Design of a Snowmaking Distribution System

A Major Qualifying Project Report

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Abstract

The objective of this Major Qualifying Project is to create a system that facilitates the distribution of machine made snow. This objective was chosen to help reduce the need for labor in the grooming of Cross Country ski trails and to help alleviate the environmental impacts of grooming. The method used to complete the design was Axiomatic Design, a theory originally articulated by Nam Suh. Current snowmaking techniques were reviewed to find places to improve snowmaking. The result of using the Axiomatic Design method was a design decomposition, heat transfer equations, and a Computer Aided Design model.

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1.0 Introduction

1.1 Objective

The objective of the Major Qualifying Project is to create a system that facilitates the distribution of machine made snow. In this context, machine made snow is defined as snow produced via a snow gun which breaks up water droplets and sends them into the air to freeze in the surrounding lower temperatures before they hit the ground (Caravello et al., 2006). The scope of the project was to complete an Axiomatic Design Decomposition as well as complete Computer Aided Design (CAD) models of the mechanism.

1.2 Rationale

Global warming is at the forefront of modern societal and technological debate. Focus has been put upon reducing energy consumption and the carbon output of industrial industries. At present, machine made snow is a complicated and heavily industrialized process. Between producing the equipment, the manpower and machinery required to install it at the ski facility, and the actual operation of the equipment, there is significant room for improvement in terms of the energy efficiency of the snowmaking process.

Snowmaking is an inefficient process. Presently, all snow is made in piles and must be distributed with large groomers (tracked snow vehicles) to its intended destination. This is especially inefficient for ski areas with features such as cross country trails, lift lines, and terrain parks. Groomers use significant amounts of energy when operational. Most have internal combustion engines and produce significant carbon products for every hour they are driven and have to cover the large area of cross country trails, lift lines, and terrain parks. (Affolter et. al. 2021)

In addition to groomer energy use, snowmaking itself also uses significant amounts of energy. Most snowmaking systems rely on large compressors, pumping stations, fans, and other devices and processes that are exceedingly lacking in energy efficiency. The infrastructure required to support snowmaking operations is vast in scale and cost. Miles of pipes and wire must typically be laid in extremely challenging conditions such as in alpine areas, uphill, or through forest glades. Fixing these pieces of infrastructure when they break can be complicated and expensive. A malfunctioning snowmaking system can have a significant negative bearing on the experience of a ski facility's guests, and by extension, the financial operations of the facility. (Vanham et. al. 2009)

A system that is more energy efficient will help reduce overhead and operating costs, simplify required equipment, and make beneficial contributions to the environment.

1.3 State-of-the-art

1.3.1 Machine Made Snow Procedure

Naturally made snow is created in the clouds at microscopic dust nucleating sites. When the temperature falls below 0°C snowflake crystals form when the atmospheric water condenses on air particles and crystallizes, growing in size as they fall to the ground. To create machine made snow, water is mixed with a nucleating agent. An atomizing nozzle is used to break up the mixed water particles into a mist when it is pressurized.

There is one main requirement to create machine made snow: wet-bulb temperature.Wet-bulb temperature is calculated from the air temperature and relative humidity. -3°C is the required wet bulb temperature to make snow. If the wet-bulb temperature is not low enough, poor quality snow with a wet consistency will be made or no snow at all. (Steiger, 2008)

There are three main nozzle types to consider: Air-atomizing, whirl, and fan. Air-atomizing nozzles provide fine atomization and flexible flow rate ranges. Axial whirl nozzles provide a distribution of two-phase spray. The internal vanes act simultaneously as static mixers and spray nozzles. Axial fan nozzles allow for directed secondary spray. Fans are commonly used in snowmaking applications where large volumes, extended throw distances, and less robust water infrastructure exists. The latter is a large advantage, as instead of relying on the pressure of the water used to propel the droplets, the fan accelerates and distributes the droplets over a much wider area. Because the fan is the primary component, the infrastructure required - pumping stations and water distribution, is largely reduced. Fan-based snowmakers are also easier to implement across wider areas at ski facilities. There are other ancillary benefits to nozzle-based and fan-based snow machines. Fan-based machines are larger and require a robust electrical infrastructure, but have the noted benefits of wider coverage. Nozzle-based machines do not require electricity and are much smaller, but require greater infrastructure to support them. (Epstein, et al., 2001)

1.3.2 Notable Patents

Typically, snow is made using pipes to supply large amounts of water to snow guns that then break water into fine droplets using a fan or nozzle, and subsequently, the droplets freeze when propelled into the air using compressed air before they land to the ground (Caravello, et al., 2006). There are three general ways this system is used to distribute snow; traditional air/water guns, single and multi-ring fan systems, and tower systems (Epstein, et al., 2001).

A key component of snowmaking is creating water droplets and freezing them. In the patent from Ichinomiya that details a snowmaking apparatus and method, the first step is making droplets. Snow guns use a pressurized air supply that is combined with water supply lines that force the water through a plurality of nozzles. This creates atomized water droplets. The water is kept at a high pressure using filters, a water pump, and a high pressure water hose. (Ichinomiya, et al., 2009)

The next step is freezing these droplets. This patent uses a circular design to push conditioned air through multiple nozzles. Conditioned air, according to the patent, is air that is -40°C with an absolute humidity of about 0.02$\frac{g}{m^3}$, and a frost point temperature of about -55°C or less. These air conditions are made using a dehumidifier that uses zeolite or absorbent material and is then cooled by a freezer to -30°C. No ice is made in this process due to the frost point being -40 °C and the air cooler freezing to -30°C. In Figure 1, the circular design can be seen where "14" represents the sprayed water, and the conditioned air is forced out, represented by "34". (Ichinomiya, et al., 2009)

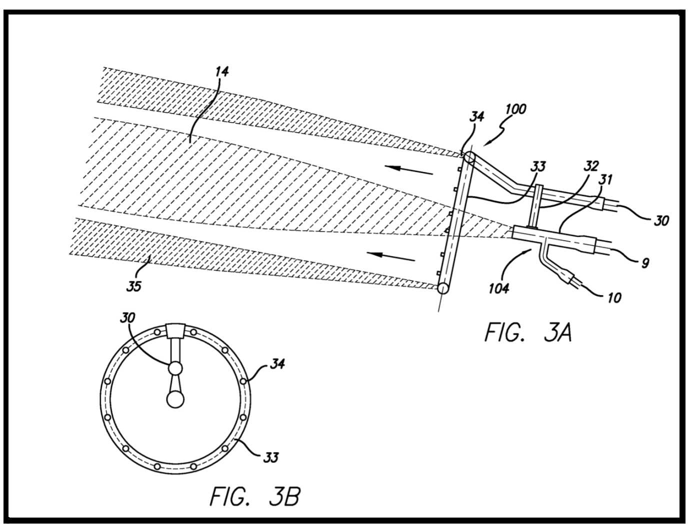

Figure 1: Ichinomiya Circular Nozzle Design of Snowmaking Apparatus and Method

Unlike the previous Ichinomiya patent, this newer patent made by Beaulac uses the more traditional fan gun method combined with an external nucleation device to produce snow. This design was made with portability in mind which is why the newer compressed air method could not be applied without an extensive pressurized air hydrant system on top of the water hydrant system. This design uses an external nucleation device to produce “snow seeds”. These snow seeds are an extensive mixture of heating and cooling in combination with a heterogeneous water solution to expedite nucleation. Heterogeneous water allows for quicker nucleation due to foreign substances within it being capable of holding heat or cold better than water. The device itself measures the levels and the temperature of the water and adjusts as needed to produce consistent snow types while in use. The snowmaker also includes flat spray nozzles similar to power washers to allow for better dispersion of snow. The design can be seen in Figure 2. (Beaulac, 2017)

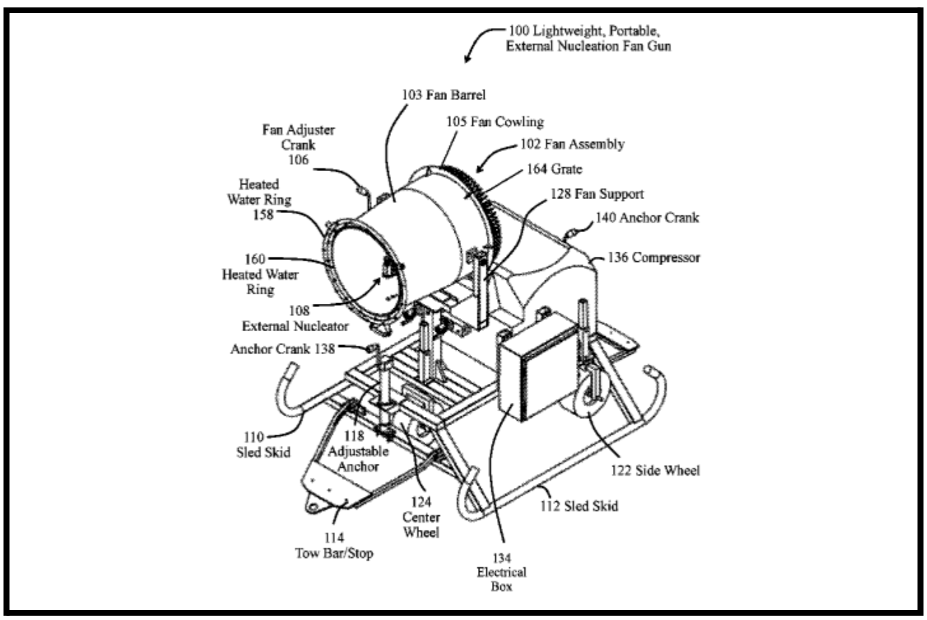

Figure 2: Beaulac Mobile Snowmaker Design

According to performance spray engineering, snow is often made by spraying water in a cold environment, growing a crystal, and then blowing the resulting snow where it is desired.A compressor or blower pushes cold air past a two stage nozzle process. The first nozzle, an atomizing nozzle, creates a fog of tiny water droplets. Those droplets then freeze to create the base of a snowflake. Next, the secondary nozzles generate larger droplets that join the smaller droplets already created. Once the snow formation is completed, the newly made snowflakes are launched into the air then onto the ground. (BETE, 2021)

1.3.3 Current Cross Country Snowmaking Practices

A typical cross country (XC) trail varies in width but needs approximately 0.46m of snow depth. Grooming ensures safe skiing by leveling the snow and the track setting provides stability. Once the snow is distributed onto the trail, a heavyweight or hydraulic press is used to carve a hip-width double track into the snow that is 0.06-0.07m wide to accommodate most cross country skis. Ideal grooming takes place at night when the temperature is between -3.9-(-1.1)°C with no more than one foot of snow on the ground. Snowcats or snowmobiles are the most common devices used for grooming. However, when grooming trails, you do not want to leave tracks from the machines. Therefore, Snowcats are the most ideal device as they automatically fill the tracks.

1.3.3 HKD Phazer

The snowmaker which the team focused on for this project is the HKD Phazer. The Phazer has a shuttle lock system where the primary internal nucleator mixes air and water. It consists of 5 water flow steps to control the water and airflow depending on the environmental conditions. Steps 4 and 5 close off the air that is fed through the top three nozzles so that only water is being fed through. This saves energy in cooler temperatures when only water is needed to create snow. When distributing snow, the Phazer produces piles approximately 0.91m wide and 1.83m tall. The snowmaker is able to project the snow 3.048-9.144m from the gun. Overall, most snowmakers have a V-shaped spray pattern that is not ideal for cross country trails. The goal of this project is to expand the capabilities of the distribution of snow by snowmakers. By designing a snowmaker that can rotate from left to right, the team can increase the length at which the snow travels during distribution. Allowing the snowmaker to adjust its height can control the amount of snow that gets carried away by the wind as well as allow for control of the hang time. Lastly, by making the angle at which the snow is projected adjustable, the width of the snow distribution can be increased or decreased. (M. Horton, personal communication, January 31, 2022)

2.0 Methods

2.1 Approach

Throughout the project, many design decompositions were made to combat the issues and problems current snowmaking systems have. One of the major problems as aforementioned is the increased price of spreading the snow along courses to ensure they are even and compacted properly to provide the best skiing conditions. Based on the many decompositions throughout the duration of our project, the team centered around distributing snow more efficiently where other snow guns cannot.

While most snow guns change the angle at which they throw snow, many of these are at fixed positions and don't allow for change to be made on the fly without wasting resources and money to change the throw angle. This is one of the problems the team hoped to rectify by changing the standard system for angling the snow gun head of the snow maker. Our designs consisted of two different ideas that would allow for proper angling without needing to stop and start the gun again.

The first idea consisted of adding stepper motors to the support system that could change the angle on the fly. Many snowmakers are supported by structural steel and pins that allow for angle adjusting. By replacing the pin system with a stepper motor the team could change the angle at any given instance. The reason the team chose stepper motors is because of the torque needed to retain the position given the snow gun's powerful backwards thrust.

The second idea was to use the pneumatic properties of the water and air pressure to apply a similar mechanism to a pop-up irrigation system. The water would displace the spring causing it to pop up and turn the head in a fixed pattern for the duration of the time water is being sent through the gun itself. The only limitation with this method is it would have to be along a fixed path.

Another limitation seen in present snowmaking systems is the proper direction of the snow when it is launched from the gun. In today's snowmaking procedures the creation of machine made snow relies heavily on the conditions at the ski resort including, wet-bulb temperature, wind, and pressure among many other factors. This could lead to improper conditions requiring the groomer to run multiple passes over the course. While most snowmaking guns calculate the throw based on the velocity of the pressurized water exiting the nozzles, our design took that into effect and expanded upon that by adding a guidance system to direct the snow throw. To that effect, our design to create snow barriers lining the snow gun portion to properly direct the snow and it's throw at any given instance is truly unique to the field. This type of system not only allows for a proper throw distance based on the type of ski trail one is on, but it would also reduce the amount of money needed to groom the snow as the piles would be in the ideal location. All of it could be controlled via a microprocessor making it extremely easy to change the throw.

2.2 Intro to Axiomatic Design

To develop a new system to facilitate the distribution of machine made snow, the team used Axiomatic Design theory. It was developed by professor Nam Suh of MIT in the 1970s with the goal of establishing overarching axioms to the design process. This design process produces design solutions that are better, faster, and cheaper. The two axioms that professor Suh established are as follows:

The independence axiom: Maximize the independence of the functional requirements

The information axiom: Minimize the information content of the solution

These axioms reduce the number of iterations required during the design process by ensuring the creation of the most simple and robust design details prior to prototyping. They also provide metrics for progress and quality through vertical and horizontal decompositions to make design choices. Horizontal decomposition encompasses four domains: the customer domain, determining the customer needs (CNs), the functional domain, determining what the products functional requirements are (FRs), the physical domain, determining what the product should look like in terms of design parameters (DPs), and the process variables, determining how the product should be made (PVs).

The vertical decomposition breaks down general aspects of a design into specific attributes. General DPs, FRs, and PVs are decomposed into their component parts, called children in vertical hierarchies. The more DPs, FRs, and PVs are decomposed, the more detailed each level becomes and the solution becomes obvious.

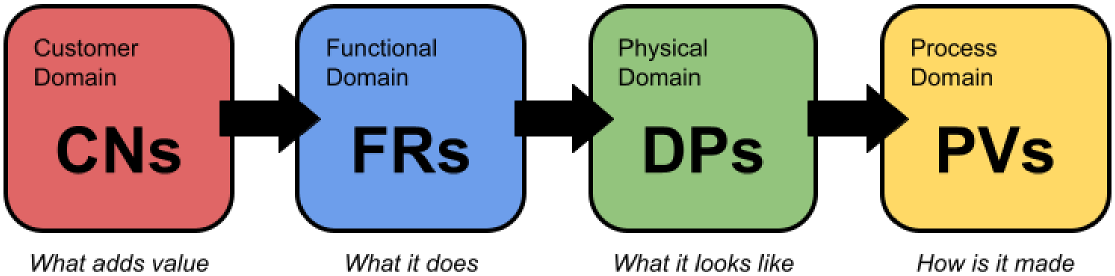

Figure 3: Four Horizontal Domains of Axiomatic Design

2.2.1 Design Decomposition and Constraints

Following the established structure of Axiomatic Design, the team created the customer domain and determined the customer needs shown in Table 1.

Table 1: Customer Needs for a Snowmaking Distribution System

Customer Needs	
Labor	• System needs to distribute machine made snow without need for snow groomers
Efficiency	• System needs to distribute machine made snow consistently along ski trails

Customer needs were used for horizontal decomposition and moved into the functional and physical domains, FRs and DPs. The team began vertical decomposition of these domains and our upper level decomposition is listed below in table 2.

Table 2: Upper Level Snowmaking Distribution System Decomposition

Functional Requirements		Design Parameters	
FR0:	Distribute making of snow for XC ski trails	**DP0:**	Distribution System of machine made snow
FR1:	Control the placement of machine made snow required to cover XC trials over a path	**DP1:**	Compressed air system to create machine made snow to cover path
FR2:	Adapt to conditions	**DP2:**	System to manage conditions

Through reviewing the literature, patents, and information from an industry professional, the team was able to identify the main problem this project will address. The objective of the project, FR0, "Distribute making of snow for XC ski trails", tackles the problem that snow distribution practices for cross country ski trails rely heavily on grooming to spread the snow produced by snow guns, due to the spray pattern of the machines. The objective of the team's decomposition aims to improve the snowmaking process, by focusing on snow distribution, rather than just snow production, with the goal of reducing the amount of manual or machine grooming required. The functional requirements for this are reflected in FR1, "Control the placement of machine made snow required to cover XC trails over a path", and FR2, "Adapt to conditions". The correlating design parameters are reflected in DP1, "Compressed air system to create machine made snow to cover path", and DP2, "System to manage conditions".

3.0 Results

3.1 Final Design Decomposition Distribution

Table 3: Final Design Decomposition Distribution

FR0: Distribute making of snow for XC ski trails	**DP0:** Distribution System of machine made snow
FR1: Control the placement of machine made snow required to cover XC trials over a path	**DP1:** Compressed air system to create machine made snow to cover path
FR1.1: Control width of path	DP1.1A: Pin-joint mechanism to adjust angle of machine made snow output DP1.1B: Multiple rows and columns of nozzles on same gun
FR1.2: Control length of path	DP1.2A: Compressed Air rotating system that changes direction DP1.2B: Different nozzle spray type (Makes piles of snow wider but not the actual distribution)
FR2: Adapt to conditions	**DP 2:** System to manage conditions
FR2.1: Control hang time	DP2.1A: Pneumatic cylinder system to raise and lower Phazer DP2.1B: Rotating nozzles to change projection of snow
FR2.2: Monitor environmental changes	DP2.2A: System to assess overall conditions: humidity, temp, wind DP2.2B: Wet bulb thermometer to read outside temperature and humidity

FR2.3: Manage loss of snow carried by wind	DP2.3A: Snow cap made of non freeze material to cover and direct machine made snow that would otherwise be blown away by the wind DP2.3B: System to change the velocity of snow output

3.2 Solidworks Model

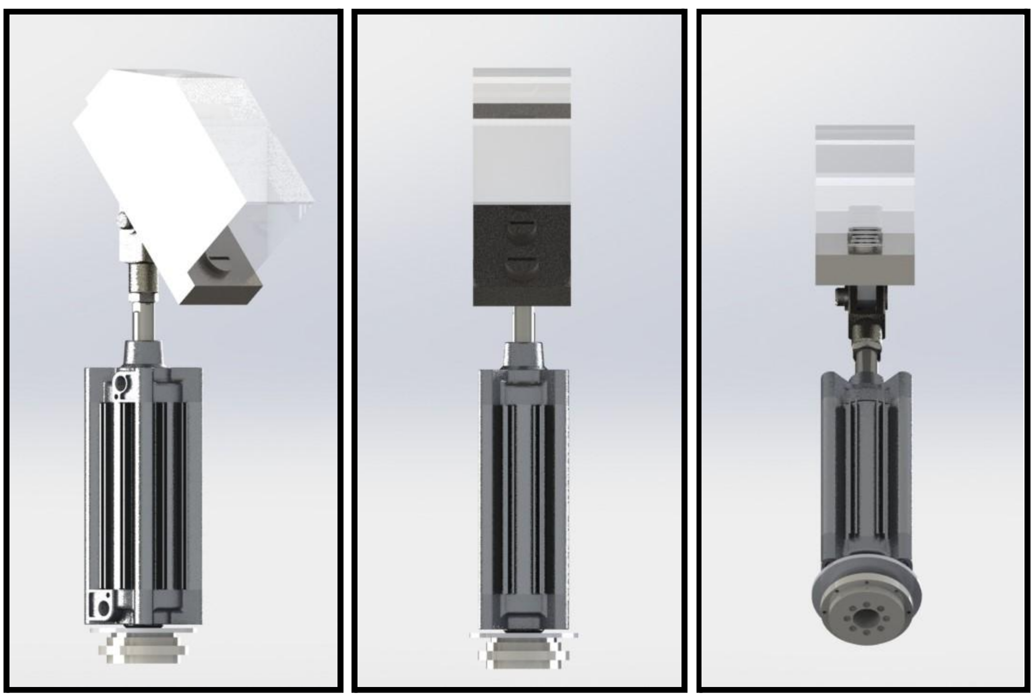

Figure 4: Solidworks Models of the Distribution Design

The final design consists of three main features represented in Figure 4. The figure shows the rotating base, customized pneumatic cylinder body, and pin joint connections.

3.3 Heat Transfer Calculations

1. 18 inches (.4572 m) snow depth for Nordic Trails
2. Water pressure powered gearbox

- Key
  - q= conductor
  - k_1= thermal conductivity of inner wall
  - k_2= thermal conductivity of outer wall
  - L= length of cylinder
  - T_i= inner temperature (temperature of water)
  - T_o= outer temperature
  - r_1= inner radius
  - r_2= outer radius
  - r_3= insulation radius
- Assumptions
  - All Equations
    - Inner diameter= 0.254m
    - Outer diameter= 0.3048m
    - Insulation diameter= 0.3556m
    - T_i=0°C
    - T_o=-2.78°C
    - L= 9.144m (from hydrant to gun head)
    - V_{vol}
  - For Nozzle Flow
    - Assume Steady Flow
    - Ideal gasses
    - W=0
    - ▲PE=0
    - Q=232.321
    - A_1/A_2=2/1
    - m_1=m_2=m
    - P_1=13.7895MPa
    - v=1416000m/s^2

Heat Loss in Pipe:

$A1 = 2\pi r1L = 2(3.14)(0.127m)(9.144m) = 7.297m^2$

$A3 = 2\pi r1L = 2(3.14)(0.1778m)(9.144m) = 10.215m^2$

$r_i = r_{conv,1} = \frac{1}{h_1 A_1} = \frac{1}{(11.31m^2)(7.297m)} = 0.012$

$r1 = r_{pipe} = \frac{ln(r_2/r_1)}{2\pi k_1 L} = \frac{ln(0.1524m/0.127m)}{2(3.14)(0.56w/m-k)(9.144m)} = 0.00567$

$r2 = r_{insulation} = \frac{ln(r_3/r_2)}{2\pi k_2 L} = \frac{ln(0.1778m/0.1524m)}{2(3.14)(23.47w/m-k)(9.144m)} = 1.119x10^{-4}$

$r_0 = r_{conv,2} = \frac{1}{h_2 A_3} = \frac{1}{(2.621m^2)(10.215m)} = 0.0374$

$r_{tot} = r_i + r_1 + r_2 + r_o = 0.012 + 0.00567 + 1.119x10^{-4} + 0.0374 = 0.0215219$

$q = \frac{T_1 - T_2}{r_{tot}} = \frac{32-27}{0.0215219} = 232.321W$

$\blacktriangle T_{pipe} = Qr_{pipe} = 232.321w(0.00567) = 1.31726007°C$

$Q = V_{vol}v = 118lpm = 0.005v = 23600m/min = 1416000m/s$

Steady flow Heat Transfer for Nozzle

$q - W = m(h_2 - h_1) + \frac{(V_2^{\ 2} - V_1^{\ 2})}{2} + g(z_2 - z_1)$

$232.321W - 0 = (2.621 - 11.31)m$

$m =- 26.7374m/s$

$P_2 = (\frac{A_1}{A_2})(\frac{V_1}{V_2})(\frac{T_2}{T1})(P_1) = (\frac{2}{1})(1)(\frac{-2.778}{-0})(P_1) = (2)(1)(4.961)(13.7895) = 136.819MPa$

4.0 Discussion

4.1 Design Decomposition Analysis

Once the team identified the objective, it was time to identify the functional requirements for the solution. Length and width are hereby defined in the skier's point of view where the width is from the downhill perspective of the skier from left to right and the length is from start to finish of the trail.

4.1.2 Functional Requirements Analysis

FR0: Distribute making of snow for XC ski trails

FR0 was created to encapsulate the objective of the project, to create a system that facilitates the distribution of machine made snow.

FR1: Control the placement of machine made snow required to cover XC trails over a path

The first top-level functional requirement in the decomposition, FR1, was chosen because of the need for the solution to improve the area a singular snow gun can cover in snow. The team learned from Mark Horton, the Vice President of HKD Snowmakers, that the HKD Phazer snow gun sprays snow over a width of approximately 0.9133m, at a distance of 3.408-9.144m in front of the snow gun (M. Horton, personal communication, January 31, 2022). Because cross country trails are long and narrow, the team wanted to control the width and length one snow gun can cover, with the plan to reduce the number of individual guns required to cover a distance along a cross country ski trail. This top-level FR, was then broken down into two, collectively exhaustive and mutually exclusive children. Thus, FR1.1, “Control width of path”, and FR1.2, “Control length of path” were included in the decomposition. By having these two separate children for the parent FR1, the width of snow sprayed across the trail can be altered to adapt to the trail width, without affecting the distribution across the length of the trail, and vice versa.

FR2: Adapt to conditions

While FR1 covers the snow placement and the area covered by the distribution system, FR2 addresses the constantly changing environmental conditions and how they affect snowmaking processes. With increasing temperatures due to climate change and fluctuations in environmental conditions, snowmaking throughout the ski season is greatly affected due to its reliance on temperature (Hart, et al, 2007). As temperatures continue to increase, producing snow gets less efficient and more expensive (López-Moreno et al., 2018). The team decided that it was important the snow distribution system incorporated a way of adapting to these changing conditions. To achieve this goal, FR2 was broken down into three children.

FR2.1, "Control hang time", was created so the team could alter the hang time depending on the ambient temperature. According to Backyard Snowstorm, the hang time needed to freeze water droplets into snow is proportional to the amount of energy that needs to be removed from the droplet ("Snowmaking Science", n.d.)). By adding this functional requirement to control hang time, the distribution system can spray snow at a lower height in higher temperatures and vice versa. Spraying only at the necessary height to produce high quality snow will allow for a more precise placement, which is crucial for narrow cross country ski trails.

FR2.2, "Monitor temperature conditions" was created in order to identify what the current environmental conditions are. Monitoring temperature conditions allows the distribution system to record humidity, temperature, and wind changes and adapt accordingly.

FR2.3, "Manage loss of snow carried by wind", aims to address the problem that portions of snow are blown away by the wind when snow guns are making snow. While this is not as big of a problem on alpine ski trails because misplaced snow is likely to land somewhere else along the trail, with narrow cross country trails, misplaced snow can easily end up in the woods or elsewhere off trail, becoming a waste of time and energy use.

4.2.2 Design Parameter Analysis

After determining the functional requirements for the design decomposition, the team came up with the corresponding design parameters. Each FR has one corresponding DP, which was chosen to solve the problem that FR addresses.

DP0: Distribution System of machine made snow

The highest level DP0 was chosen because the team decided it was important to focus on snow distribution rather than snow creation. By creating a system focused solely on distribution, the team relied on an existing snowmaking process that works effectively and created a distribution system surrounding this to improve its snow placement.

DP1: Compressed air system to create machine made snow to cover path

The next top-level design parameter DP1, focuses on producing snow in the desired distribution pattern. The team is using a compressed air system because it is the most widely used in the industry and creates the best quality snow. To do this, DP1 was broken down into 2 children.

DP1.1, “Pin-joint mechanism to adjust angle of machine made snow output”. This mechanism will angle up and down to distribute snow output along the width of the cross country ski trails.

DP1.2, “Compressed Air rotating system that changes direction”. This compressed air system will rotate to distribute snow output along the length of the cross country ski trails. The compressed air will facilitate the rotation of the system.

DP2: System to manage conditions

DP2 addresses the need for the distribution system to adapt to the constantly varying temperature and wind conditions. By incorporating a system to adapt to the weather into the distribution system, the distribution system will be as efficient as possible and eliminate any wasted snow that might be lost due to the weather conditions. This top-level DP was broken down into three children.

DP2.1, “Pneumatic system to raise and lower Phazer”. This air piston system will raise and lower in a telescoping fashion to adapt to the ambient temperature. The compressed air will push the telescoping rod that is connected to the snow gun head up and down depending on whether the temperature is higher, therefore requiring a greater hang time for water droplets to freeze, or lower, requiring less hang time for the droplets to freeze.

DP2.2, “System to assess environmental conditions”, is included because the system cannot adapt to the environmental conditions without first monitoring them. This system would measure temperature and wind speed, which are two factors that greatly affect how snow is produced and distributed. From there, changes can be made to the positioning of the snow gun to affect snow placement.

DP2.3, “Snow cap made of non-freezing material to cover and direct machine made snow that would otherwise be blown away by the wind”, is included to eliminate machine made snow being wasted by blowing off trail. The cap would be attached to the top of the snow gun head where the nozzles are located. The cap would be angled outward to allow snow to spray out of the nozzles without being blocked, but block the snow from spraying outside of the desired cone shape of the nozzle. The cap would be made of a freeze resistant material to eliminate the chance that the water droplets being sprayed from the nozzles will freeze on the cap and cause ice build up. The cap will slightly redirect the snow spray to a more downward direction, helping the distribution system place the snow in the appropriate location.

4.2.3 Alternate Design Parameters

When creating the design decomposition, the team thought it would be helpful to have multiple ideas for each lower-level design parameter. As the team brainstormed ideas, they took note of each design parameter option and then decided on final choices for each DP in the final decomposition, labeled with a capital A next to the DP number. Each alternative DP, which was ultimately not chosen for the final design, is labeled with a B next to the DP number. These can all be seen in the decomposition in section 3.1 Final Design Decomposition Distribution**.**

For the first lower level DP, DP1.1, the alternative DP to the chosen DP was to have multiple rows and columns of nozzles on the same snow gun head. The HKD phazer currently has one column of nozzles, so by increasing the number of columns, therefore increasing the width of snow spray, the gun would cover a wider area with snow. While this is an improvement to the current gun, the team thought it would be more innovative and effective to have the entire snow gun head capable of rotating to cover a much larger length of trail. The area covered by rotation would be much greater than that of adding more nozzles, and this solution would result in a more even distribution than solely relying on the placement of snow from the nozzles, which is generally in a pile. DP1.1B would simply increase the area of the snow pile, rather than causing a greater, even snow distribution, which is why the team went with DP1.1A.

The alternative DP for DP1.2 was changing the shape of the individual nozzles to achieve a different spray pattern. While this has the potential to increase the width the snow gun can cover in snow, it is a permanent change to the design that cannot be adapted to different widths of trails without changing the nozzle shape accordingly. DP1.2A, which the team selected for the final design, is more adaptable to various trail widths.

The lower-level DPs under DP2 also all have alternatives that the team ended up not using in the final design. DP2.1B was to have the individual nozzles on the head of the snow gun rotate to change the projection of the snow, allowing for it to be sprayed higher when a longer hang time is required for the droplets to freeze. The team went with DP2.1A instead because it was a simpler method of achieving the same results. A pneumatic cylinder system can easily be raised or lowered, whereas adjusting the nozzles to allow the appropriate amount of hang time would require trial and error.

The alternative DP for DP2.2 is to use a wet bulb thermometer to measure the temperature in the environment so the snow gun positioning can be adjusted accordingly. The team went with DP2.2A instead because it allows for a more complete assessment of environmental conditions by including wind measurements and other environmental conditions that could affect snow distribution.

The final alternative DP, DP2.3B, incorporated a system to change the velocity of snow output by the snow gun. This would involve changing the snowmaking process, which is outside the scope of this project, as the team is focusing solely on how the chosen snowmaking system can be adapted for improved snow distribution, which is ultimately why the team chose DP2.3A instead.

4.2 Final Design Conclusions

Our final design consists of three main features which can all be seen in Figure 4. The first is a rotating base that will connect to the water pipes. This base rotates similarly to a revolving tray or gun turret with at least 90° of rotation left and right from the forward facing position. This will increase the area of snow coverage from down the distance of the trail. Attached to the rotating base will be the second feature, a pneumatic cylinder. The pneumatic cylinder will be customized so that pressurized water can still pass through to the nozzle. This will allow the nozzle gun to move up and down to the height best needed to control the hang time based upon the environmental surroundings. Lastly, the pin joint feature will connect the nozzle gun of the snowmaker to the pneumatic cylinder. This will allow the angle at which the snow is projected to be adjusted to expand the amount of the trail covered in snow from one side of the trail to the other (width of trail from skiers perspective). Overall, the system will be powered by the already used pressurized air.

4.3 Project Shift

During the final term the team shifted focus from creating a snowmaking machine to creating a system to distribute snow from an existing snowmaking machine. The current machine model used was the HKD Phazer. This allowed the team to redesign the system so that the Phazer nozzle will project snow further lengthwise and widthwise. This design shift came from focusing on the functional requirements the team thought was most important from our beginning decompositions. The shift in decompositions is shown from decomposition 13 to 14 and can be seen in Appendix 8.2.3.

4.4 Heat Transfer

Heat Transfer equations in Section 3.3 involve calculating the fluid flow for both the pipeline system leading from the hydrant to the snow gun itself. Most of the calculations completed involved assumptions provided to us from Mark Horton from HKD Snowmakers. Using HKD's Phazer gun as a reference point for our equations, the team figured that the water pressure leaving each individual nozzle should calculate to 136.819MPa. The calculations also provided a temperature change between the insulated pipe and the nozzle of 1.317°C under which it would get colder due to the ideal outdoor snowmaking temperature of -2.78°C.

4.5 Future Expansion

It is our hope that another project group takes up where the team left off and continues designing the snowmaking gun. There were many difficulties with our project, but the most notable problem the team came across was the feasibility of being able to create a physical product on campus. As mentioned earlier, snowmaking requires a large amount of power to provide the correct pressures in both water and air to create snow. It is difficult to replicate these types of situations to see if our design will hold true given the forces that cannot be replicated on WPI's campus. Another consideration is working/forming a partnership with a snowmaking company that can provide additional funding and resources to make these ideas come to fruition. Lack of hard knowledge and resources held this project back in a major way, and having a company that has experience in the field would allow for one to find the information needed very easily to produce a product that has not been seen before.

5.0 Conclusions

- Axiomatic Design was used to decompose the project objective into a detailed assessment of customer needs, functional requirements, and design parameters that address the gap in the market of snowmaking for cross country ski trails
- The team created a Solidworks Model to visualize the final design created from the design decomposition
- The project objective shifted direction from focusing on snow production to snow distribution midway through the project time frame
- Heat transfer calculations demonstrate the effectiveness of the final design in improving snow distribution without affecting the quality of snow produced
- The project could be added to in the future by a new project team and possibly a sponsor from the snowmaking industry

6.0 Broader Impact

6.1 Engineering Ethics

Snowmaking and well-maintained ski trails greatly enhance the safety of those participating in winter sports. As such, a system that can efficiently achieve the linear distribution of snow across the trail fits nicely with the first canon of Engineering Ethics: hold paramount the safety, health, and welfare of the public.

6.2 Societal and Global Impacts

Skiing and other winter sports are enjoyed by many across the globe. Snowmaking has revolutionized winter sports, allowing for the beginning and end of each traditional snow season to be extended. The Olympics, one of the cornerstones of international competition, rely on snowmaking systems to provide a world-class environment for the athletes competing. The design explored in this project enables the snowmaking process to be streamlined and improved, allowing for more individuals to enjoy winter sports..

6.3 Environmental Impact

Snow is traditionally made in piles and pushed around by large tracked grooming vehicles. These vehicles contain large engines and other carbon producing apparatus. A linear distribution of snow greatly reduces the use of groomers, therefore causing a reduction in carbon emissions at the facility.

6.4 Economic Factors

On cross country ski trails, snow must commonly be made in large piles, and distributed with the use of large tracked grooming vehicles. These vehicles are expensive, and require skilled workers to operate. A system that achieves the linear distribution of snow across the entire cross country trail would be financially advantageous because it would reduce or eliminate the use of these groomers. Labor costs would go down significantly, as workers are no longer needed to distribute snow and maintain the trails every day. While the snowmaking system may have higher upfront cost, it would not involve the protracted costs of a conventional machine made snow operation.

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8.0 Appendices

8.1: Interview Notes with Mark Horton

Interview Notes with Mark Horton, Vice President of HKD Snowmaker, 1/31

https://www.hkdsnowmakers.com/products/phazer/

1. Phazer Snow Gun Notes:
    - 1.1. 2,000-3,000 lbs water pressure
    - 1.2. Creates piles around 3 ft wide depending on wind
    - 1.3. Projects snow 10-30 ft in front of snow gun
    - 1.4. Very adjustable, multiple pin joints to change angles and output direction
    - 1.5. Tight spray pattern which creates a contained pile (about 6 ft high by 3 ft wide)
    - 1.6. Alpine: More area to cover and is groomed so the snow guns are spaced around 80 ft apart. This depends on weather though, for example when it snowed more often in the past they were placed 150 ft apart
    - 1.7. Nordic: Less snow is needed since grass is cut and trails are smaller. The typical depth is 18 in of snow
    - 1.8. Phazer projects snow really nice
    - 1.9. Riker uses Phazer on 5 K length of ski trails
    - 1.10. Lake Placid Olympic jumps include 7 Phazers along the hill down
2. Phazer nozzle breakdown
    - 2.1. Shuttle lock: Primary internal nucleator is always on (mix air and water), upper nozzles are external (center is water, around is air),
        - 2.1.1. 5 water flow steps to control water and airflow depending on surrounding temperatures
        - 2.1.2. Step 4 and 5 close off air feeding top 3 nozzles running no air and only water. This is because in cold temperatures air is not needed to turn water into snow. This saves a lot of energy.
3. Hydrant always attached to snow gun (KLIK manual or auto hydrant)
    - 3.1. This starts and stops the snow gun by opening and closing valve
    - 3.2. Water hydrant and air hydrant into snow gun
    - 3.3. Time saving due to being able to walk or snowmobile down the trail and turn snow guns on one after the other

4. Freezing in pipes
    4.1. An inch of water is not a big deal
    4.2. Air is used to blow water out of the pipes to prevent freezing

8.2: Design Decompositions

8.2.1: A-Term Design Decompositions

Decomp 1

After the first decomp and getting feedback from our advisor, the team gained a better understanding of CNs, constraints, FRs, and DPs

Decomp 2

From this decomp, the team learned that there are constraints, selection criteria, and design problems as well

Decomp 3

In this decomp, the team broke down the FRs in children to better clarify our end mechanism

Decomp 4

The team redefined our project at this time and broadened with an new objective, CN's, constraints, selection criteria, FRs, and DPs

Decomp 5

The team took our new project objective and focused in on 3 FRs to outline our idea

Decomp 6

This was our final decomp for A term, the team felt that the project was in a good spot with a clear objective to move forward in B term and extrapolate our FRs and DPs to then come up with a variety of designs

8.2.2: B-Term Design Decompositions

Decomp 7

Simplified DPs and added extras design ideas to design idea warehouse

Decomp 8

Added Functional and Physical Metrics to the FRs and DPs from Decomp 7

Decomp 9

Reorganized FRs and added FR3. Edited Functional and Physical metrics

Decomp 10

Broke Decomp 9 down to make FRs and DPs more specific. Divided the six person group into teams of two to work on an FR per team

Decomp 11

Removed FR 3. Added more detail to FR1: Creating water droplets. Looked at past MQP structures to imitate their decomp structure

Decomp 12

Included feedback from the previous decomp. Modified FRs according to feedback

8.2.3: C-Term Design Decompositions

Decomp 13

Developed FRs and DPs into further children and added more detail in teams of two over Winter break

Decomp Distribution 14

The Team decided as a whole to focus solely on the mechanism for distribution and started a brand new decomposition in order to complete the project in a timely manner. This meant that FR0 became about distributing snow and new FRs and DPs were brainstormed.

Decomp Distribution 15

Focused on the wording of the FRs and DPs to accurately display what the team was thinking in terms of movements for distribution

Decomp Distribution 16

FRs and DPs were expanded to be more detailed. Used lawn sprinkler as real life inspiration for movement

Decomp Distribution 17

Reworded FRs to have best verbs for the function. Expanded the FRs into more subcategories to add more detail. Added more DPs to show our different design ideas instead of using an idea warehouse