MGSC 662: Decision Analytics

Snowmaking Optimization

Date: 8 December 2024

Submitted by:
Hazel Foo
Hana Kalinova
Jonah Lee
Clement Orcibal
Atharva Vyas

Introduction

During the months where the temperature drops below freezing and weather conditions are unfavourable to most, one of the few ways in which the harsh Canadian winter can be best embraced is through skiing, snowboarding, and snowshoeing. Blue Mountain Resort is the largest ski resort in Ontario and a hub for winter tourism. Known for their easy-to-moderate terrain, the mountain is accessible and family-friendly, positioning itself attractively for those who are interested in getting into the sport. Furthermore, being located only two hours away from Toronto and located just off Lake Ontario, it attracts a wide demographic ranging from lakefront homeowners and cottagers to city tourists looking for a weekend escape.

Beyond the resort itself, Blue Mountain surrounds several neighbouring towns that, as a product of tourism to the resort, have economies that heavily depend on it. These communities are known for their local orchards, breweries, and markets, all of which benefit from increased foot traffic from the resort. Another key aspect of this is the housing market, as the development of vacation homes and rentals continue to boost property values within these towns. Additionally, not only does the operations of the resort provide opportunities for jobs, but also for industries such as construction, transportation, and local tourism to continue to stimulate the economy.

It is evident that not only the operations of the resort, but the surrounding township as well, depend heavily on consistent snow conditions in order to provide optimal conditions for skiing. However, in recent decades, the reliability of natural snowfall has been significantly disrupted by climate change. Rising global temperatures have led to shorter and more unpredictable winter seasons, placing immense pressure on ski resorts to maintain the quality of their slopes. As natural snowfall becomes increasingly unreliable, ski resorts have turned to snowmaking infrastructure to sustain operations and extend their seasons.

Snowmaking has become a critical component of resort operations, ensuring adequate snow coverage during periods of low or no natural snowfall. While effective, snowmaking also represents one of the largest operational costs for ski resorts. It demands substantial capital investment in snow guns, pumping stations, and pipelines, as well as recurring expenses for energy, water, labour, and maintenance. Producing artificial snow is energy-intensive, often requiring freezing temperatures and high-pressure systems, and the process places additional strain on local water resources. Inefficiencies in snowmaking operations exacerbate these challenges, driving up operational costs, increasing energy consumption, and overusing water resources. This not only impacts the economic viability of ski resorts but also raises environmental concerns, as resorts face growing scrutiny to reduce their carbon footprint and adopt sustainable practices. Balancing these competing demands is one of the most pressing challenges facing ski resorts today. Achieving this balance requires a strategic and optimized approach to snowmaking that accounts for factors such as slope characteristics, equipment efficiency, weather conditions, and resource availability.

Thus, this project focuses on developing an optimal snowmaking solution to address the challenges outlined above, aiming to improve both operational efficiency and sustainability. With snowmaking becoming a critical operational component for ski resorts, the primary objective of this project is to optimize the placement and selection of snowmaking equipment. By doing so, the project seeks to minimize installation and operational expenses while ensuring high-quality snow coverage that meets guest expectations.

Problem Description & Formulation

To achieve our objectives, we will strategically determine the most efficient snow gun usage and placement across ski slopes, considering geographical factors such as temperature, humidity, terrain, and altitude that affect snow production. The project will also explore the optimal balance between different types of snow guns based on their performance characteristics, energy consumption, and water usage. This approach aims to match equipment to specific slope needs and weather conditions for optimal snowmaking efficiency. By optimizing snowmaking processes, this project aims to strike a balance between cost minimization, environmental sustainability, and the reliability of snow coverage. The solution developed will help ski resorts navigate the increasing pressure to reduce their carbon footprint and maintain competitive, attractive destinations for winter tourism, even as natural snowfall becomes more erratic. Our approach, however, simplifies real-world complexities to focus purely on the snowmaking process itself. Constraints such as water pipe routing, electrical cabling, manpower availability, and operational costs are excluded from this model due to the lack of publicly available data and the inherent complexity of integrating these factors. This allows for a more direct analysis of snow gun efficiency and placement strategies.

Key Assumptions & Environmental Factors

Given the challenges associated with fluctuating weather conditions across an entire ski season, we chose to model temperature using average values. This approach bypasses the complexity of modelling hourly or daily variations while still providing realistic insights for optimization. Other critical climatic factors, such as humidity were incorporated into the model using wet-bulb temperature calculations, which assess snowmaking feasibility. Geographic elements like elevation were also prioritized for their impact on temperature gradients and snow coverage. However, specific constraints such as slope steepness, sun exposure, and wind conditions—which can influence snow retention and distribution—and grooming practices were excluded to reduce complexity and focus on the core factors influencing snowmaking efficiency. These considerations set the foundation for determining the optimal placement of snow guns, ensuring effective snowmaking across varying conditions while focusing on key factors.

Demac Lenko Snow Guns

The optimization model utilizes Demac Lenko snow guns, widely recognized as one of the best in the snowmaking industry. The company offers two primary types of snow guns:

1. Fan Guns: High-capacity snow guns designed for large-scale snow production with a wide coverage range.
2. Lances: Simpler, energy-efficient snow guns with narrower coverage with lower water and energy consumption.

While newer technologies like Snow Factories exist, they are excluded to better simulate the decision-making process between fan guns and lances, which remain the most common snow guns in ski resort operations.

Four-Phase Implementation Framework

To reflect the planning considerations undertaken by ski resorts, the project is implemented in four phases, each introducing more complexity.

<u>Phase I: Optimal Placement of a Single Snow Gun Type</u>

Phase I simplifies the snowmaking optimization process to its most basic form, establishing a clear framework for understanding the dynamics of snow gun placement. This phase focuses exclusively on a single snow gun type—Fan Gun Ventus, a top-performing snow gun. primary objective is to determine the minimum number of snow guns needed to achieve complete slope coverage while meeting key operational constraints: (i) throwing range (i.e. how far artificial snow can be distributed) (ii) minimum operating temperature, above which the gun cannot function (iii) minimum distance between snow guns, ensuring placement avoids overlap. Mathematically, we have the following:

- Decision variable: $x_{i,j} \in \{0,1\}$ representing the presence of a snow gun at location (i, j)
- Objective function:

$$Minimize \sum_{i=0}^{height-1} \sum_{j=0}^{width-1} x_{i,j}$$, where height and width refer to dimensions of the ski slopes

- Subjected to:
  a) Coverage constraint: Every section of the slope needs to be covered

$$\sum_{ni=i-a}^{i+a} \sum_{nj=j-a}^{j+a} x_{ni,nj} \geq 1, \text{ where a} = \left\lfloor \frac{coverage\ size}{2} \right\rfloor, \text{coverage size } = \text{ range of snow gun}$$

  b) Temperature constraint: Lance can only be placed if the temperature of the slope is below the minimum operating temperature

$$x_{i,j} \cdot (T_{i,j} - T_{min}) \leq 0 \quad \forall \text{ (i, j)},$$

where $T_{i,j}$ = temperature at (i, j), T_{min} = minimum operating temperature for Fan Gun Ventus

  c) Minimum distance constraint: Snow guns cannot be placed within distance *d* of each other

$$x_{i,j} + x_{k,l} \leq 1, \forall \text{ (i, j), (k, l) such that } |i - \text{k}| + |\text{j} - 1| \leq d$$

Phase II: Introducing Multiple Snow Gun Types & Environmental Impact

Phase II builds upon the foundational work in Phase I by introducing multiple snow gun types, including 3 Fan Guns and 2 Snow Lances, to better reflect real-world snowmaking operations. Each snow gun type differs in energy consumption and water usage, simulating the decision-making process ski resorts face when selecting equipment that balances performance with environmental and financial considerations. In Canada, snowmaking alone consumed 478 GWh in 2023, which would require approximately 155000 acres of forest to offset the carbon emissions produced by this energy consumption. Water consumption reached 43.4 million m^3, with between 7-35% lost to evaporation, all of which has significant implications for local ecosystems. The goal of this phase is to minimize total cost incurred from energy and water consumption, while ensuring sufficient snow coverage across all sections of the ski resort. Mathematically, these changes involve the following:

- Decision variable $x_{i,j,k} \in \{0,1\}$ representing the presence of snow gun k at (i, j)
- Objective function:

$$Minimize \sum_{i=0}^{height-1} \sum_{j=0}^{width-1} \sum_{k=0}^{4} x_{i,j,k} \cdot cost\ per\ snowgun_k$$

- Subjected to:
  a) Coverage constraint: Every section of the slope needs to be covered

$$\sum_{k=0}^{4} \sum_{ni=i-a_k}^{i+a_k} \sum_{nj=j-a_k}^{j+a_k} x_{ni,nj,k} \geq 1,$$

$$\text{where a}_k = \left\lfloor \frac{coverage\ size_k}{2} \right\rfloor, \text{coverage size}_k = \text{ range of snow gun k}$$

  b) Minimum distance constraint

$$x_{i,j,k} + x_{ni,nj,nk} \leq 1, \ \forall\ k, nk, \ \forall (i,j), \ (ni,nj),$$

subject to $|i - ni| + |\text{j} - nj| \leq max(\min distance_k, \min distance_{nk})$ and *(i, j) ≠ (ni, nj)*

  c) Placement constraint: Only 1 snow gun can be placed on each section of the slope

$$\sum_{k=0}^{4} x_{i,j,k} \leq 1, \forall\ i \in [0, height - 1], \forall\ j \in [0, width - 1]$$

  d) Temperature constraint

$$x_{i,j,k} \cdot (T_{i,j} - \min temperature_k) \leq 0, \ \forall \text{ (I, j, k)},$$

where min temperature $_k$ = min operating temperature of snow gun k

Phase III: Terrain-Specific Snowmaking Requirements

In Phase III, the model evolves to capture the unique snowmaking requirements of different terrain types, including green, blue, and black runs, reflecting the diverse needs of a modern ski resort. By incorporating terrain-specific snow production demands, this phase enables the resort to allocate resources more effectively to maintain optimal conditions for skiers of all skill levels. Key enhancements include integrating each snow gun's production capacity and aligning it with the snow coverage requirements of various slope types. These refinements ensure that snowmaking efforts are tailored to maximize operational efficiency and customer satisfaction. While the core objective remains minimizing snowmaking costs, this phase brings a sharper focus on balancing cost-effectiveness with the resort's ability to meet the specific needs of its terrain, providing a strategic advantage in enhancing the overall guest experience. In addition to the constraints in Phase II, there is an additional constraint that needs to be considered – snow production constraint which is formulated as follows:

- Snow production constraint: Total snow production for each section of slope must meet or exceed the minimum snow production required for the slope type

$$cell\ snow\ production_{i,j} = \sum_{k=0}^{4} \sum_{n_i=\max(0,i-a_k)}^{\min(height,\, i+a_k)} \sum_{n_j=\max(0,j-a_k)}^{\min(width,\, j+a_k)} x_{ni,nj,k} \cdot snow\ production_k,$$

$$cell\ snow\ production_{i,j} \geq required\ snow_{i,j},$$

where $cell\ snow\ production_{i,j}$ = snow production at (i, j), $snow\ production_k$: snow production by snow gun k, $required\ snow_{i,j}$: minimum snow requirement for (i, j)

Phase IV: Safety Considerations

The final phase represents the culmination of the modeling process, designed to most accurately reflect the real-world decision-making process at a ski resort. By incorporating a safety score, the model addresses the critical trade-offs between operational efficiency, environmental considerations, and the safety of visitors and employees. This comprehensive approach mirrors the complex process behind snowmaking operations while adhering to safety and sustainability priorities. This phase transitions the model from a purely cost-focused optimization to a multi-objective framework, where the goals are to minimize snowmaking costs and maximize safety outcomes. The introduction of the safety score prioritizes the placement of snow guns on or adjacent to non-skiable terrain – areas less frequented by skiers and snowboarders, thus reducing the likelihood of collisions and accidents during slope grooming. Beyond the human cost, ski accidents also carry significant financial implications, including medical expenses, legal liabilities, and increased insurance premiums. Reports indicate that the rising number and severity of ski accidents have led to a substantial increase in associated costs, placing additional financial pressure on resort operators. By addressing these considerations, the model not only enhances safety but also mitigate the financial risks associated with accidents.

This final phase builds upon earlier iterations, integrating progressively complex constraints and objectives, culminating in a decision-making tool that effectively balances operational, financial, environmental, and safety concerns. This holistic approach ensures that the model is well-aligned with the strategic priorities and practical challenges faced by ski resort operators in real-world scenarios. Mathematically, the second objective for maximizing the safety score is defined as:

$$Maximize \sum_{i=0}^{height-1} \sum_{j=0}^{width-1} \sum_{k=0}^{4} x_{i,j,k} \cdot$$

$$\left(3 \cdot nonslope_{i,j} + 2 \cdot \sum_{n \in N_1(i,j)} nonslope_n + 1 \cdot \sum_{n \in N_2(i,j)} nonslope_n\right), where$$

- $nonslope_{i,j}$=1 in absence of ski slopes,
- $N_1(i,j)$: set of adjacent cells from (i, j) given by $\{(i-1,j),(i+1,j),(i,j-1),(i,j+1)\}$ which are bounded by the grid dimensions:

  max (0, i-1), min (height – 1, i+1), max (0, j-1), min (width-1, j+1)
- $N_2(i,j)$: set of cells 2 steps from (i, j) given by $\{(i-2,j),(i+2,j),(i,j-2),(i,j+2)\}$, which are also bounded by the grid dimensions:

  max (0, i-2), min (height – 1, i+2), max (0, j-2), min (width-1, j+2)

The scoring system is structured with different levels of safety, reflecting the proximity of snow guns to cells not covered with snow in the positional matrix for our ski slopes. For each snow gun placed, a security score of 3 is added for each cell not covered with snow directly adjacent to it. A score of 2 is added for each uncovered cell that is 1 cell further away, and a score of 1 is added for each uncovered cell that is 2 cells away. Placements with lower scores are less ideal because they are closer to areas actively used by skiers and snowboarders, increasing the likelihood of accidents or interference with slope grooming activities. Implementing this weighted scoring ensures that snow guns prioritize coverage in nearby uncovered areas, balancing slope safety, usability, and operational efficiency. Extending the model to include safety score will ensure that the placement of snow guns is optimized while maximizing the well-being of visitors and employees.

Numerical Implementation & Results

Extracting geographical data for Gurobi

We implemented the map by first taking the actual map available on the resort's website. Our initial goal was to extract the outline of each slope, but this approach did not work due to the excessive amount of details in the original map. To address this, we manually colored in black what was considered a slope and left the rest as white, giving us a clear visual representation of the areas requiring snow coverage. To transform this into a matrix, we loaded the image and converted it into a NumPy array. Then, we divided the image into a grid of 100 rows and 200 columns, calculating the size of each cell based on the image dimensions. For each section, we checked if any pixels fell below a defined color threshold to identify areas corresponding to slopes. This process generated a binary matrix with True for slopes and False for non-slope areas. Using the same procedure, we then created three separate masks to distinguish between beginner, intermediate, and hard slopes based on their respective sections on the map (Fig A1-3). Thus, the end product was a 100 x 200 positional matrix, with position X_{ij} denoting the presence of snow where $X_{ij} = \{True\ if\ the\ point\ is\ a\ slope,\ False\ otherwise\}$. Given that the Blue Mountain has an elevation gain of 220m, each grid in the represents a 10m x 10m area.

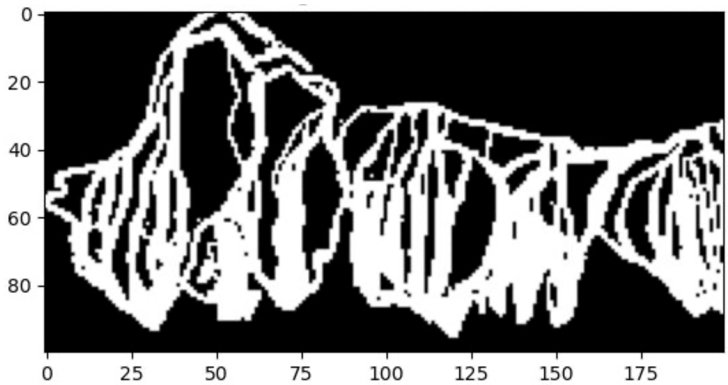

Fig 1: Positional matrix of the ski slopes in Blue Mountain Ski Resort

Temperature implementation

Based on weather data from the past two decades, Blue Mountain's ski season typically experiences an average high temperature of -2°C and an average low of -13°C, alongside a humidity level of 75-80%.

However, for modelling purposes, the wet bulb temperature was used instead of the dry air temperature. Wet bulb temperature accounts for both temperature and humidity, offering a more accurate representation of conditions that influence snowmaking. This metric is critical as it reflects the cooling effect of evaporation, which significantly impacts the efficiency and feasibility of artificial snow production. Using a dry air temperature of -2°C as the baseline at the mountain's base, the wet bulb temperature was calculated. To simulate the elevation-dependent temperature variation across the slope, a standard atmospheric lapse rate of 6.5°C per 1000 meters was applied. This linear temperature gradient was incorporated into the model to adjust the temperature at each elevation band realistically, ensuring an accurate representation of environmental conditions that influence the placement of snow guns. Snow guns have varying minimum operating which are critical for efficient snow production. By factoring in the elevation-dependent temperature drop, the model aligns the placement of snow guns with areas where their operating thresholds are met.

Snow gun implementation

Using the snow matrix in Fig 1, the throwing range of each snow gun was adjusted in multiples of 10 to align with the grid dimensions. For simplicity, the throwing range was represented as a coverage area, allowing for more straightforward modeling of snow production. For instance, the Fan Gun Ventus, with a throwing range of 70m, was modeled to cover a 70m x 70m area. This approach facilitated the integration of snow gun specifications (Table 1) into the model, enabling precise placement and operation adjustments based on the characteristics of the terrain and the environmental constraints represented in the snow matrix.

Using the binary slope matrix, where 1 indicates snow-covered areas, we ensured that each snow-covered cell was within the range of at least one snow gun by checking all neighboring cells within the snow gun's range, staying within grid boundaries, and added a constraint to guarantee coverage. Once solved, we extracted the results into a placement matrix indicating the optimal positions of snow guns.

Snow gun types	**Fan Gun Titan**	**Fan Gun Evo**	**Fan Gun Ventus**	**Lance EOS**	**Lance DUO**
Snow Production (m^3/h)	120	80	90	69	80
Power Consumption (kW)	23.0	14.2	20.0	2.0	4.8
Energy Consumption (kWh/m^3)	0.192	0.178	0.222	0.029	0.060
Water Consumption (L/h)	43200	28800	32400	24840	28800
Throwing Range (m)	80	60	70	30	30
Min Temp Requirement (°C)	-2.5	-2.5	-2.5	-4.0	-4.0
Min Distance Requirement (m)	35	35	35	20	20

Table 1: Technical specifications of snow guns that were implemented in the model

Cost implementation

To account for the operational costs associated with energy and water consumption of snow guns, all cost considerations in the model were standardized based on hourly usage. This assumption simplifies the calculation of operating expenses while ensuring that the cost implications of each snow gun's efficiency and performance are accurately reflected in the model. The energy consumption cost, set at \$0.125 per kWh, was derived from the rates provided by Hydro One, the energy supplier for the area surrounding Blue Mountain. Additionally, the water consumption fee was based on the charges stipulated by the City of Toronto, which serves as the local water provider in proximity to the resort.

Multi-Objective implementation

In Phase IV, with the introduction of two conflicting objectives—minimizing costs and maximizing safety—a weighted approach was necessary to operationalize the optimization within Gurobi. Specifically, assigning a weight of -1 to the safety score effectively inverted its direction, transforming the maximization objective into a minimization problem. This step was critical because Gurobi's optimization framework inherently requires all objectives to be formulated in the same direction (either all minimization or all maximization) for a multi-objective optimization problem.

This redefinition aligned both objectives within a unified structure, enabling the model to compute and balance trade-offs efficiently. By incorporating this adjustment, the optimization model could process the conflicting priorities coherently, ensuring that the solver's algorithms could evaluate and integrate the objectives on a comparable scale.

Phase I results & Insights

The placement of 186 snow guns (Fig 2) across the map ensures sufficient snow cover in critical areas, with a focus on avoiding over-concentration that could lead to resource wastage. Snow guns are strategically placed in regions with lower temperatures, such as higher elevations, where snow production is more effective. In narrower ski trails, where less snow is required, fewer snow guns are used, while wider slopes feature a higher concentration of snow guns to meet their greater coverage needs. The map shows no large gaps without snow guns, minimizing the risk of under-snowed areas and ensuring comprehensive coverage. This finding provides valuable logistical insights by determining the number of snow guns required and identifying patterns in their placement, which can inform future extensions of the project, such as optimizing water and electricity infrastructure placement. At this phase, no costs are associated with the analysis since the cost aspect has yet to be introduced.

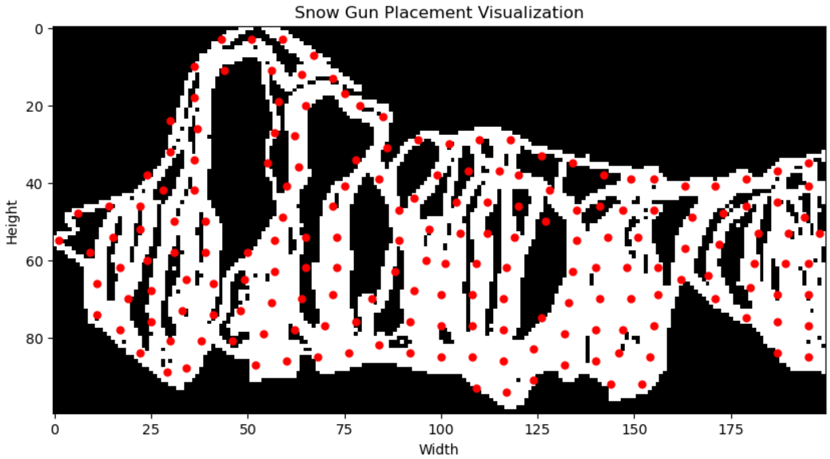

Fig 2: Snow gun placement matrix in Phase I

Phase II results & Insights

The snow gun counts change from Phase I, with Fan Gun Titan totaling 39 guns, Fan Gun Evo at 23 guns, and Fan Gun Ventus at 105 guns, making a combined total of 167 guns (Figure 3). All selected machines are fan guns, likely chosen due to their superior efficiency compared to lances. Having a higher minimum temperature requirement of -2.5°C makes them well-suited for the conditions modelled on the slopes. Additionally, their expansive throwing range and coverage capabilities enable uniform snow distribution across the terrain, making them an optimal choice for large-scale operations at resorts like Blue Mountain.

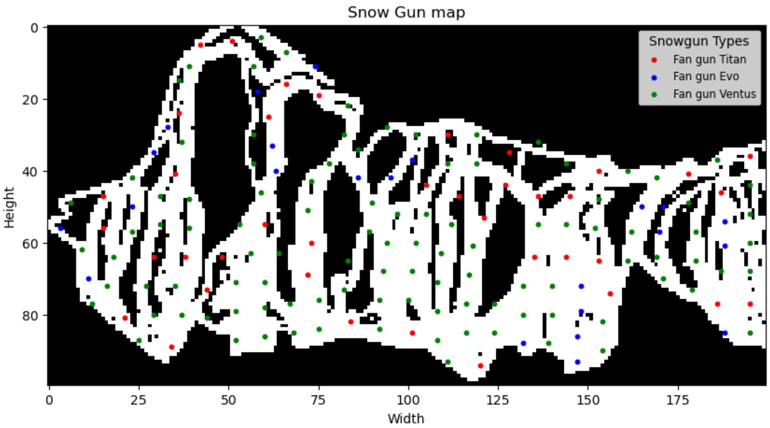

Fig 3: Snow gun placement matrix in Phase II (Titan: 39, Evo: 23, Ventus: 105, Lances: 0)

As seen in Fig 3, Titan guns are strategically placed in areas that require broader snow coverage, maximizing efficiency with fewer guns. In contrast, the Evo guns are used in regions requiring medium-sized coverage, balancing efficiency and cost-effectiveness. The Ventus guns, despite their smaller individual coverage, are the most numerous and effectively fill the remaining gaps.

From a cost perspective, the total resource expenditure for water and power amounts to $18,582.92, broken down as follows: 105 Ventus guns at $11,012.82, 39 Titan guns at $5,436.09, and 23 Evo guns at $2,134.01. Ventus guns, while moderately priced at $104.88/hr, contribute the most to overall costs due to their high count, making them indispensable for achieving full coverage. Titan guns, with the highest hourly cost of $139.39/hr, justify their placement in critical, high-demand areas with their large coverage size. Evo guns, the most economical at $92.78/hr, provide the best cost-to-coverage efficiency, making them a preferred choice in medium-sized regions.

The placement reflects this cost-performance trade-off, with Fan Gun Ventus dominating the map due to their high count and effective gap coverage, while Fan Gun Titan and Fan Gun Evo are strategically distributed in larger, high-traffic, or medium-coverage areas. Larger open trails feature Titan guns to address higher snow demands, while Ventus and Evo guns are used for smaller trails and gaps to maintain efficiency.

Phase III results & Insights

The slope snow requirement constraints ensure that snow-making resources are allocated based on the snow demands of each slope type. Beginner slopes require the most snow production at 500 m³/h to ensure safety and usability, while Intermediate slopes require a moderate amount of 300 m³/h. In contrast, Hard slopes demand the least snow, at 200 m³/h, due to their steep terrain and lower demand (refer to Fig A1-3 for visualization of individual slopes).

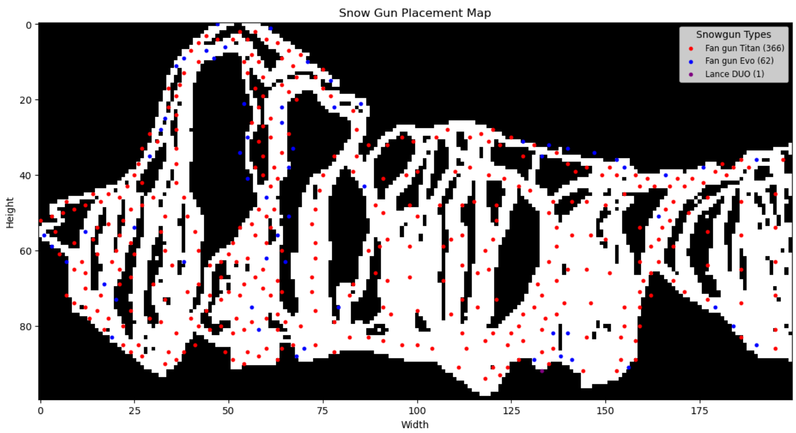

Fig 4: Snow gun placement matrix in Phase III (Titan: 366, Evo: 62, Lance DUO: 1)

The operational costs now reflect the impact of snow production requirements. The total operational cost reaches $56,859.80, broken down as follows: Fan Gun Titan contributes the largest share, costing $51,015.64 due to its large count (366 units) and resource demands. Fan Gun Evo incurs a cost of $5,752.55 for 62 units, offering a balance between efficiency and resource usage. The single Lance DUO, despite being minimal in usage, contributes $91.61. These numbers highlight a significant cost increase compared to previous phases, as the model now incorporates nuanced snow production constraints for varying slope types. The introduction of slope-specific constraints marks a key difference from earlier maps. Beginner slopes dominate the map, necessitating the heavy use of high-capacity Titan guns to meet snow production needs efficiently. The placement strategy optimizes resource allocation by balancing snow production demands without overuse of resources, ensuring that Beginner, Intermediate, and Hard slopes receive adequate snow coverage tailored to their specific requirements. This phase highlights how operational costs rise when snow-making decisions incorporate detailed slope needs, creating a more precise and realistic resource allocation strategy.

Phase IV results & Insights

In this final phase of the modeling process, a safety score is incorporated into the snow gun placement optimization, transitioning the model from a purely cost-focused framework to a multi-objective approach. The inclusion of safety constraints ensures an effective balance between operational efficiency, environmental considerations, and skier safety. Snow gun placement is now optimized to prioritize safety while maintaining robust snow coverage across all slope types.

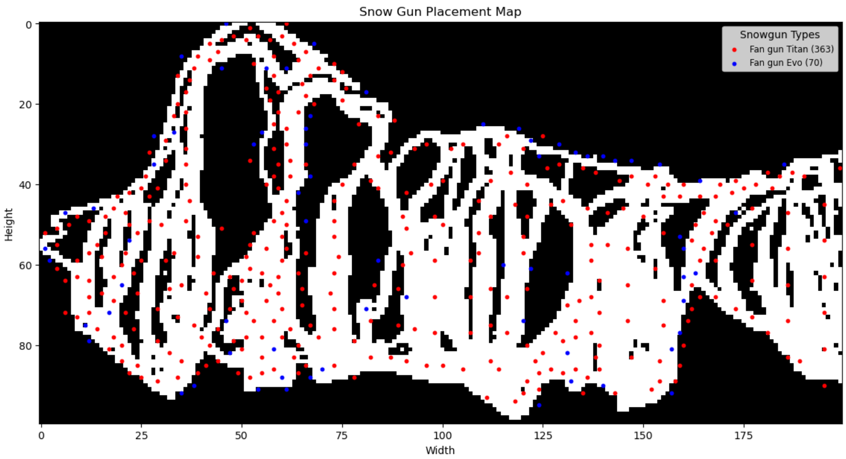

Fig 5: Snow gun placement matrix in Phase IV (Titan: 363, Evo: 70)

The Fan Gun Titan continues to dominate the map due to its high snow production capacity of 120 m³/h and broad coverage. However, in this phase, many Titan guns have been strategically shifted closer to non-skiable terrain, reflecting the safety-driven placement priorities. The Fan Gun Evo is selectively placed in tighter regions, particularly around Intermediate and Hard slopes, balancing efficient snow coverage and cost. Evo guns also align with the safety objectives by focusing on areas adjacent to or near non-skiable zones. Notably, the Lance DUO has been replaced with additional Evo guns and fewer Titan guns, further streamlining coverage. A key adjustment in this phase is the visible clustering of snow guns near non-skiable terrain (black regions on the map). This aligns with the weighted safety scoring mechanism, which prioritizes snow gun placement in or near non-skiable zones. By situating guns away from high-traffic skiable terrain, the model effectively reduces risks such as collisions and equipment interference during slope grooming. Additionally, this placement ensures that snow guns do not hinder future grooming processes, making operations safer and more efficient.

From an operational perspective, the model maintains efficient snow coverage across Beginner, Intermediate, and Hard slopes while upholding cost efficiency. The Fan Gun Titan dominates large coverage zones, while the Fan Gun Evo efficiently fills smaller gaps. Despite the introduction of safety constraints, the operational costs remain controlled, with a total cost of $57,092.29, which is just a slight increment compared to Phase III where snow guns could be situated throughout the ski slopes. This includes 363 Fan Gun Titans contributing $50597.48 and 70 Fan Gun Evos costing $6494.81.

The final model achieves a security score of 2503, a metric primarily serving as a comparative and inferential measure rather than having absolute significance. This score reflects a marked improvement in safety, emphasizing a shift towards safer and more customer-friendly snow gun placements. In particular, compared to Phase III, the repositioning of snow guns on Beginner and Intermediate slopes to adjacent non-skiable zones illustrates the model's prioritization of safety without sacrificing coverage efficiency.

This phase underscores the model's capability to balance cost, operational efficiency, and safety considerations effectively, showcasing a robust and realistic optimization tailored for ski resort operations. It is important to note that the security score should be interpreted in the context of relative improvements and priorities within the framework rather than as an isolated, inherently meaningful value.

Problem Extension & Recommendation

Through the four-phase implementation framework, though the optimization model accounted for key factors like snow gun placement, energy consumption, and water usage, many additional real-world considerations still need to be addressed. These include natural snowfall variability, wind conditions, and potential constraints on water and energy resources, all of which significantly impact both the cost and efficiency of snowmaking operations. To ensure that snowmaking remains efficient and sustainable under real-world conditions, these factors should be integrated into the optimization framework.

For instance, natural snowfall can help reduce the demand for artificial snow, providing opportunities to optimize resource usage. By analyzing historical and real-time weather data, resorts can adjust snow production accordingly, conserving both energy and water. However, wind conditions can undermine the effectiveness of snowmaking by redistributing snow in unintended directions, leading to inefficiencies and increased snow production to compensate for lost snow. Incorporating wind forecasts into the model would allow the prediction of areas prone to snow loss, enabling better strategic placement of snow guns and adjustments to their output.

Moreover, snowmaking operations are energy-intensive, influenced by the resort's operational schedules, ambient temperatures, and surrounding energy demand patterns. To optimize energy consumption and manage costs, ski resorts can analyze demand profiles to identify peak consumption periods. Scheduling snowmaking during off-peak hours when energy prices are lower offers a cost-effective strategy, if weather conditions and water availability are favorable. Additionally, partnerships with energy providers may offer preferential rates or demand-response agreements, allowing resorts to align snowmaking operations with periods of lower grid demand. This approach not only helps reduce operational costs but also contributes to the broader goal of environmental sustainability.

Given that water is a finite and essential resource for snowmaking, with its availability fluctuating based on seasonal precipitation patterns and temperature shifts, it is crucial to consider water constraints, which were not addressed in the original model. Integrating these constraints into the optimization framework would enhance sustainability and efficiency. By assessing factors such as reservoir levels, snowmelt, and projected precipitation, the model could dynamically adjust snow production to ensure that water usage aligns with available resources. This would allow for real-time adjustments, such as reducing snow depth in less-frequented areas or adjusting snow gun usage, to conserve water during critical shortages, while maintaining optimal snow coverage across the resort.

Another important extension involves the integration of physical infrastructure constraints such as the placement of snow guns, pipelines and slope access. These infrastructure elements are vital for optimizing snowmaking operations, as their positioning directly impacts snow distribution, energy consumption and water usage. Additionally, considering slope access allows the system to adapt to real-world operational limitations, such as geographically constrained areas that are difficult to reach or that lack sufficient access for snowmaking equipment. Incorporating these considerations would lead to a more realistic, operationally feasible model that accounts for the challenges inherent in the physical environment of snowmaking.

The vision for the model includes the development of a centralized application platform designed to enhance snowmaking operations. This platform would allow ski resorts to input crucial operational data, such as weather forecasts, energy and water availability, and terrain-specific details. By processing this data within the optimization framework, the platform would offer tailored recommendations for snowmaking strategies. Further functionality could be integrated by linking real-time data from advanced weather platforms, such as Windy. These platforms would provide high-resolution, real-time weather data on temperature, wind, precipitation, and humidity, all essential for precise snowmaking decisions. This integration would enable resorts to adjust snowmaking operations dynamically as weather conditions evolve, improving both operational efficiency and resource conservation. The platform would also support real-time resource management and scenario planning, helping resorts optimize their operations, reduce costs, and enhance sustainability. Beyond operational benefits, it could serve as a knowledge-sharing tool, allowing ski resorts to exchange best practices and innovative solutions for common challenges. By incorporating external weather data platforms, the app would become a comprehensive, data-driven tool adaptable to different geographical and operational environments.

By integrating these considerations, the project achieves a holistic approach to snowmaking optimization. It enhances operational efficiency, reduces environmental impact, and ensures resilience to climate variability. This comprehensive strategy positions the resort as a pioneer in sustainable snowmaking, aligning resource management with guest satisfaction and long-term viability.

Conclusion

As a tourist-dependent economy, Blue Mountain Resort and its surrounding township rely on providing visitors with an exceptional skiing experience. Our project first prioritized the coverage of snow across the mountain, recognizing that the quality of the terrain is paramount and is something that continues to grow in reliance on the production of manmade snow as our winters get warmer. Furthermore, environmental concerns such as the addition of varying snow gun costs based on their consumption levels as well as the implementation of an environmental score reflect the Resort’s commitment to sustainability and efforts in maintaining the region’s eco-friendly atmosphere. We also incorporated other critical factors such as the optimization of snow coverage across terrains of varying difficulty and the safe placement of guns across the slope to continue to push the resort’s appeal as a family-friendly destination. In conclusion, our project aimed to highlight the complex tradeoffs that business managers must navigate in balancing the operations of a task as deceptively simple and trivial as snowmaking, to achieve the best outcomes not only for the organization, but also for the municipalities who rely on its success.

Appendix

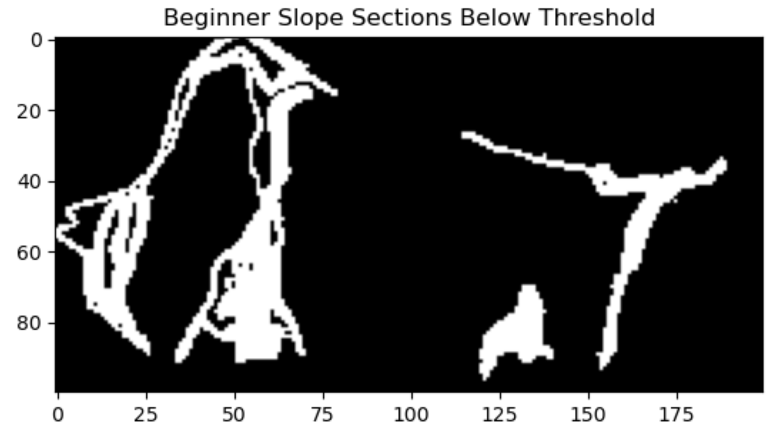

Fig A1: Visualisation of beginner slopes (green runs) on Python

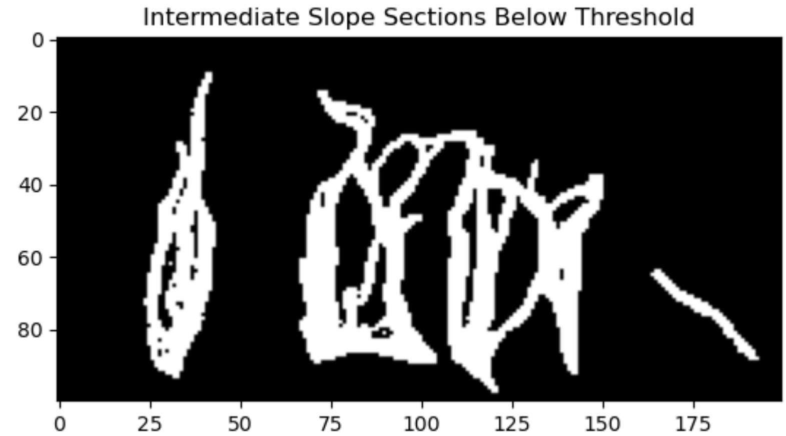

Fig A2: Visualisation of intermediate slopes (blue runs) on Python

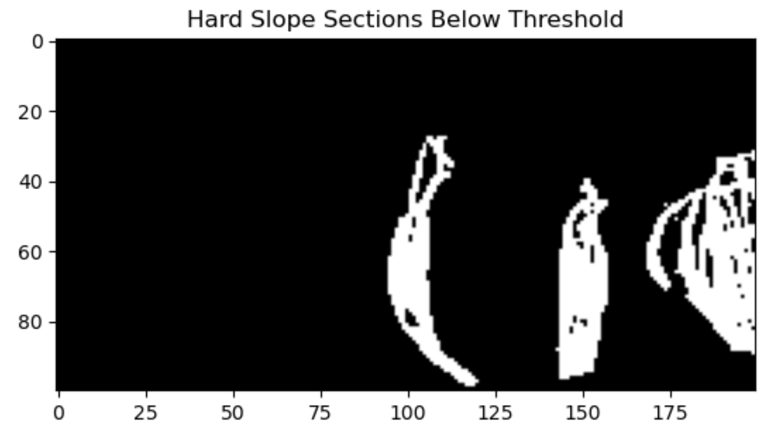

Fig A3: Visualisation of hard slopes (black runs) on Python

References

Blue Mountain Resort. (n.d.). Blue Mountain Resort brochure. https://www.bluemountain.ca/-/media/blue-mountain/mountain-report/maps/fy25/winter/maps/bmr-winter-25-mountain-web.pdf?rev=da3491df1096415e85db4d6755901829

Bukowski, A. (2023, December). *The Cost of Ski Season, From Staffing to Snowmaking and Everything in Between*. Features | Northern Express. Retrieved December 6, 2024, from https://www.northernexpress.com/news/feature/the-cost-of-ski-season-from-staffing-to-snowmaking/

Demac Lenko. (n.d.). https://www.demaclenko.com

Determining the Wet-Bulb temperature. (n.d.). https://www.technoalpin.com/en/wet-bulb-calculator

Gartner, J., & Weibel, D. (2015). Snowmaking and the management of water resources in ski resorts. *Environmental Research Letters*.

Historical - the Weather network. (n.d.). The Weather Network. https://www.theweathernetwork.com/ca/historical/ontario/blue-mountain-ski-area

Knowles, N., Scott, D., & Steiger, R. (2023). Sustainability of snowmaking as climate change (mal)adaptation: an assessment of water, energy, and emissions in Canada's ski industry. *Current Issues in Tourism*, 1–18. https://doi.org/10.1080/13683500.2023.221435

Spandre, P., Morin, S., Lafaysse, M., Lejeune, Y., François, H., & George-Marcelpoil, E. (2016). Integration of snow management processes into a detailed snowpack model. *Cold Regions Science and Technology*, *125*, 48–64. https://doi.org/10.1016/j.coldregions.2016.01.002

Stein, C., Holzinger, M., & Funke, M. (2020). The impact of wind drift on snow distribution and snowmaking. *Snow Research Journal*.