not being at all interested in a service like PROSNOW®. Two of them explicitly stated a reason: one small ski resort of only a few slope kilometres reported it focused mainly on (non-skiing) operations during the summer season. Another respondent explained their disinterest by the uncertain nature of forecasts for more than the next five days.

Respondents also assessed the importance of a service like PROSNOW® for snow management in their ski resort as quite high. On a five-tier scale from "*not very important*" to "*very important*", 13% of the 31 responding resorts assigned the highest score, another 52% the second highest score. Areas of application for which the largest fractions of responding resorts rate a service like PROSNOW® to be useful or very useful include the optimisation of water and electricity use (81% and 74% of respondents), the avoidance of snow overproduction (71%) and snowmaking decisions for the upcoming week (68%). Snowmaking decisions for the upcoming season, by contrast, represents the area of application that showed the highest fraction of respondents being sceptical about PROSNOW®'s usefulness (see Fig. 5).

Similar outcomes were found among the pilot ski resorts in survey B. All eight responding resorts had either actually experienced or at least imagined PROSNOW® to be of use in the areas of snowmaking decisions for the upcoming hours, optimisation of water and energy use and planning of resources. Further areas of application, for which a great majority of pilot ski resorts (7 out of 8) attested to PROSNOW®'s actual or expected usefulness, included snowmaking decisions for the upcoming days, avoidance of snow overproduction and support in internal and external communication, the latter being an additional category within survey B.

4.6. Service design and willingness to pay

Questions about service design and WTP concentrated on the group of pilot ski resorts, due to their knowledge of and experience with PROSNOW® from the co-design process and the real-time testing. Six of the eight respondents to survey B answered the part on the limit conjoint analysis[3]. As illustrated in Fig. 6.a, the individual preference structures derived from the respondents' rankings of the product profiles vary noticeably. The greatest diversity in preference orders is found for the attribute *types of support*, where four of the (in total, six) possible orders occur among the respondents. *Consulting* is ranked highest by three respondents. Another two respondents prefer *training*, whereas one respondent favours *no support*.

Regarding the spatial coverage of the forecasts, most (four out of six) but not all respondents prefer more over less SRUs (i.e. slope segments), with different utility gains from *1* to *5* SRUs and from *5* to *>100* SRUs. For two respondents, by contrast, *5* SRUs represent the optimum of the three considered levels.

In terms of the attribute *forecast horizon*, all respondents show a clear preference for forecasts that span all days until season end, but there are differences in the ranking of forecasts spanning the next 4 days and forecasts spanning the next 10 days.

For the last considered attribute, we would expect the respondents' utility to increase with decreasing prices in terms of plausibility. This is actually the case for all respondents with one exception. Since the part-worth utilities of respondent 6 violate the plausibility criterion of a negative price effect[4], this respondent is excluded from further analyses on WTP.

Respondents show a great diversity, not only in terms of their preference orders within the single attributes, but also in terms of the relative importance of the different attributes for overall preference formation (see Fig. 6.b). This relative importance is indicated by the highest normalised part-worth utility within the considered attribute. For three respondents, the attribute *forecast horizon* is dominant in preference formation, but each time with different intensity. The remaining respondents react most sensitively to changes in the *price* attribute (2) or the *number of SRUs* (1). Such heterogeneous preference structures suggest using a modular product design, where customers can choose to add modules of predefined types of support or additional SRUs

[3] The two resorts who did not answer the question on the limit conjoint analysis indicated a low and very low overall testing intensity of PROSNOW® during the winter season 2019/20, due to too late readiness of the service for their resorts.

[4] Note that directly asking pilot ski resorts about their WTP revealed a negative price effect for respondent 6.

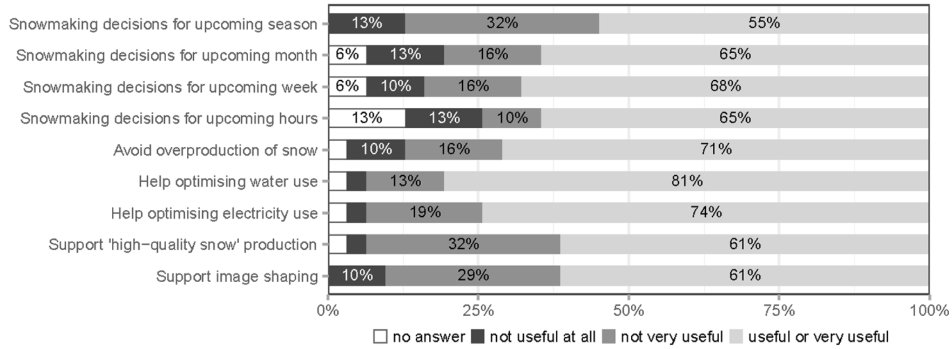

Fig. 5. Respondents' assessment of PROSNOW®'s usefulness for different areas of application (note: deviations from 100% are due to rounding differences; n = 31).

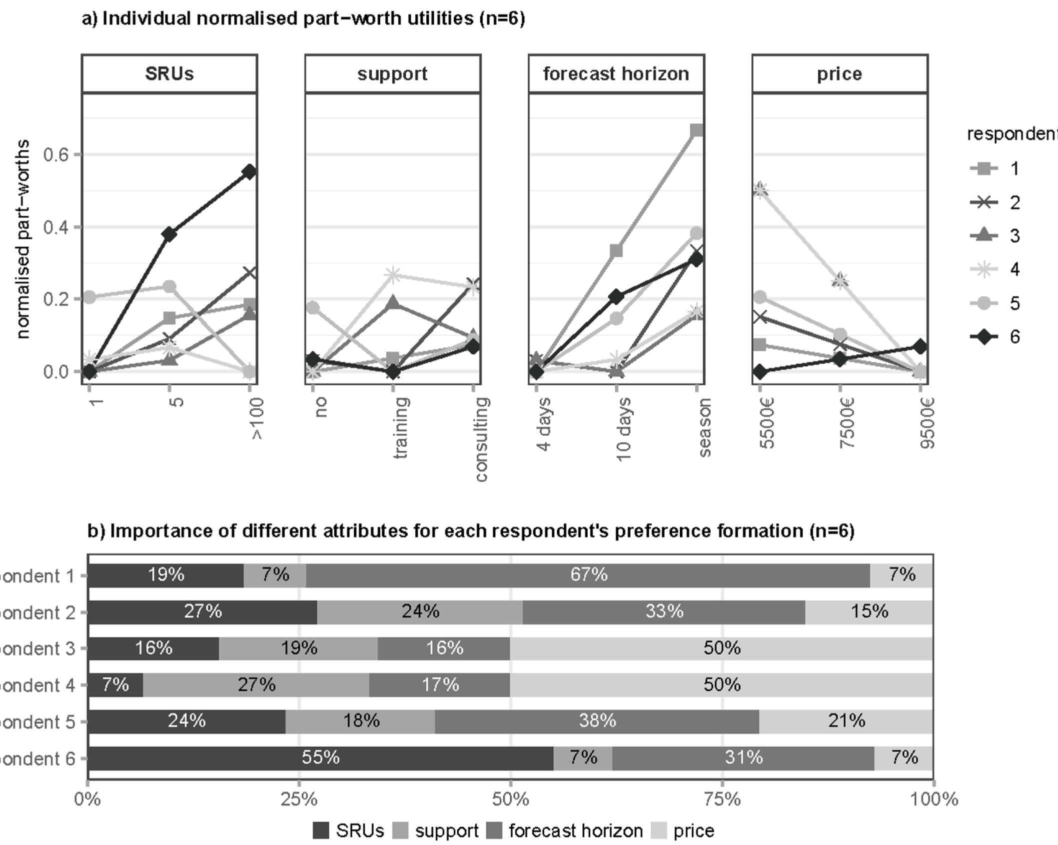

Fig. 6. Results from the limit conjoint analysis. a) Individual normalised part-worth utilities and b) relative importance of the different attributes for each respondent's preference formation.

Table 4
Profile with highest total utility per respondent and willingness to pay (WTP) for this profile.

Respondent	Product profile			WTP
	SRUs	Support	Forecast horizon	
1	>100	consulting	season	€10,500
2	>100	consulting	season	€12,700
3	>100	training	season	€8,600
4	5	training	season	€7,400
5	5	no	season	€12,400
6	>100	consulting	season	–

to their base package.

The inclusion of the price as one assessment dimension allows derivation of the maximum price each respondent is willing to pay (WTP) for a particular simulated product profile, based on the estimated part-worth utilities. For each respondent, Table 4 points out the most preferred product profile together with the maximum price the respondent would be willing to pay according to their answers to the limit conjoint exercise. Depending on the respondent, WTP for the most preferred profile ranges from €7,400 to €12,700 per season. Note that a higher self-assessed overall testing intensity of PROSNOW® during the winter season 2019/20 usually coincided with a higher WTP.

5. Discussion and conclusions

Compared with the number of existing Alpine ski resorts, the samples covered by the presented surveys are rather small; nevertheless, they encompass a meaningful range of different ski resort sizes and locations in four different Alpine countries. Hence, although the presented results might not be representative for Alpine ski resorts in general, they shed further light into the composition of ski resorts' operating costs, their snow management practices, their risk attitudes towards uncertain forecasts for planning their snow production and the value of improved capacity to anticipate. This provides some valuable insights for the development and provision of (sub-)seasonal CS addressing daily operational decision-making in ski resorts' snow management.

Our results show that – depending on the ski resort – snow management can account for a considerable fraction of total operating costs (5% to 40% in our sample). This makes the optimisation of snow management a highly relevant topic for some ski resorts. Moreover, climate change is expected to further amplify this need for optimisation (Hock et al., in press). There is hardly a ski resort in the survey samples not drawing on any products or services for supporting their snow management. Besides products, tools and services for snowmaking, snow depth recording, and grooming management, the use of weather forecasts is particularly common among survey participants. Despite their widespread use, the capacity to anticipate upcoming meteorological and snowpack conditions remains limited, however, and causes the production of "snow safety buffers". Based on evidence from the pilot ski resorts, this "uncertainty surcharge" of snow produced due to imperfect knowledge about upcoming weather and snow conditions paired with high risk aversion is likely to represent a noticeable share of total snow production and related water consumption as well as of total snow management operating costs. Depending on the pilot ski resort, respondents expect that perfect knowledge would reduce the amount of technical snow needed by 10% to 45%, the amount of water needed by 10% to 40%, and total snow management operating costs by 5% to 20%. Hence, there seems to be room for services that are able to improve the ski resorts' current ability to anticipate weather and snow conditions.

This is also supported by the fact that the majority of ski resorts covered by the surveys showed interest in a forecasting service like PROSNOW® that aims at improving ability to anticipate and considered such a service important for snow management. Areas of application, for which the largest fractions of responding ski resorts rated a (sub-)seasonal service like PROSNOW® to be (very) useful included the optimisation of water and energy – note that according to Jevons' paradox (see e.g. Alcott, 2005), optimisation does not necessarily imply actual reductions in resource use – and the avoidance of snow overproduction. As highlighted by the comments of some survey participants, actual uptake and usage of (sub-)seasonal CS by ski resorts will depend greatly on their reliability; particularly in the case of very risk averse snow managers.

Overall, risk attitudes among ski resort managers towards potentially false forecasts seem to be quite diverse. Many ski resorts responding to survey A turned out to decide on a no-risk or low-risk strategy when it comes to building a basic snow cover in the pre-seasonal period. On the other hand, there was also a considerable fraction that – to varying degrees – showed willingness to consider uncertain information on subsequent meteorological conditions when deciding about whether actually exploiting current periods of adequate snowmaking conditions within the pre-seasonal period. One reason for some degree of risk taking could be limited water resources (e.g. due to limited capacities of snowmaking reservoirs, limited amounts of water allowed to be taken from waterbodies for filling the snowmaking reservoirs, etc.). Since melted snow does not directly go back into the snowmaking reservoirs, for ski resorts with limited water availability, the premature melting of produced snow in early season may impose a double cost: apart from the money wasted, their remaining water resources might not suffice to make up for the lost snow and result in fewer operating days. Hence, they need to weigh the risk of a wrong forecast against the risk of wasting water. Another reason for some degree of risk taking could be high enough altitudes and hence high chances for sufficient snowmaking hours without the necessity to make use of snowmaking windows that coincide with some risks of subsequent melting conditions.

Although our surveys revealed and confirmed several aspects with a positive impact on the theoretical demand for (sub-)seasonal CS in the field of ski resorts' snow management – including high saving potential from perfect or improved knowledge of upcoming weather conditions in some ski resorts, widespread experience in the use of forecasts and snow management tools, and a noticeable portion of actors willing to consider uncertain information in decision-making to some extent – WTP for (sub-)seasonal CS seems somewhat limited. Deriving the pilot ski resorts' WTP by systematically varying selected product attributes in a limit conjoint analysis resulted in maximum chargeable prices between €7,400 and €12,700 per season for the respondents' most preferred PROSNOW® product packages (excluding system set-up). There are several potential reasons for this limited WTP: (i) The market for weather forecasting products is characterised by a huge amount of freely available information, which is likely to level down WTP for forecasting services in general, including (sub-)seasonal CS addressing daily operational decision-making in ski resorts' snow management. (ii) Some ski resorts already spend a lot on snow management tools and they may require hard evidence and a number of success stories about profitability and added value before being willing to spend more on new, not yet proven services. (iii) Pilot ski resorts only had one season for testing PROSNOW® and for some resorts, late readiness of the web-based demonstrator further shortened actual testing. Resorts that indicated a very low or low testing intensity either did not answer the question on WTP or showed a lower WTP than resorts with a medium or high testing intensity. Hence, our results might not fully reflect resorts' WTP after intensive testing. Moreover, it is expected to take some time before users learn how to best make use of the information provided by (sub-)seasonal services in their decision-making processes and to fully exploit the potential added value of a particular service. Hence, WTP could change over time.

Several lessons for the development and provision of (sub-)seasonal CS in the field of snow management can be learnt from the empirical data presented in this paper. (i) For the actual uptake and success of (sub-)seasonal CS it is crucial to clearly demonstrate the added value over currently used – and most often freely available – weather forecasting products. (ii) It is also important to demonstrate where and how even uncertain information can be of added value for decision-making. Fully exploiting uncertain information may require training and capacity building, which could be part of the service offer. (iii) Since WTP seems somewhat limited, providers of (sub-)seasonal CS need to carefully weigh the costs of provision of each single service component against added value for customers in order to design commercially viable packages. (iv) It is to be expected that the added value of and the willingness and ability to pay for (sub-)seasonal CS vary noticeably from ski resort to ski resort, depending amongst other things on the resort's size, its dependence on technical snow and water availability, but also on the degree of its technisation in the field of snow management. A flexible and modular product design, resulting in different price categories, could help to account for these differences.

Most of these lessons also apply to other sectors with similar risk aversion and strong weather or climate sensitivity including, amongst others, agriculture and energy. Not only the PROSNOW® concept (impact-based and seamless across time scales) but also the methodology for assessing the demand side of the market could be inspiring for such sectors.

CRediT authorship contribution statement

Judith Köberl: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Hugues François:** Conceptualization, Methodology, Writing – review & editing. **Jonathan Cognard:** Methodology, Software, Investigation, Writing – review & editing. **Carlo Carmagnola:** Conceptualization, Investigation, Writing – review & editing. **Franz Prettenthaler:** Writing – original draft, Writing – review & editing, Supervision. **Andrea Damm:** Writing – original draft, Writing – review & editing. **Samuel Morin:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Météo-France, Dianeige and to lesser extent INRAE are involved in the commercial exploitation of the PROSNOW® service.

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Appendix A. Supplementary data

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