Artificial snow optimization in winter sport destinations using a multi-agent simulation

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Abstract. This paper presents the Juste-Neige system for predicting the snow height on the ski runs of a resort using a multi-agent simulation software. Its aim is to facilitate snow cover management in order to i) reduce the production cost of artificial snow and to improve the profit margin for the companies managing the ski resorts; and ii) to reduce the water and energy consumption, and thus to reduce the environmental impact, by producing only the snow needed for a good skiing experience. The software provides maps with the predicted snow heights for up to 13 days. On these maps, the areas most exposed to snow erosion are highlighted. The software proceeds in three steps: i) interpolation of snow height measurements with a neural network; ii) local meteorological forecasts for every ski resort; iii) simulation of the impact caused by skiers using a multi-agent system. The software has been evaluated in the Swiss ski resort of Verbier and provides useful predictions.

Keywords: Multi-agent simulation, artificial snow optimization.

1. Introduction

Since the early 2000's, the use of artificial snow to guarantee the economic viability of ski resorts has been confronted with the paradigms of climate change and sustainable development [11]. Publications on climate change show that this situation will not improve [4]. Currently, no other economic model seems to be attractive enough to replace the ski economy. The Juste-Neige project is a scientific and commercial attempt to contribute to a more sustainable management of the resources needed for mass skiing. It was developed for the company GeoSnow (www.geosnow.ch), in cooperation with the Swiss cableway companies of Verbier, Champéry, Zermatt and Saas-Grund. To achieve this, Juste-Neige predicts the snow height on the ski runs of a resort using a multi-agent simulation software. Its aim is to facilitate snow cover management in order to i) reduce the production cost of artificial snow and to improve the profit margin for the companies managing the ski resorts; and ii) to reduce the water and energy consumption, and thus to reduce the environmental impact, by producing only the snow needed for a good skiing experience.

The result of the project is a tool that, based on meteorological factors and the usage intensity of the ski runs, provides maps with the predicted snow heights for up to 13 days. On these maps, the areas most exposed to snow erosion are highlighted. The persons responsible for the ski runs can then adapt their snow management. The software proceeds in three steps: i) interpolation of snow height measurements with a neural network; ii) local meteorological forecasts for every ski resort; iii) simulation of the impact caused by skiers using a multi-agent system. The software has been evaluated in the Swiss ski resort of Verbier for two seasons and provides useful predictions for the management of the ski runs.

Related literature on ski resort models and the prediction on snow height cover several aspects. The first topic concerns the study of ski resorts infrastructures [1], which discusses mainly graph aspects, without simulations. The second aspect concerns sociological and behavioral descriptions of skiers [13]. There is then an important amount of work on economical studies on ski resorts [6]. Among those works, [9] presents a very interesting analysis of management decisions on effectiveness of ski resorts. To achieve this, the authors have realized a simulation with skiers moving from cableways to cableways, however without simulating skier movements on slopes and therefore without simulating the impact on snow. Finally, several work concentrate on past snow height measures [2] and snow behavior in itself [8] thus mainly from a physical point of view. The Juste-Neige project mainly innovates in binding research on the infrastructure (graph aspect), skier behaviors with their simulation on the graph, and their impact on the snow cover of all slopes of the resort. Thus, the main novelty concerns the interaction between the snow cover and its usage.

This paper presents the software in general and the multi-agent simulation in particular. It is subdivided as follows: Sec. 2 presents the general aspects of the Juste-Neige software, the required data and the steps involved. Sec. 3 presents the multi-agent simulation of the skiers and of the impact calculation. In Sec. 4, a validation of the software is discussed, followed by a conclusion.

2. General description of the Juste-Neige software

The Juste-Neige tool presents many similarities with geographic information systems (GIS). The users can move, zoom and filter information in the cartographic environment. It manages two types of spatial representations: i) bitmap representation (for surfaces), based on a value matrix; and ii) vector representation (for cableways, runs, etc.), based on geometric primitives (point, line, circle, polygon), each with a certain number of attributes (position, color, filling).

To make predictions, the following *data* is needed for every resort: i) a map of the ski runs in a database format; ii) a digital terrain model (DTM) with a resolution of at least 5 meters (a DTM is described as a grid with squares of a specific length resolution); iii) map of the cableways in a vector format; iv) concavity map showing the density of the concave areas (derived from the DTM); v) meteorological data (e.g. fresh snow in cm during a 24-hour span, rain-snow altitude, altitude where the temperature is -10°C; vi) a grid of snow height measurements; vii) dates of school holidays; viii) daily number of cableway passengers of previous years (Skidata).

Juste-Neige carries out a simulation in the following *three steps* (the results of each step are used for the next step):

Automatic analysis of snow height. The goal of the first simulation step is the *spatial interpolation* of unknown points, which is a problem that can be found in many applications (e.g. [5]). The problem is the following: using measurements from the monitoring network of one or several variables, the goal is to predict a variable of interest at the places where there are no measurements. If this prediction is carried out on a grid, then a map can be produced. Several methods from Machine Learning can be used. Juste-Neige uses general regression neural networks (GRNN), because of some useful features: automatic tuning of parameters (using leave-one-out cross-validation technique) and its ability to define so-called "validity domain", i.e. domain where reliable predictions can be performed. The input of the algorithm is an incomplete map of snow heights that was produced by georadar on the snow grooming machines (snow grooming machines cannot cover the whole ski resort every day). The details of the applied GRNN have been published in [12] and are out of scope of this paper, which concentrates on the multi-agent simulation.

Meteorological simulation. The map resulting from GRNN is then integrated into the simulation model of meteorological factors, that uses an algorithm acting like the influence of the weather on the snow height variation. The definition of this algorithm is based on the measurements of fresh snow and of snow heights made in Verbier in 2009. The data of local weather stations was used and corrected according to the daily snow reports. Assuming that the snow heights are known for the day in question (day D), the variation of the snow height Dh 24 hours later is calculated, i.e. for day D+1 (at the same time as on day D and at approx. 7.30 am the next day). To calculate the variation Dh for more than one day, this process is used iteratively up to 13 days. The result will be a new map of the different snow heights.

Multi-agent simulation. The impact of the skiers is caused by the friction of their skis on the snow. To produce a map that takes into account every individual skier‘s friction, we need a way to simulate every single skier individually, and its singular impact on the ski runs. From a methodological point of view, a model such as differential equations cannot calculate this kind of impact. This is however possible using an agent-based simulation of the skiers that will make it possible to study the erosion impact of individual skiers. This is what the 3rd step of Juste-Neige does: the skiers in a resort and their impact on the snow are simulated. Every impact depends on several parameters such as the pressure exerted on the floor by the skier, the contact surface, the type of material, and the intrinsic qualities of the snow cover. The agents' movement can be seen even during the simulation. The result of the simulation of the flow of skiers can be finally seen on a map of the resort. The remainder of this paper explains how the multi-agent simulation is carried out.

3. Impact caused by skiers (multi-agent simulation)

The multi-agent simulation used to study the skiers' impact can be subdivided into four steps: i) estimation of the number of skiers in every cableway; ii) simulation of the flow of skiers to determine their distribution in the resort; iii) cinematic simulation of their behavior for their distribution on the ski runs; iv) simulation of their impact on the snow cover. The aim of the first two steps is to simulate the daily load of the network (cableways and ski runs). Through statistical reasoning, we can estimate the number of agents per cableway by analogy with similar situations from previous years for which the daily number of skiers is provided by the cableway companies thanks to the Skidata system. Using probabilities based on the number of skiers at the bottom of the cableway and on a field study, we can simulate the flow of skiers from the top of the cableway stations to the bottom of another cableway station. A cinematic simulation allows us to simulate the skiers' movements and to coherently animate them on the ski runs. It allows estimating the skiers' distribution on the ski runs. Combined with a snow erosion law, we get the result of the skiers' impact on the ski run. In the remainder of this section, the stages of the multi-agent simulations are explained.

Our multi-agent simulations use two kinds of data: *The number of users of the different cableways in every resort,* obtained through the Skidata system (http://www.Skidata.com/), gives us information about the number of passenger transports for every cableway on every day of the past season. Using it, we can estimate the number of skiers for every day of the simulation.

The simulation then uses the results of a *survey* on different criteria (visitor influx, weather, snow quality, etc.) that may influence the probability of the skiers' choice of a ski run [3]. This survey has shown that among the 14 factors that influence the skiers' behavior, the snow quality and the weather have a significant influence on the choice of the ski run difficulty and provides the percentage of skiers who choose a blue, red, black or yellow run (difficulty levels). Those factors were integrated into the software as a set of rules.

Definition of standard days

A simulation of 13 days in the future is required. For every day, the number of skiers and their distribution in the resort must be estimated. Based on the Skidata database, the past day most similar to the simulation day has to be determined first. Past visitor traffic data of the cableways is used to determine the skiers' distribution in the resort.

Using statistical data analysis methods, it is possible to create representative groups of a situation. These groups are called *standard days* (e.g. *holiday, weekend,* *cloudy)*. By defining a method for finding the standard day that is the closest possible to the day to be simulated, the number of skiers most likely to be present during the simulation of the day in question can be determined. In order to choose standard days, we carried out a multivariable statistical analysis to determine influential factors and confirm their interrelations and to eliminate redundant variables. The result is the following: i) holiday, weekend or weekday; ii) sunny, cloudy, with or without rain or snow; iii) temperature at midday at an average altitude of the resort. In a second phase, we used the factor scores of correspondence analysis to construct a robust classification system of the standard days, using a 3-step process: i) **Hierarchical ascendant classification** (HAC) according to individual scores on the factorial axes, in order to discover the optimal structuring of the data set. However, as the individuals are sometimes incorrectly classified, we used the k-means method to construct the effective classification: ii) **K-means classification**, that guarantees a good classification of the individuals in the different groups with the number of clusters provided by the HAC of the previous step; and iii) **Discriminant factor analysis** of the k-means classification to evaluate the robustness of the classification of standard days, using the confusion matrix between the a priori classified individuals (k-means method) and the a posteriori classification (discriminant factor analysis).

Finally, we have subdivided the statistical groups into four subgroups: holidays and weekends, holidays and weekdays, non-holiday weekends and non-holiday weekdays. This considerably reduces ambiguities and allows us to define the characterization rules for the standard days. As a final result, a standard day was attributed to every day to be simulated. The visitor information for this standard day (available through Skidata) was used to distribute the number of skiers to simulate and to calculate the probabilities of their trajectories.

Simulation of the flow of skiers

The number of skiers on every cableway is defined based on the Skidata data for the chosen standard day. We therefore know how many skiers leave the point of departure (cableway top station) and how many arrive at the point of arrival (cableway bottom station), as the number of arriving and departing skiers is the same. In the example in Figure 1, 600 + 1500 skiers arrive at the point of arrival A1 and 1500 + 300 leave from the point of departure D2.

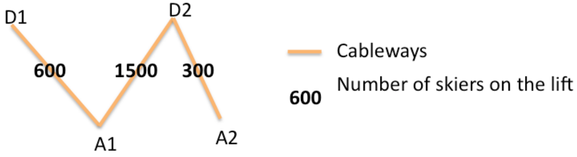

Figure 1: Flow of skiers on cableways

To simulate the flow of skiers in our resort, we first have to model the resort as a directed graph. In this graph, each ski run section is a directed arc and each intersection is a node (cf. Figure 2). The processing speed can be optimized by deleting the points, which are not intersections from the ski runs, and by keeping only decision points. The agents will move along these arcs to their point of arrival.

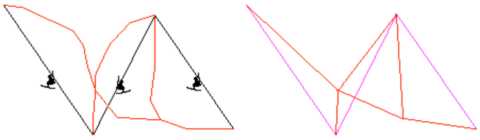

Figure 2: Creation of the flow graph

Once the graph has been designed and the number of skiers per cableway is known, the skiers must know their point of arrival at the bottom of the ski runs. This destination must comply with the constraint concerning the number of skiers (i.e. the number of skiers at the bottom and the top of the cableway stations given by Skidata) and the probabilities of the choice of a ski run based on the surveys.

From its starting point (at the top of the slope), a skier has many different possible destinations. We need therefore to calculate in advance all ***probabilities to arrive to all destinations***. For that, we use an iterative probability weighting algorithm that bases on Skidata counts of the cableways. Intuitively, the algorithm considers the chances of a skier as higher to go where the greatest number of skiers has arrived (given by the numbers in the cableways). For the four resorts in study, the algorithm converges in approximately 100 iterations. We do not present here details of the algorithm because of lack of space.

With this method, we can thus find the point of departure and arrival of all skiers of our simulation, using only the Skidata visitor information. We can now determine the ***trajectory of every skier to reach the point of arrival*** (the simulation of their movements will be made in the cinematic simulation section below). To determine a skier's route between the point of departure and the point of arrival, he must be moved along the graph. To avoid random movements or lost skiers, the nodes that are most likely to be passed are referenced in an efficient data structure. Only the nodes that allow the skier to go from the point of departure to the point of arrival are taken into consideration. The flow of skiers is then moved from referenced node to referenced node until a decision point is reached (point where the skiers have to decide on a route). At this point, the flow is divided according to the ski run probabilities provided by the survey. Finally, we obtain a number of skiers for every route and the number of skiers who have passed through every arc of our graph (cf. Figure 3).

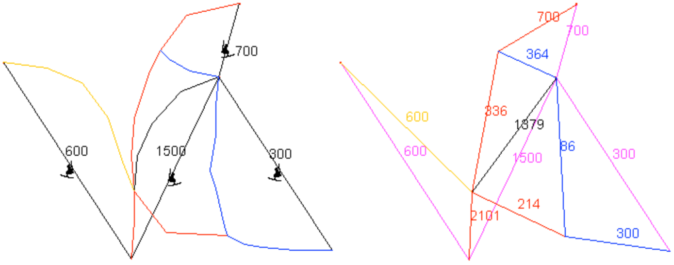

Figure 3: Result of the distribution of the skiers

Cinematic simulation

With the cinematic simulation, we assimilate the skiers with agents. We use a physically inspired cinematic simulation, similar to Craig Reynolds' algorithm [10] for the simulation of bird flocking. This type of simulation is based on the fact that the displacement of a body is nothing else than the sum of the forces that act on it. In our case, a skier's behavior can be assimilated to a body influenced by its attraction to the subsequent point on the ski run, the oscillation around the axis of the ski run and a random vector ensuring a homogeneous distribution. In our simulation, we made the assumption that all skiers remain on the runs. In reality, a small amount of skiers may choose sometimes to go outside the runs.

After a short estimation based on a worst case scenario for a ski resort such as Verbier, we envisage to simulate up to 100,000 agents per simulation day, i.e. 1,300,000 for 13 days. This means though that we have to use a simplified skier behavior model and that we need to considerably optimize the corresponding algorithm.

Action plan. To link the flow simulation and the cinematic simulation, we have introduced an "action plan". The action plan is an ordered list of points that represent the route of a skier. At the end of the flow simulation, we design an action plan for every route that has been found. The arcs are successively decomposed into ski run points. This action plan is then used to create the corresponding number of skiers.

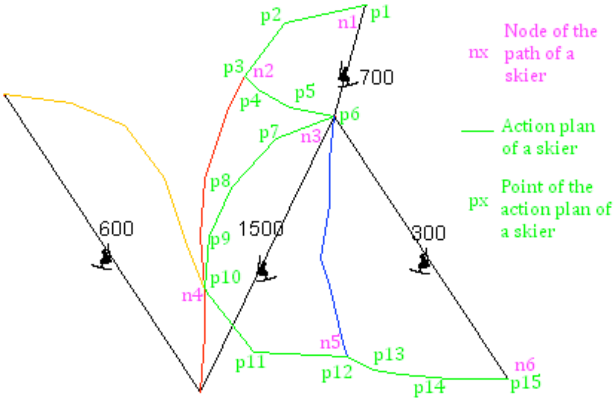

Figure 4: Action plan

In the example of Figure 4, the flow simulation has resulted in the estimation that x skiers have taken the following route: n1 => n2 => n3 => n4 => n5 => n6. The route is decomposed into points on the ski run (p1, p2 … p15), which form the action plan. Hence, x skiers are constructed with this action plan.

Modeling of the skiers' behavior. Next, the skiers' behavior has to be modeled and implemented. The aim is not to create a realistic skier behavior – which would be far too complex to model and to simulate – but to create a model that allows a distribution of realistic routes of the skiers on the ski run. The behavior is thus relatively simple: it does not take into account the skiers' individual features (weight, level of expertise) or the events that could change their actions (collision). These simplifications allow us to disregard the time factor: all agents leave at the same time. The thrust is therefore to move the agents from point to point with a trajectory that is similar to the one of a real skier. We model this behavior using three influence vectors:

- *Directional vector*: It is recalculated at every time step and directed towards the next target point (i.e. the next point to reach in the action plan). Its norm is unitary in order to preserve the mathematical properties of the oscillation vector, cf. below.
- *Oscillation vector*: It is characterized by a sinusoidal curve whose attributes are described hereafter: i) the axis is the straight line that goes through the last node and the following node; ii) the amplitude of the oscillation is a random value between 0.4 and 0.9 times the width of the ski run; iii) the period is a random value between 20 and 40 meters; as the directional vector is unitary, the period is not disturbed. The attributes of the sinusoidal curve evolve progressively in order to avoid discontinuity problems with the trajectories.
- *Random vector*: Allows a homogeneous distribution of the skiers. Its norm is unitary so not to distort the skier's trajectory too much.

The results for one skier (cf. Figure 5a) and for 1,000 skiers (cf. Figure 5b) show a satisfactory distribution.

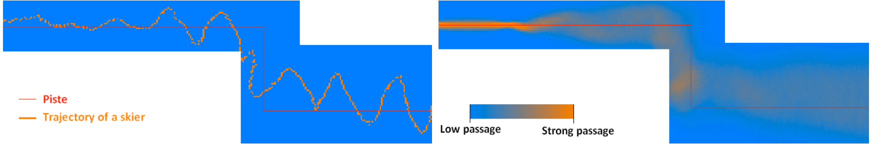

Figure 5: a) Trajectory of a skier and b) distribution of skiers on the ski run

Law of skiers' impact on snow cover

Now, the impact of the skiers' passage on the snow has to be determined. The characteristics of the ski run (incline, hardness, concavity) at the moment of passage have to be taken into account. We define an impact law that quantifies the erosion of the snow cover for the skiers who have passed through. We base on the assumption that there exists an average coefficient of the pressure factor of a skier according to his weight and level, the material and the contact area with the ground. This enables us to ignore the particular features of the skier. This estimate is justified for two reasons: i) the relative homogeneity of the types of skiers in a resort; ii) a sufficient number of skiers to envisage an average coefficient for all of these phenomena.

The analysis of the snow heights in the different resorts has shown that the impact of the skiers mainly depends on three parameters:

- *Slope of the ski run:* The flatter the ski run, the less the skiers oscillate and the less they erode snow. This is expressed by a slope coefficient linked to the difference in altitude between two nodes of the run, divided by the distance between them.
- *Concavity of the ski run:* The snow has a tendency to accumulate in the concave parts of the ski run. We have therefore designed a concavity map based on the digital terrain model, which has a concavity coefficient in every cell of the raster.
- *Hardness of the ski run:* The warmer the snow cover, the bigger the skiers' impact. We have therefore established a hardness equation based on the distribution of the temperatures measured at 7 am during the entire winter season. This equation defines a hardness coefficient.

The product of the coefficients of the ski run, the concavity and the hardness gives an overall form of the skiers' impact, weighted by parameterizable coefficients that integrate the average coefficient of the pressure factor.

4. Validation and conclusion

The tests carried out for a 13 days prediction have shown that the Digital Terrain Model's (DTM) resolution plays an important role for the quality of the simulation. Long-term simulations have to be carried out on DTMs with high resolutions for the estimations being usable for the decision-makers. The results of the test station in Saas-Grund have shown that with a DTM resolution of 5 m, the errors exceed 1 m, which is inacceptable for the ski run managers. However, with a resolution of 1 m, the estimation can considerably be improved: the maximum error is approx. 90 cm and 85% of the errors are inferior to 75 cm. This result is extremely interesting given the fact that it is only based on one set of values taken 13 days prior. This shows that the Juste-Neige software can produce quite efficient estimations if the DTM is relatively precise. The error histogram shows a tendency towards overestimation though, which means results that can be compared to a long-term meteorological prediction. Currently, developments are being made to integrate this information into the predictions by calculating a quality index, which will be introduced into the outputs.

Version 1.0 of the Juste-Neige software is operational and has been deployed in the four participating ski resorts. Its commercialization is underway. The multi-agent simulation method has proved to be adequate for predicting the skiers' impact. The projections on the potential for improvement are important. In Zermatt, for instance, the production of 1 m^3 of artificial snow costs 2.50 CHF. With 1,300,000 m^3 of snow produced, this corresponds to yearly production costs of 3.2 million CHF. In addition, the surface where artificial snow is being used corresponds to approx. 250 ha. Thanks to this software, the production of artificial snow could be reduced by 10% within the next five years. Consequently, the snow production and management cost will be reduced by 320,000 CHF per year. Currently, 1,300,000 m^3 of snow are produced, which requires 565,000 m^3 of water. With an economy of 10%, 56'500 m^3 water could be saved in Zermatt. New developments, such as the optimization of the flow of skiers, are planned. In the long term, we can expect a complete environment for the sustainable management of the ski industry.

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