# Optimization of snowmaking in high mountains ski resorts

Authors: Loubier JC(2); Kanevski M (2); Schumacher M(1);
Timonin V(2); Claret S (1); Zieba A (1); Doctor M(1);
Affiliations: (1) University of Applied Sciences Western Switzerland Valais;
(2) University of Lausanne, Switzerland

**Abstract :** Ski resorts are deploying more and more systems of artificial snow. These tools are necessary to ensure an important economic activity for the high alpine valleys. However, artificial snow raises important environmental issues that can be reduced by an optimization of its production. This paper presents a software prototype based on artificial intelligence to help ski resorts better manage their snowpack. It combines on one hand a General Neural Network for the analysis of the snow cover and the spatial prediction, with on the other hand a multiagent simulation of skiers for the analysis of the spatial impact of ski practice. The prototype has been tested on the ski resort of Verbier (Switzerland).

**Keywords**: Snowmaking; spatial prediction; environment; multiagent simulations; General Regression Neural Network

**PROBLEM OF ARTIFICIAL SNOW MOUNTAIN**

Since the early 2000s, the use of artificial snow to ensure activity in ski resorts is controversy: the paradigms of climate change and sustainable development appear to be opposed to the economic necessities of winter tourism. Recent publications on climate change (IPCC, 2007 and OcCC, 2007) combined with the dynamic development of production facilities of snow, for exemple in France (Fig 1) show that this conflict of interests will widen further in coming years.

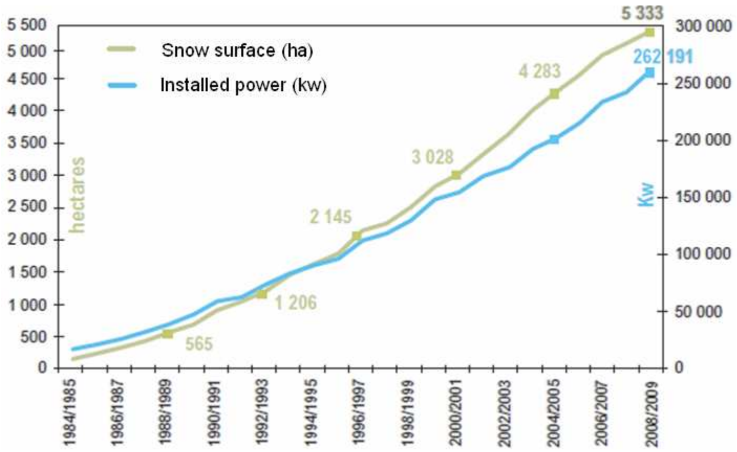


**Figure 1: Evolution of snow-covered surfaces in France (ODIT France 2009)**

In Switzerland, 10 years ago, only 5% of the slopes were covered with artificial snow. Nowadays, this figure rises to 20%. However, compared to other countries in the Alps, Switzerland has a low production of artificial snow. Austria covers over 50% of its ski snow culture, France 60% and Italy almost 80% (www.swissinfo.org, 29.05.07).

It is unrealistic to forbid the production of artificial snow. The economy of snow in Switzerland and in the Alps produces wealth. Ski resorts are also local development enablers that keep large volumes of people in the respective regions. Currently, no other economic model seems attractive enough to replace snow tourism.

The ski economy therefore plays a strategic role in the high alpine valleys, allowing the maintenance of a local economy and social fabric. To ensure activity, ski resorts are investing heavily in production facilities of snow. This poses two problems:

1. The installation costs of the production systems and the maintenance of the snow coat weights heavily on costs of the resorts. For example, the cost of producing a m3 of artificial snow was estimated to 0.85 Euros during the 2009-2010 season. A hectare needs approximately 8000m3 of artificial snow. If we add to this the cost of the facilities and their depreciation, we arrive to 8.5% of sales at a cost of m3 between 1 and 3 Euros depending on the source (CIPRA 2004, Agrawala 2007).

2. Environmental issues related to the production and use of this snow is still poorly understood and evaluated. These problems can be classified according to three criteria: the water problem, the problem of specific impacts on the area and the problem of energy usage. Furthermore, there is an impact that reduces the overall biodiversity (Wipf et al 2005; Pröbstl 2006). Therefore, snow usage seems to be inconsistent with expected sustainable development.

**Project “Juste Neige“**

The project "Juste Neige" presented in this paper lies at the interface between economy and environmental issues. It is developing a software tool for managing the production of artificial snow by simulation. Its result is a prediction map of the height of the mantle. In this way, it will be possible to:

- Reduce production costs and improve profit margins for companies operating ski areas;
- Reduce environmental impacts by producing less snow for good practice. This way, water and energy production will be reduced.

The Juste-Neige tool is therefore interesting from two points of views. Firstly, the profitability of lifts is maintained and allows the preservation of the local economy due to the presence of ski resorts. Secondly, the environmental impact of artificial snow is reduced to the strict necessary to ensure the activity of snow sports. Furthermore, this last point allows the resorts involved in the project to communicate an image conscious of the environment with an engagement in sustainable development issues.

**Innovative aspects**

The innovative aspect of this project lies in the research directly focused on studying the evolution of the snowpack as a function of its use, particularly when it comes to the ski industry. There are already maps of height measurements of the snowpack (Verbier Geosat 2008). However, there are still no maps that show the changes in height of the snowpack. It is therefore necessary to regularly produce a map that shows the updated evolution of the snow mantle based on positive entries (weather prediction) and negative outputs (erosion of the mantle due to its abrasion passages and fusion). Those maps will help the decision-maker on the activation of artificial snow at appropriate timing.

**General architecture of the prototype simulation**

The tool consists of two modules in connection with a database that allows storage and exchange of information. (Fig 2)

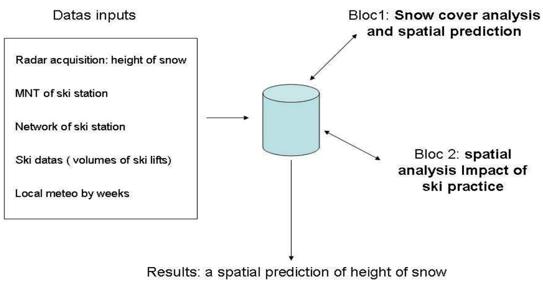


**Figure 2: General architecture of the simulation tool**

The treated data is modeled as a grid referenced in space, from a DTM with a mesh. The heights of the snowpack and the various impacts are calculated with a resolution of 5M. Each block operates independently and returns its results in the database. Finally, results from the two blocks are merged into a final map of the height mantle. We describe hereafter the formalisms in action for each block.

## BLOCK 1 : SNOW COVER ANALYSIS AND SPATIAL PREDICTION

For final modeling and spatial predictions/mapping of snow depth along the ski-tracks, GRNN model was selected and applied. This machine learning model was chosen, because of some of its 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. GRNN is an efficient and reliable model for operational use, which is important for in real decision making process. The first results obtained are quite promising.

**General Regression Neural Network: background**

A General Regression Neural Network (GRNN) is the one of the most effective method for performing a regression task. A GRNN is just another name of a well-known statistical nonparametric method - Nadaraya-Watson Kernel Regression Estimator (Nadaraya 1964 and Watson 1964). In 1991 it was interpreted by Specht in terms of neural networks (Specht 1991). This method is based on kernel nonparametric density estimation proposed by Parzen (Parzen 1962). Omitting the details of the mathematical background, let us present the final formula for the regression estimation of Z(x) using Gaussian kernel and available measurements $Z_i$:

$$Z(\boldsymbol{x}) = \frac{\sum_{i=1}^{N} Z_i \exp\left(-\frac{\|\boldsymbol{x}-\boldsymbol{x_i}\|^2}{2\sigma^2}\right)}{\sum_{i=1}^{N} \exp\left(-\frac{\|\boldsymbol{x}-\boldsymbol{x_i}\|^2}{2\sigma^2}\right)} \qquad (1)$$

where $N$ is a number of training points, $Z_i$ is a function value (measurement) of the $i$-th training point having coordinate $x_i$.

Using the normalised weighting function as a function of **x**

$$W_i(\boldsymbol{x}) = \frac{\exp\left(-\frac{\|\boldsymbol{x}-\boldsymbol{x_i}\|^2}{2\sigma^2}\right)}{\sum_{j=1}^{N} \exp\left(-\frac{\|\boldsymbol{x}-\boldsymbol{x}_j\|^2}{2\sigma^2}\right)} \quad i = 1, 2\ldots, N$$

$$\sum_{j=1}^{N} W_j(\boldsymbol{x}) = 1 \quad \forall \boldsymbol{x} \qquad (2)$$

One can present (1) in the simplified form

$$Z(\boldsymbol{x}) = \sum_{j=1}^{N} W_j(\boldsymbol{x}) z_j \qquad (3)$$

According to (3), the GRNN is a linear estimator (prediction depends on weights linearly), but weights are estimated non-linearly according to the non-linear Gaussian kernel (2).

The only adaptive (free) parameter in the GRNN model with a simple Gaussian kernel is σ - the width of the kernel. Application of kernels with larger than optimal values of σ leads to over-smoothing of data; smaller than optimal values of σ produces overfitting of data. To find optimal value the cross-validation procedure may be implemented. In order to find an optimal value of kernel bandwidth usually a grid search is used. It is necessary to define an interval of σ values [$\sigma_{low}$, $\sigma_{high}$] and M – the number of steps. Then the cross-validation procedure is performed for all M σ values

$$\sigma_i = \sigma_{low} + (i-1)\frac{\sigma_{high} - \sigma_{low}}{M} \quad i = 1, \ldots, M \qquad (4)$$

The final result (optimal σ value) corresponds to the model with the smallest cross-validation error. The interval and the number of steps have to be consistent in order to catch the expected optimal (with minimum of the error) value. Reliable limits are the minimum distance between points and size of the area under study. In fact, really effective interval is much smaller and can be defined in accordance with the monitoring network features and/or by using prior expert's knowledge about studied phenomenon.

**Application to snow depth estimation**

The GRNN with 3 inputs (X,Y and altitude) and 1 output (depth of the snow) was used. On the first step, all duplicated points (within distance less than 5 m) were removed. The minimum value was used for replication. Then optimal parameter of the $\sigma$ value was estimated with cross-validation procedure. Number of steps M in (4) is 5. Finally, the result is a contentious map of the snow depth. Note that prediction was made on "validity domain" only. It means in case of effective radius of correlation 5-10 meters, prediction can not be made for points which too far from measured locations. In GRNN model (Eq. 1), the denominator can be used as an "index" of validity of prediction. Low value of it means that predicted point is too far from all measurements and prediction in this point can not be significant.

Example of the measured data for one day is presented in Fig. 3 (left), predicted map in Fig. 3 (right).

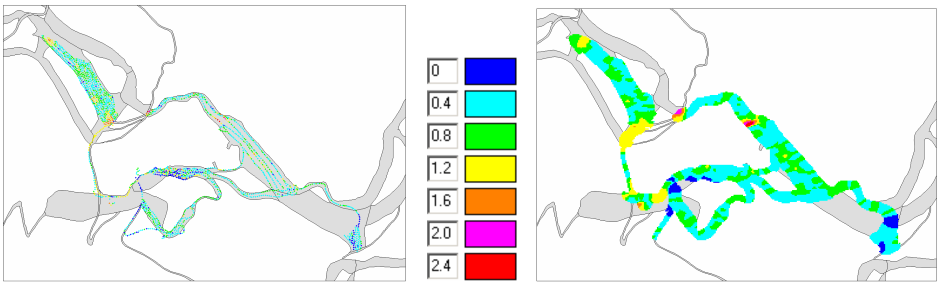


**Figure 3. Measured data of the snow depth for one day is on the left, predicted continuous map is the right. Note that prediction is not made on all ski run, only on validity domain of the model, were prediction is relevant.**

## BLOCK 2: SPATIAL ANALYSIS IMPACT OF SKI PRACTICE

The second block models the impact of skiers on the snow. It is a complex problem that we deal with the technique of multiagent systems (Wooldridge 2009). The idea is to simulate the passage of skiers (modeled as autonomous software agents) on slopes based on an analysis of the average behaviors of skiers. The repetition of simulations converges to an impact by slope.

The approach of using a multiagent system is fairly common in the study of flow analysis such as those of an airport. The problem of skiers on the network of a ski resort is a similar problem. Our agent-based simulation is based on Repast (Tatara et al. 2006).

We realize the simulation in two steps:

- First, we simulate the flows at a global level for the whole resort;
- Then, we run micro-simulations for each slope with the statistical data given from the results of the first step.

We explain hereafter those two steps.

**Global level**

The first step runs on the global graph of the ski resort. This graph is made by the different mechanical installations and the slopes. Each slope is a directed route from one node to the other, maybe with several branches. Those branches may rejoin after separating.

The goal of the first step is to determine for each possible route in the resort graph (from a slope departure to a slope arrival) the number of skiers to simulate. We denominate $D = \{D_1, D_2, \ldots, D_p\}$ as the slopes starting nodes, and $A = \{A_1, A_2, \ldots, A_q\}$ as the slope arrival nodes.

The starting data that we need are the total daily counts of each mechanical installation. Those counts are taken from the statistics of each mechanical installation of a whole year. To define which statistics to use, we have clustered our past statistics on specific example days by using variables such as the meteorological conditions, the time of the year (holiday period, etc.) or the week day. We then choose the statistics of the nearest similar day.

We thus know for each specific installation the number of skiers of a specific day. Therefore, we now the number of skiers that arrived on the top of this installation and that started ski from this departure node. We define this number as $n(D_i)$. Thus, for each slope departure node $D_i$, we know the slope arrivals nodes $A_j$. We denominate this set as $S_i$.

Our goal is to compute the probability to achieve a node $A_j$ from departure $D_i$:

$$P(Aj \mid Di) = \frac{n(A_j)}{\sum_{A_k \in S_i} n(A_k)} \quad (5)$$

We compute this for all possible nodes. We can thus know the number of agents that will choose to go from one starting node to arrival nodes.

**Local level**

At this level, we model the impact of a skier on the snow cover. For this, we run a micro-agent simulation of each specific route in the graph of the ski resort. This is done on the GIS grid.

The first operation is to decide for each agent the route that it will follow to achieve its destination node. Actually, different routes may be possible. For this, we take into account the difficulty of the slope (blue, red, black) and the class of agent (beginner, middle, good skier).

The second operation is to transform the ski slopes into a GIS grid. This is the only way we have to model the movement of a skier on a ski slope. Each skier is thus simulated as an agent that goes down on the slope, roaming from one square of the grid to the other. For the time being, we have modeled a very simple skier behavior that will be revised in a later version of the software.

We can then let run all agents on the slope, and count for each grid square the number of passages of skiers. We then combine all slope grids into one unique grid.
Finally, the calculation of the impact is the erosion of skier passages on a mesh. The impact of a day is the sum of all passing skiers. Each mesh has a corresponding elevation of snow at a relative height of 1000 and the impact "removes" a quantity of height between 1 and 10 every time the agent goes on a mesh.(fig 4)

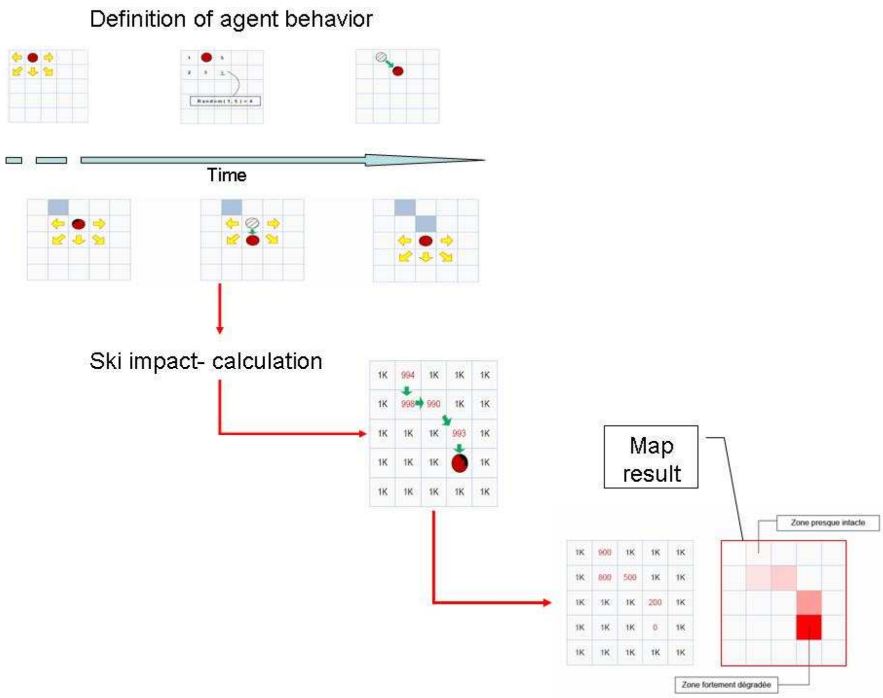


**Figure 4: Process in action in micro-agent simulation**

## ACTUALS RESULTS AND VALIDATION STRATEGY

Currently the system is being finalized, particularly in the area of interaction of the two blocks to provide a seamless map of height prediction. However, each block provides individual outputs that allow a validation control.

For the calculation block of the mantle height, this validation will occur through a campaign to capture data during the winter 2009-2010 in the resort of Verbier in Switzerland. The quality of positioning time points will be guaranteed by the use of a groomer on which are installed a radar (for measuring height resistivity) and a differential

GPS (to ensure the quality of positioning). The groomer will follow a course previously recorded to ensure data consistency validation.

For the block of skier management, the validation is based on a statistical approach. In our SMA, behavioral data are inherently complex and unclear. To derive reliable constitutive laws, we will count on the support of a behavioral survey of skiers made during winter 2008-2009 and a video corpus provided by the resort Zermatt in Switzerland. The validation will compare the results from the simulation with the actual behavior in the resort observed by the service tracks

.

**CONCLUSION**

The"Juste-Neige" project is innovative in two aspects. Firstly, our work focuses on a topic that has almost not been discussed: the dynamic management of snow in ski resorts. Our initial results show that a simulation of the evolution of the mantle heights by probabilistic methods is possible. During the Winter season 2009-2010, our project plans new measurements in the ski resorts of Zermatt, Champery and Sass Grund (all in Switzerland). Furthermore, we plan more measurements in Verbier that should verify the accuracy and robustness of our prediction at local level (what happens to the scale of the resort) and with various topoclimatic situations.

Secondly, our project is a new approach in operational research. It shows the potential of optimization in the space field, particularly in the area of conflict between the objectives of sustainable development and economic needs. The current work also demonstrates the potential of simulation to address the complex interactions of men and environment. We hope this paper will encourage other teams to focus on issues related to simulation needs to implement the objectives of sustainable development in a territory or economic model.

**References**


Agrawala, S. (Editor), Climate Change in the European Alps:Adapting Winter Tourism and Natural Hazards Management., OECD, (2007)

CIPRA, International Commission for the Protection of the Alps (ed.) "The artificial snow in the Alps - Summary Report"(2004)

IPCC,: Climate Change 2007, The Scientific Basis. WMO, UNEP, (2007)

Nadaraya, E.A.: On estimating regression. Theory of Probability and its Applications, vol. 9, pp. 141-142 (1964)

OcCC,: Klimaänderung und die Schweiz 2050. Erwartete Auswirkung auf Umwelt, Gesellschaft und Wirtschaft. Bern, (2007)

ODIT France,:Les chiffres clés du tourisme de montagne en France; 7ème edition, pp 45 (2009)

Parzen, E.: On estimation of a probability density function and mode. Annals of Mathematical Statistics, vol. 33, pp. 1065-1076 (1962)

Pröbstl, U, “Kunstschnee und Umwelt. Entwicklung und Auswirkungen der technischen Beschneiung”, Berne.(2006)

Specht, D.E.: A General Regression Neural Network. IEEE Transactions on Neural Networks, vol. 2, pp. 568-576 (1991)

Swissinfo, : Le réchauffement limite les possibilités d'enneigement artificial 07/12/2007/ Available at address: http://www.swissinfo.org.

Tatara, E., M.J. North, T.R. Howe, N.T. Collier, and J.R. Vos, "An Introduction to Repast Modeling by Using a Simple Predator-Prey Example," Proceedings of the Agent 2006 Conference on Social Agents: Results and Prospects, Argonne National Laboratory, Argonne, IL USA.

Watson, G.S.: Smooth regression analysis. Sankhya: The Indian Journal of Statistics, Series A, vol. 26, pp. 359-372 (1964)

Wipf, S., C. Rixen, M. Fischer, B. Schmid et V. Stoeckli, "Effects of ski piste preparation on alpine vegetation", Journal of Applied Ecology Vol 42: pp306-316.(2005)

Wooldridge, M.: An Introduction to MultiAgent Systems - Second Edition. John Wiley & Sons (2009).