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# Feasibility study of Preventing Snow Accumulations on Roofs using Airflows

Preliminary Computational Fluid Dynamics (CFD) simulations followed by exploratory experiments using compressed airflows

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# Abstract

This thesis is intended to contribute to research in cold climate engineering. Further it intends to provide a principle solution for structural and avalanche safety due to snowfall on roofs. We have conducted a feasibility study of preventing snow from accumulating on roofs using airflows. This includes empirical, numerical and experimental methods.

Snow loads on roofs makes great impact on structural safety and is the cause of annual injuries due to snow removal. Studies have shown that incidents related to snow clearing activities occurs more frequent in winter seasons with heavy snowfall (Bylund, Johansson & Albertsson, 2016, p. 107). At the same time, several climate projections predict that the annual rainfall will increase significantly, along with increased global temperature. However, for several places in cold climate regions, the rise in temperature will not be enough for the rain to stay liquified. The consequences of increased snowfall can be severe, especially for lightweight structures or structures built according to outdated standards. Regardless of the climate changes, risks for humans associated with snow loads on roofs is present. To assess the risks for human and assets a PHA is conducted and supported by risk matrices and bow-tie method.

The experiments are based on empiricism and CFD simulations of airflows. To generate airflows, a compressor was used as source and pneumatic hoses from Festo was applied. The falling snow seemed to behave as intended - to a certain extent - by the influence of airflows. Due to challenges related to the experiments, we were not able to efficiently prevent snow from accumulating at the surface. However, from the results and discussion it emerges potentials for achieving the purpose. If the design chosen in this study is applicable and how it can be improved is concluded in the last chapter, followed by suggestions for further work.



**Keywords:** Snow; Roof; Airflows; CFD; Snow Engineering; Technology; Construction safety; Cold regions; Cold climate engineering; PHA; Risk assessment; Bow-tie diagram; Risk Matrix; Roof avalanches; Icicles; Cornices; Reliability; Barriers; Pneumatic.

# Preface and acknowledgement

The thesis concludes the completion of my master's degree in Technology and Safety in the High North at the Faculty of Science and Technology, UiT – The Arctic University of Norway. The thesis has been completed between January and July 2020.

First of all, I would like to thank my enthusiastic and always optimistic supervisor, Hassan Abbas Khawaja, for his unquestionable support throughout the whole process. Further, I appreciate the interest that SINTEF Nord gave my project and the opportunity to present the initial project. Also, thanks to Ståle Antonsen and Jim Asle Olsen for being great assistance in the initial phase of the experiments and laboratory work.

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Tromsø, 13 of July 2020

# Definitions

**Accessibility** Having sufficient working space around a machine, piece of equipment, system, subsystem, or component to diagnose, troubleshoot, and complete maintenance activities safely and effectively (Houshyar, 2004, p. 204).

**Active barrier** "A barrier that is dependent on the actions of an operator, a control system, and/or some energy sources to perform its function" (Rausand, 2011, p. 594).

**ALARP** (As low as reasonably practicable): "A level of risk that is not intolerable, and cannot be reduced further without the expenditure of costs that are grossly disproportionate to the benefit gained" (Rausand, 2011, p. 594).

**Availability** "The ability of an item (under combined aspects of its reliability, maintainability, and maintenance support) to perform its required function at a stated instant of time or over a stated period of time" (IEC 60050-191, referred in Rausand, 2011, p. 594).

**Hazard** "A potential to threaten human life, health, property, or the environment" (IMO, referred in Rausand, 2011, p. 598).

**Hazardous event** "The first event in a sequence of events that, if not controlled, will lead to undesired consequences (harm) to some assets" (Rausand, 2011, p. 599)

**HAZID** "The process of describing in detail the hazards and accidents associated with a system, and defining accident sequences" (DEF-STAN 00-56, referred in Rausand, 2011, p. 599).

**HAZOP** "Hazard and operability study. A systematic functional hazard identification process that uses an expert group to conduct a structured analysis of a system using a series of guide words to explore potential hazards" (Rausand, 2011, p. 599)

**Interchangeability** "As an intentional aspect of design, any component, part, or unit can be replaced within a given product or piece or equipment, by any similar component, part, or unit" (Dhillon, 1999, p. 85).

**Passive barrier** "A barrier that is integrated into the design of the workplace and does not require any human actions, energy sources, or information sources to perform its function" (Rausand, 2011, p. 601).

**Proactive barrier** "A barrier that is installed to prevent or reduce the probability of hazardous event." (Rausand, 2011, p. 366)

**Reactive barrier** "A barrier that is installed to avoid, or reduce the consequences of a hazardous event" (Rausand, 2011, p. 366).

**Risk tolerability** "It refers to a willingness to live with a risk so as to secure certain benefits and in the confidence that it is being properly controlled" (HSE, 1992, p. 2)

**Serviceability** "[…] the ability to provide suitable service" (Bontempi, Giuliani & Konstantinos, 2014, p. 2) or ease of the act of service.

**SWIFT** **(**Structured What-If Technique): Checklist based hazard identification method. Can be used as a simplified HAZOP and applied to the same type of system. (Rausand, 2011, p. 216)

**Trigger event** "An event or condition that is required for a hazard to give rise to an accident" (Rausand, 2011, p. 68)

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# 1 Introduction

Climatic conditions have always been, and will probably always be, both a prerequisite and a restraint for constructions. Through time we have reduced restraints due to climate and weather conditions by gaining knowledge and developed new technology. Snow related challenges are often among the most important climatic conditions that constructions must endure (Thiis, 2005, p. 3). A number of standards and regulations in association with these challenges must be compiled to ensure safety.

Some of these formal requirements states critical snow load on buildings and the responsibility entrained by the owner of the building regarding avalanches. In order to comply with these requirements, accumulated snow on roofs often need to be removed. There are several methods used to handle this, which are presented in subchapter 2.8. Some of the methods are both impractical and risky. To reduce the risk for human life, health, material and roof damages, there is room for improvements.

Resources used to deal with cold climate challenges are enormous. According to Bardin, referred to in Gray & Male (1981, p. 3), these resources reduced the US GDP[1] by $20 billion in 1976-77. Furthermore, by drawing parallels to the winterized infrastructure in Norway, SVV's[2] resources spent on snow clearing increased by over 20% in the winter of 2018 (NTB, 2019). The same year, the municipality of Oslo spent NOK 1.3 million daily on clearing and removal of snow from roads and buildings. Nearly half of this amount was used for removal of snow which did not include roads (Bjørntvedt, 2018). Researching towards new solutions and measures for snow deposition on roofs can be helpful to reduce associated costs and risk concerning human life and material loss.

## 1.1 Background and Problem Statement

The climate forecasts indicate that there will be changes in snowfall in several places in Norway in the years to come. Most places will experience a negative trend, but there are municipalities that could experience positive trends (Hanssen-Bauer et al., 2015, p. 67). The report from Sintef

[1] Gross Domestic Product

[2] Statens vegvesen

(Kvande, Tajet & Hygen, 2013, p. 17) states that 34 of the municipalities in Norway will experience an increase in snowfall within the year 2100. All the latter municipalities were encouraged to make the roofs stronger, of which no one followed the advice. This led to collapses of several houses, barns and warehouses in the winter of 2018 (Kesser, 2018). Croce, Formichi, Landi & Marsili (2017, p. 49) also refers to recent structural collapses in Europe. Climate change related implications can make a huge impact on snow loads, especially on lightweight structures.

As Thiis (2018) trivially said; it cost more to build stronger. Construction safety is a balance between economy and the desired degree of safety. The same applies to the desired safety level when applying measures to avoid avalanches from roofs. Perhaps the simplest solution would be to cover the whole roof with heating wires to solve the problems. On the other hand, it is doubtfully justifiable in terms of energy supply. This establishes the fundament for research towards an alternative method, which purposely is implementable and justifiable in terms of efficiency and energy supply.

## 1.2 Aim and Objective

The aim of this thesis is to investigate the feasibilities of using airflows as a measure to prevent snow from accumulating on roofs. The objective for the thesis is to contribute with an innovative principle solution to prevent snow accumulations on roofs. However, a complete system ready for implementation is not the objective. There are several aspects of snow related challenges which could be solved or improved by researching this objective. Among the challenges are snow avalanches from roofs, risk associated with people climbing on roofs to clear snow, the designed load capacity of roofs and non-uniform snow distribution. The idea is to use the airflows to blow away snow crystals before they reach the surface of the roof, which purposely is easier and safer than removing it after it accumulates. The intention is to use adequate velocity – from an air compressor - to steer the snow particles away by creating sufficient drag force. Based on this purpose, the adequate airflows are empirically calculated, and different streamlines have been simulated using ANSYS® Workbench.

Further, the analyzed results from the simulations are the base for the experiments. The aim for the experiments is to test the validation of the initial calculations and simulations. To conduct the experiments, a model had to be assembled. This testing model have the same characteristics as the model made for the simulation part. The objective for the experiments is to test the principle of blowing the snow away before it reaches the surface. Limitations related to the experiments is presented in subchapter *1.4.*

## 1.3 Research Questions

The study is divided into several research questions (RQ) to address the various sub-problems included in the problem statement. This section also makes it easier to guide the reader through a structured discussion and conclusion later in the report.

RQ 1: What risks are associated with accumulation of snow on the roofs?

RQ 2: How changes in weather conditions effect snow accumulation?

RQ 3: Is it possible to prevent snow accumulations on roofs using airflows?

RQ 4: Would the system be justifiable in terms of efficiency, energy supply and reliability requirements?

RQ 5: Is the system implementable in a practical point of view, or is there other more efficient designs?

## 1.4 Limitations

- The thesis focuses on the principle solution for a self-cleaning roof. Thus, investigating the feasibilities of using airflows to keep a surface free from snow accretions. In the experiments the surface corresponds to a defined part of a roof. Testing of the principle on a full-scale roof will not take place. However, it will be discussed along with the results from the experiments.
- Two different approaches were considered in the planning phase but only one model could be assembled due to both time and extent of the project. The final design of the model appeared more practical than the alternative. The alternative will be presented in the chapter for further work. An ideal situation would be to test more than one approach for the experiments. However, the design – which were anticipated to be the most efficient – is also supported by promising CFD simulations and initial calculations.
- The materials used in the experiments are partly used due to its practical properties and partly because of the availability and budget, which makes a clear restriction regarding

scale of the experiments. The source for the airflow is the most vital equipment, which first were chosen to be a leaf blower. A leaf blower was early considered to satisfy the required airflow and velocity, and at the same time be within the funding range from the faculty. However, throughout the experiment planning process, uncertainties associated with the use of a leaf blower in the experiments started to appear. The new source of airflow was changed to a compressor. Further discussion about the materials is provided in the experiments chapter 3.5.

- Unwanted snow accretions on solar panels for instance, is relevant for the principle solution as they often are located at roofs, nonetheless it is not the scope of this thesis. However, a few ideas and suggestions for further work will be presented in chapter 5. Conclusion, Challenges and Further Work.
- We are only looking at the velocity convergence for the simulation part conducted in ANSYS. The argumentation for not concerning pressure and energy convergence in this study is because we are only interested in the drag force from the air, which depends on the velocity of the surrounding airflow. This recognition is also the reason for the chosen mesh density in the CFD model. A more detailed review of the simulation set-up is described in subchapter 3.3.

## 1.5 Regulations

The presence of global warming and climate change is unambiguous. Although there is an increasingly focus on this subject, we must take into account the non-reversible consequences that will follow. The overall rules in accordance with structural safety are regulated in the regulations on technical requirements for construction, also known as the technical building regulations (TEK17). The regulation sets the limit for the minimum requirements a construction must have in order to legally be constructed in Norway. Further the guide explains the requirements of the regulation and provides pre-accepted benefits to meet the requirements. §10-3 second paragraph, states that;

*The structure must be secured so that ice and snow cannot fall into places where people and livestock can be resided. The purpose of the provision is to ensure that avalanches from roofs does not harm peoples or livestock.*

Furthermore, it appears that areas included in the provision are sidewalks, roads, and outdoor recreation areas. This also applies to balconies and terraces not protected from avalanches. In general, one must assume that it is safe for people to reside and children to play around buildings, as long as the area is not physically closed off (TEK17, 2017, §10-3., second paragraph).

It appears from the Norwegian Labour Inspection Authority (Arbeidstilsynet) that fall accidents are one of the main causes of workplace injuries and deaths. The statistics gives us all reasons to believe that the number of accidents per time of exposure is not substantially different for private homes either. The relevance for statistics regarding work at heights are due to the fact that it is a commonly used method to clear off snow. Therefore, it is important for the employer to identify hazards and assess risks so that the work is done safely. Work at heights is regulated at the regulation concerning the performance of work. This regulation states that: "The purpose of these regulations is to ensure that work is executed and work equipment used in a safe manner so that employees are protected against harm to life and health". Further it states that: "If there is a risk of falling from height, a safety harness shall be used" (Regulation concerning the performance of work, 2011, § 17-25). Furthermore, it appears from Arbeidstilsynet (n.d.) that one should try, as far as reasonable practice, to avoid that employees work at heights.

## 1.6 Structure of Thesis

- **Chapter 1**
  In this chapter the background and motivation of the thesis is presented firstly. In the following subchapters the aim and objective has been described and then research questions was derived. Related limitations have been presented here and finally relevant regulations are included.
- **Chapter 2**
  This is the literature review chapter where all the theoretical background is systematically presented. The first three chapters regards theory about snow, with the two first chapter covering snow conditions and formation of snow. The third chapter consider the wind effect on deposition of snow. Chapter 2.4 gives us most of the equations regarding fluid dynamics. Roof design, reliability and risk management follows before the last chapter where existing measures are presented.
- **Chapter 3**
  First the research methodology is explained and later the process of empirical, numerical and experimental methods is described in detail. A presentation of the preliminary study is also included here.

- **Chapter 4**

  This is the largest chapter, consisting of both the results and discussion. Results from the three fundamental aspects; empirical, numerical and experimental methods are presented and discussed consecutively. A separate chapter for the risk assessment and reliability analysis is also included. At the end of this chapter, comparison of the results is conducted and finally the research questions are discussed.

- **Chapter 5**

  In the final chapter, several sub-conclusions are formulated. Suggestions for further work and challenges related to the completion of the thesis is presented.

# 2 Literature Review

This chapter is meant to give the reader a theoretical framework in order to get knowledge about fundamental principles used in the study. Literature regarding snow conditions, formation and the behavior of deposition are given particular attention. Further, theory regarding reliability and maintenance aspects in cold climate conditions are contributing to the understanding. At the end of this chapter, the risk assessment methods applied for this study are presented. The last subchapter is a selection of relevant existing measures to prevent or remove snow accumulation, which finalizes the literature review.

## 2.1 Snow Conditions in the High North

Norway is a country with wide variations in snow cover. The maximum amount of snow varies from around zero to 2000 mm and the number of days with snow cover also varies from close to zero to over 200 days (more than 5 cm cover). Analyzes conducted with over 100 years of data series shows that some places have positive trends concerning maximum daily snow depth (MDSD) (Hanssen-Bauer et al., 2015, p. 67). MDSD is a useful variable regarding snow load calculations on roofs. Although the foundation of this project is to keep the snow from deposit on the roof in the first place, the variable is highly relevant for this study as well. MDSD is especially valuable in terms of energy supply estimation regarding sufficient airflows.

The climate in Norway report (Hanssen-Bauer et al., 2015, p. 67) also points towards positive trends in general for snow depth at the inland of Norway over the last 50 years (1961-2010). As mentioned earlier, most places are predicted to experience less snow in the years to come in this country, but the interesting ones are the exceptions. The predicted changes in snowfall is mainly based on the expectation of several degree increase of mean annual temperature, combined with an increase in annual rainfall of approximately 18%. This explains why most coastal areas in Norway will experience less snow towards the next century. The increase in temperature will not be sufficient in many inland areas, which means that the increased annual rainfall will fall as snow instead. As a supplementary illustration, the amount of snow from March 2019 is shown in Appendix B, for the region of Tromsø. Throughout March there is a gradually increasing deviation from the normal. Storfjord, which is among the 34 municipalities mentioned earlier, is marked with a red ring in the appendix.

## 2.2 Snow Crystal Characteristics

Water covers most of the earth's surface, by far, and the solid state of water is also one of the most common materials found at the surface, either as snow, glaciers, fresh- or saltwater ice. Even though the formation and physical properties is different from the various types of ice, they all play important roles in a broad spectrum of environmental, meteorological and physical processes, to mention a few. For buildings and roofs, snow and freshwater ice are among the most important external climate conditions that has to be endured. Sometimes snowflakes fall almost undisturbed from the sky (Figure 1) and sometimes they behave like a visualization of the wind itself, by floating with the moving air. The latter combined with the vast amount of different snow crystals and different temperature related behavior, have been the source of curiosity and scientific study on this subject for several centuries (Libbrecht, 2017, p. 272). The difference between snow a crystal and snowflakes are most commonly described as a single crystal and several crystals stuck together, respectively (Dolce, 2020; Libbrecht, n.d.). However, we also find other interpretations in the literature, where snowflakes are a generic term and snow crystal refers to the categories (Elischer, 2018). In this study, the most common way to distinguish these is used.

*Figure 1: Calm snowfall at night, Tromsø. 27. Mars 2020.*

As it appears, the first person to look at snow crystals from a scientific point of view, was Johannes Kepler at the beginning of the 1600s. Kepler tried to describe the possible origin of the snow crystal symmetry in his work. In 1931, Wilson Bentley made a collection of several thousand snow crystal images, which he acquired over decades. Bentleys collection prompted one of the most famous physicists in the field of snow crystal, Ukichiro Nakaya, to conduct the first in-depth study of snow crystal growth in a laboratory in the 1930s. Nakaya categorized natural snow crystals under different meteorological conditions and designed a diagram of the results (Figure 2 on page 23). This diagram was later known as the Nakaya-diagram or snow crystal morphology diagram (Libbrecht, 2005, p. 858).

### 2.2.1 Snow crystal morphology diagram

The diagram illustrates the growing of snow crystals from water vapor in air at near 1 atm, as a function of temperature and supersaturation relative to ice. The diagram shows a rather simplified picture of the large variations of snow crystals found in the atmosphere and there are still details that are incomplete. However, it provides a reasonable framework of the various physical processes underlying of the snow crystal growth dynamics. The size of the snow crystals shown in the diagram refers to the real ratio of the crystals, although it is simplified. Thus, one can see that the largest snow crystals is dendrites growing at -10 to -20°C with high level of supersaturation (Libbrecht, 2012, p. 2; Libbrecht, 2005, p. 858.)

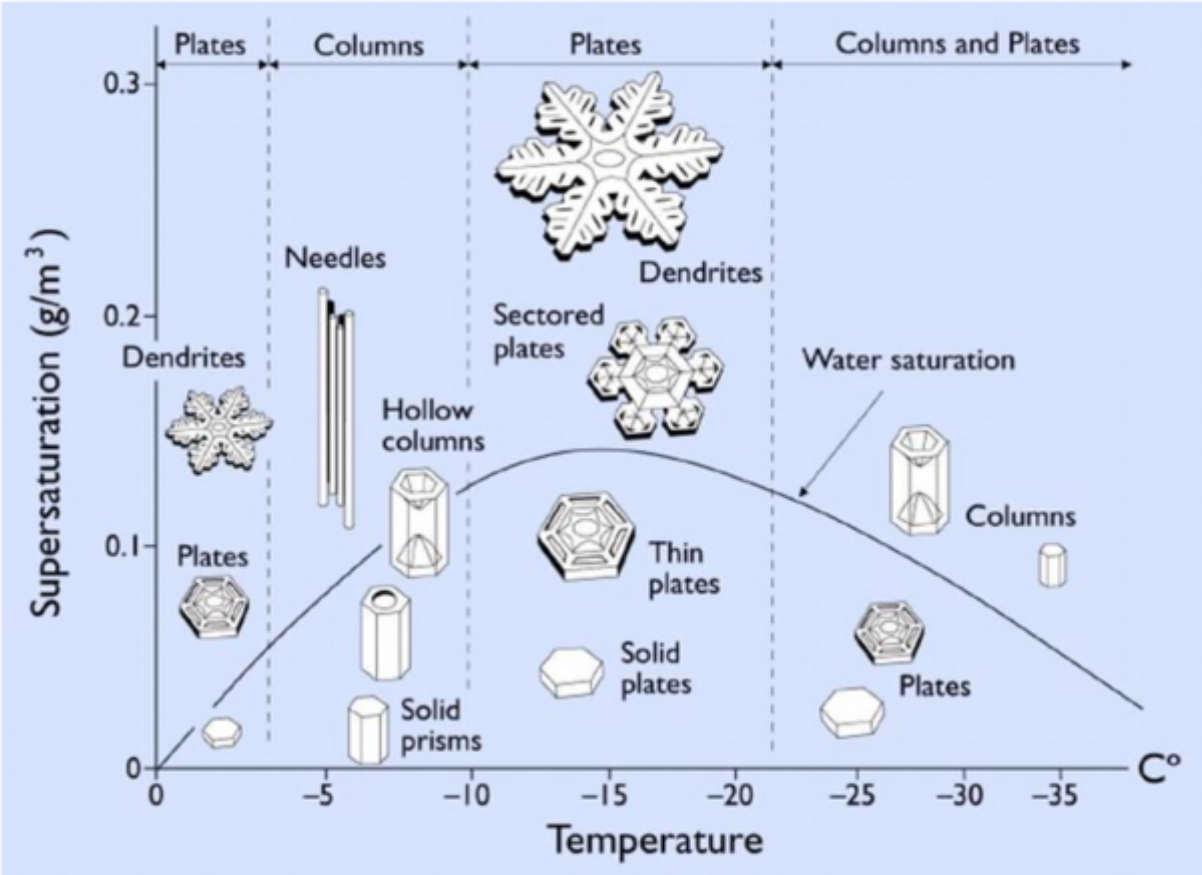



*Figure 2: The snow crystal morphology diagram (Libbrecht, 2012, p. 2)*

The water saturation line in the middle of the diagram, gives the supersaturation of supercooled water, as can be found in a dense cloud. Supersaturation occurs when the water vapor in the air begins to condense. In a meteorological context this phenomenon occurs when the air cools down to below the dew point, the water vapor in the air then begins to condense into water droplets. The dew point is the temperature at which a gas quantity must be cooled down to be saturated, without changing the pressure or vapor content. At the dew point, the relative humidity in the air will be 100% and saturation is achieved. In order for snow crystals to form, the dew point must be below the freezing point. Hence, the Nakaya chart starts at zero degree Celsius (Gleick, 1996, referred in USGS; SNL, 2017).

As we can see from the diagram, the morphology (structure) of the snow crystals switches from plates ($\mathrm{T} \approx -2°\mathrm{C}$) to columns ($\mathrm{T} \approx -5°\mathrm{C}$) before it switches back to plates ($\mathrm{T} \approx -15°\mathrm{C}$) and then to primarily columns again ($\mathrm{T} < -30°\mathrm{C}$) as temperature decreases. In general, the temperature determines whether the snow crystals grow into plates or columns, and higher supersaturations produces more complex structures. The complexity of the crystal structure also increases with growing size. Observations from studies done after Nakaya have also shown additional change in behavior at temperatures down to -70 °C (Libbrecht, 2017, p. 272; Libbrecht, 2012, p. 2).

### 2.2.2 Life cycle of airborne snow crystals

Many factors contribute to the processes of formation, growing and falling snow crystals. The formation of atmospheric snow crystals is a many-body problem which, to a great extent, remains an unsolved problem. However, there are many aspects of snow crystal growing from water vapor that are well understood, at least at a quantitative level. Some of these aspects are crystal structure of ice, the interactions between water molecules (attachment kinetics) and generally much of the phase transitions. Nevertheless, one apparently basic aspects of this phenomenon, the physical mechanism responsible for the unusual temperature-dependent structure of growing crystals, are not yet fully understood. (Libbrecht, 2017, p. 272; Libbrecht, 2005, p. 57-62; Libbrecht, 2003, p. 1)

The story of a falling snow crystal starts - not very unexpectedly - in the clouds. Clouds usually consist of a large amount of liquid water droplets nucleated on dust particles. Water droplets does not freeze at 0 °C in the clouds, but rather at temperatures far below zero. This phenomenon is occurring due to decreasing volume of water droplets combined with high purity of the droplets. Thus, small water droplets found in clouds typically begins to freeze when the temperature in the clouds drops to about -10 °C (Pruppacher & Klett, 2010, Chapter 7). All the water droplets will not freeze simultaneously, since some ice nucleators are better than others. Nucleation tend to be sensitive to impurities in the water droplets, which is the main reason why exceptionally pure water droplets can be supercooled down to temperatures as low as -40 °C before freezing (homogenous nucleation). When the water droplet already is crystalized, it quickly accumulates water vapor from the surrounding air and starts growing. As the snow crystal starts growing in size, it gets heavier and starts falling towards the ground. It is also common that several crystals get stuck into each other on their way down. Along its way through the clouds and a typical 30-minute lifetime of growing, it experiences different humidity and temperature, thus the growth behavior changes as a function of time (Libbrecht, 2017, p. 276; Libbrecht, 2005, p. 861-862).

## 2.3 Wind Effect on Snow

Snow deposition usually occurs uniformly distributed over the open landscape without influence of wind. In the presence of wind, a variety of different factors appears when determining how the snow moves and eventually deposits. The snow will be deposited in "aerodynamic shadow zones" made by unevenness or obstacles in the terrain, i.e. leeward ("lefonn") in the wind (Buska & Tobiasson, 2001, p. 340). The snow settles in these shadow zones due to reduction in wind velocity. The snow could also settle elsewhere, e.g. at the windwards ("lofonn") side of an obstacle (Figure 3), which is also due to decreasing velocity. A bit simplified, the main principle is that the snow will deposit where the wind velocities are low and eroded where they are high (Bovim, 2009; Thiis, 2005, p. 15; Erichsen, 2014, p. 11).

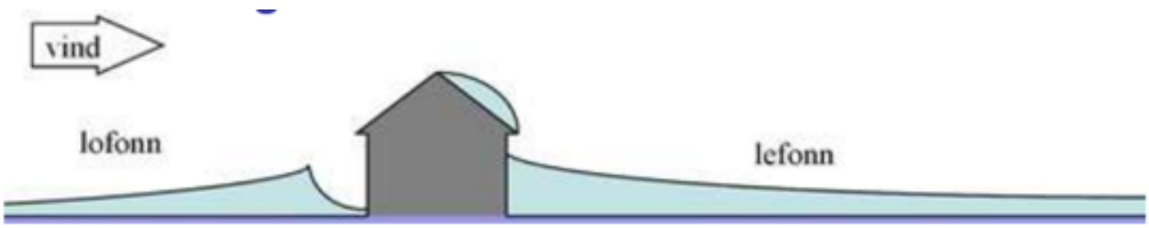



*Figure 3: Snowdrift formation (Sundsbø, referred in Bovim, 2009)*

The wind can also drive the snow along the ground (creep), lift it a few centimeters (saltation) or several hundred meters above the ground (suspension). The last one is also known as turbulent diffusion. Figure 4 below illustrates the drift patterns for these snow drift modes. Suspension could also redistribute snow from the ground and up to rooftops, which makes this drifting pattern relevant for the design and location of the supplied airflows. These three basic snow transport phenomena are important to understand the impact of the wind on snow deposition patterns (Mellor, 1965, p. 5).

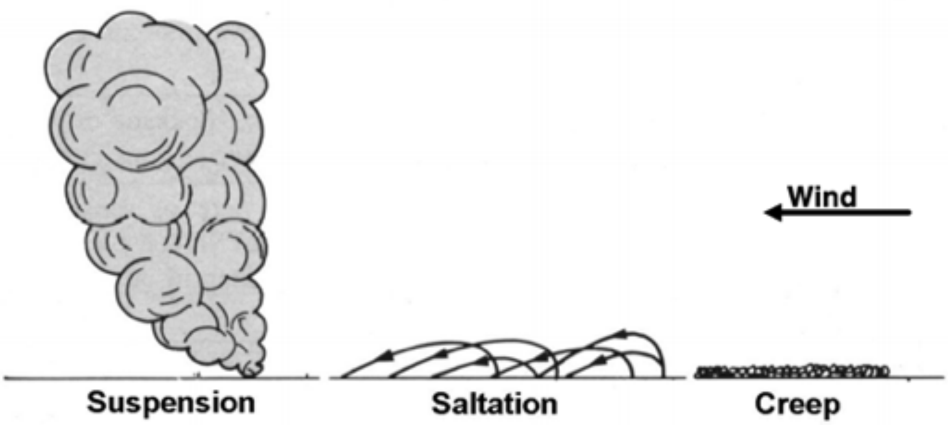



*Figure 4: Modes of snow transport by the wind (Thiis, 2005, p. 11)*

## 2.4 Fluid Dynamics

Feasibility research for applied airflows in order to prevent snow from accumulating, demands a fundamental understanding of fluid dynamics. The applied airflows have to be accelerated and transported or guided to the predefined area where the snow falls. These processes can be done in various ways, in this study, the air is accelerated by using a compressor and transported by using pneumatic hoses. The full review of the experiments is found in subchapter 3.4. Knowledge regarding the diffusion of airflows into the free air is also an essential aspect as we depend on the ability to control the air velocity and create sufficient drag forces. Furthermore, determining the range occupied by the outflowing free stream is necessary in relation to the angle and direction of the outlet.

### 2.4.1 Diffusion of airflows

We are only interested in the air velocities in the free stream flowing out of the cylindrical hoses, this flow can be explained using the schematic view in Figure 5. The schematic view illustrates the outflow of air from the turbulent free stream of a circular jet (Zawadzki, Cichoń, Jarzebowski & Kapusta, 2010, p. 39). The area occupied by the airflow increases proportionally to the distance from the outlet and the maximum air velocity, in the assumed cross-section of the flow, is inversely proportional to the distance from the outlet. The characteristic cone starts at point O (pole), which is located at a theoretical distance $l_0$ from the outlet. The mean velocity flowing out from the hose outlet is $V_0$. At the centerline of the airflow the velocity is constant and equal to the initial velocity $V_0$ at the interval $l_1$ and at distances greater than this interval the velocity decreases. The air at the boundary of the air stream (mixing zone) is theoretically stationary, though micro whirls will occur at the boarder due to the turbulent flow. Hence, the theoretically axial velocity at boarder of non-stationary and stationary flow $V_x$ is zero.

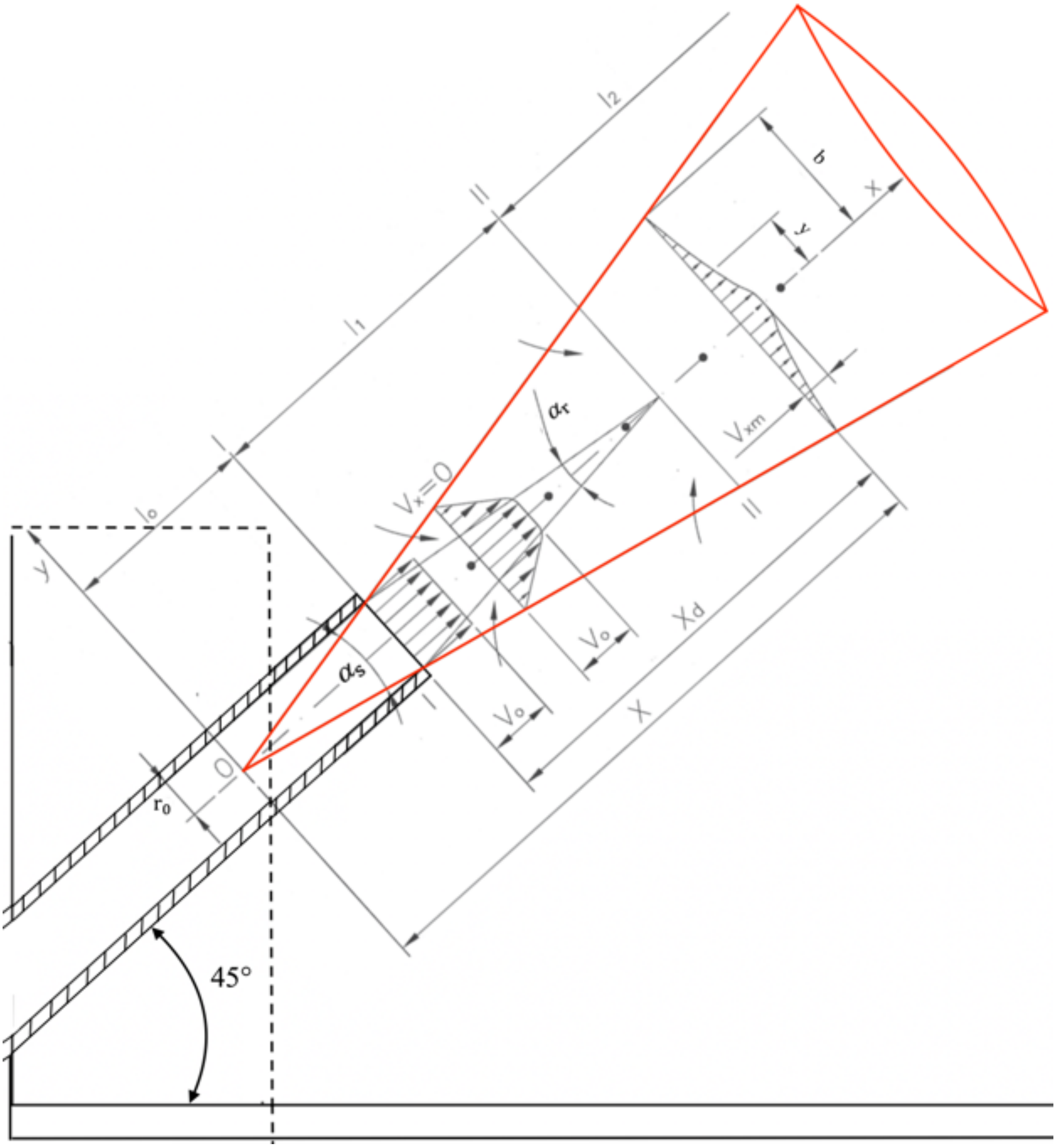



*Figure 5: Illustration of Zawadzki et al. (2010, p. 39) schematic view of turbulent free airflow from a circular cross-section.*

Further the maximum velocity along the centerline at the interval of $l_2$ is $V_{xm}$. The top angle of the cone is denoted as $\alpha_s$ and is dependent of the inner radius $r_o$ of the hose and the length $l_0$. The angle of the stream core at constant velocity $\alpha_r$ is derived from the relation between $r_0$ and $l_1$. The radius of the stream at any cross-section is b and $X_d$ is the distance of the control plane from the outlet. The distance from the centerline y is used to calculate the velocity distribution at that particular point and X is the distance of the control plane from the pole.

The cross-sections I-I and II-II marks the border between the characteristic intervals, for any other cross-sections, we can use a set of equations from Zawadzki et al. (2010, p. 40) to determine the velocity distribution at any point:

*Equation 1: The pole distance*

$$l_0 = \frac{0.29\, r_0}{a} \tag{1}$$

Where $a$ = [0.066, 0.076]

The experimental coefficient $a$ is for jets of a circular cross-section, for higher initial turbulence it is suggested to use a = 0.089. According to Zawadzki et al. (2010, p. 40) one should determine this value experimentally. The subject for Zawadzki and his colleagues' paper is to experimentally determine this value and they concludes with, among other things, using $a$ = 0.08 for a turbulent flow with Reynold's number equal to about $125 \times 10^3$. Since the Reynold's number of the air flowing out from the hose outlets in this study varies from about $25 \times 10^3$ to $51 \times 10^3$, which is significantly lower than $125 \times 10^3$, the value for $a$ is chosen to be 0.068.

*Equation 2: Initial interval*

$$l_1 = \frac{0.29\, r_0}{a} \tag{2}$$

*Equation 3: Cone angle*

$$\alpha_s = \frac{\arctan r_0}{l_0} = 2 \cdot \frac{\arctan a}{0.29} \tag{3}$$

*Equation 4: Core angle*

$$\alpha_r = \frac{\arctan r_0}{l_1} = 2 \cdot \frac{\arctan a}{0.29} \tag{4}$$

*Equation 5: Distance of the control plane from the end of the outlet*

$$X_d = \frac{b}{3.4\, a} - \frac{0.29\, r_0}{a} \tag{5}$$

*Equation 6: Velocity along the centerline of the air stream*

$$V_{xm} = \frac{const}{x} \tag{6}$$

Where x = $X_d + l_0$ for distances greater than $l_0 + l_1$ and

*Equation 7: Constant contributing to determine $V_{xm}$*

$$const = 0.96\, V_0 \frac{r_0}{a} \tag{7}$$

$V_0$ has to be calculated as well in this case, this is conducted by rearranging the volumetric flow rate equation:

*Equation 8: Volumetric flow rate*

$$V = \pi {r_0}^2 V_0 \tag{8}$$

$V_{xm}$ is also used in calculation of the velocity distribution $V_x$ at any other point along cross-section.

*Equation 9: The velocity distribution at any point of the control cross-section*

$$V_x = V_{xm} \left[1 - \left(\frac{y}{b}\right)^{3/2}\right]^2 \tag{9}$$

### 2.4.2 Computational fluid dynamics (CFD)

Computational fluid dynamics (CFD) as a research and design tool goes back to the 1960s and 1970s, driven by the aerospace community (Anderson, 1995, p. 13). CFD has been frequently used by prominent snow engineers like Thomas Thiis and Michael O'Rourke in later years. Mostly to simulate the drifting patterns of snow particles. Further, CFD is a third approach in fluid dynamics, a third dimension, contributing to understand and solve problems involving fluid flows with use of numerical analysis. It also enhances the basis for interpretation of results achieved when going from theory to experiment, and vice versa. The results from this approach of fluid dynamics is directly analogous with the ones obtained in e.g. wind tunnel experiments, the difference is that it is carried out in a computer program. The fact that it is not a physical simulation of fluid flows give rise to endless opportunities, beyond limitations that may occur in a wind tunnel experiment. Numerical experiments can sometimes help to interpret or even ascertain basic phenomenological aspects not achievable in an experiment, when carried out in parallel (Anderson, 1995, p. 6-8). Figure 6 illustrates the relationship between theory, experiment and CFD.

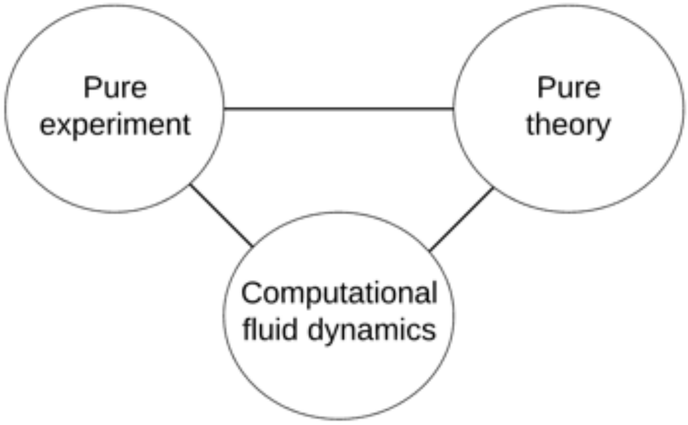



*Figure 6: Illustration of "The 'Three dimensions' of fluid dynamics" (Anderson, 1995, p. 6)*

The CFD is based on conservation of mass, momentum and energy, which is three different basic physical principles. To solve a fluid dynamic problem using this simulation method, a number of non-linear partial differential equations are solved in the background of the simulation. CFD problems needs to be discretized in space dimensions in order to be solved, this is done by dividing the model into elements and nodes (Figure 7). Here the nodes represent where e.g. pressure and velocities are being calculated in the space domain. The elements represent the underlying equations related to the different parameters, i.e. Navier-Stokes, continuity equation or energy equation (Khawaja, 2018, p. 313).

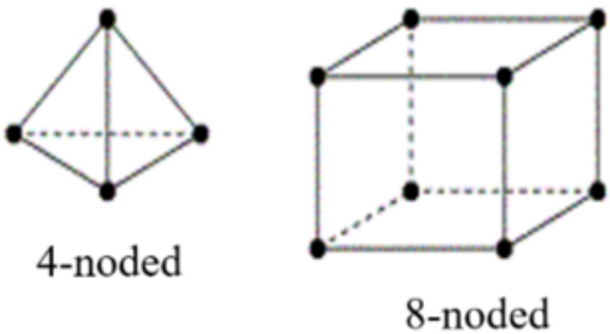



*Figure 7: Four and eight noded 3D elements (Khawaja, 2018, p. 315)*

### 2.4.3 Head loss

"Head loss accounts for the irreversible conversion of mechanical energy into internal energy due to friction" (Moran, Shapiro, Munson & DeWitt, 2003, p. 283). One reason to consider head loss is because it can be used to analyze and solve pipe flow problems. Head loss is divided into major losses and minor losses. The annotations do not necessary mean that the largest losses are found in major loss, as it is very dependent on the pipe system. Major loss is associated with viscous effects (friction) of fluid flowing through straight pipes and is dependent on the Reynold's number. Minor loss is fairly independent of the Reynold's number and is related to components in the pipe system. Losses regarding components like elbows, tees, entrances, exits etc. are dependent on the angle of the elbow for instance and whether pipe joints are flanged or threaded (Moran et al., 2003, chapter 14). The following equations from Moran et al. (2003, chapter 14) is applied to determine the head loss.

*Equation 10: Total head loss*

$$h_L = h_{L,major} + h_{L,minor} \ [Pa/m] \tag{10}$$

*Equation 11: Darcy-Weisbach*

$$h_{L,major} = f \frac{\ell}{D} \frac{V^2}{2g} \tag{11}$$

$\ell$ - pipe length

$D$ – inner diameter of pipe

$\frac{V^2}{2g}$ – velocity head (g is gravity force)

Where the friction factor (f) is determined by,

*Equation 12: Blasius formula*

$$f = 0.316/Re^{1/4} \tag{12}$$

and Re is the Reynold's number determined by,

*Equation 13: Reynold's number*

$$Re = \frac{\rho V D}{\mu} \tag{13}$$

$\rho$ – density of fluid

$V$ – average velocity

$D$ – inner diameter of pipe

$\mu$ – viscosity

*Equation 14: Minor head loss*

$$h_{L,minor} = K_L \frac{V^2}{2g} \tag{14}$$

Where the fraction is the velocity head in this equation as well and $K_L$ is the loss coefficient for pipe components.

The friction factor from the head loss equation is dependent on relative roughness ($\varepsilon/D$) in additional to the Reynold's number. Where the $\varepsilon$ is the equivalent roughness. Since the pneumatic hoses from Festo can be considered as hydraulically smooth ($\varepsilon = 0$), we use the Blasius formula to calculate the friction factor. From Figure 8 below we see an illustration of the turbulent flow - which is the case in this study – and how hydraulically smooth regime differ from the other regimes.

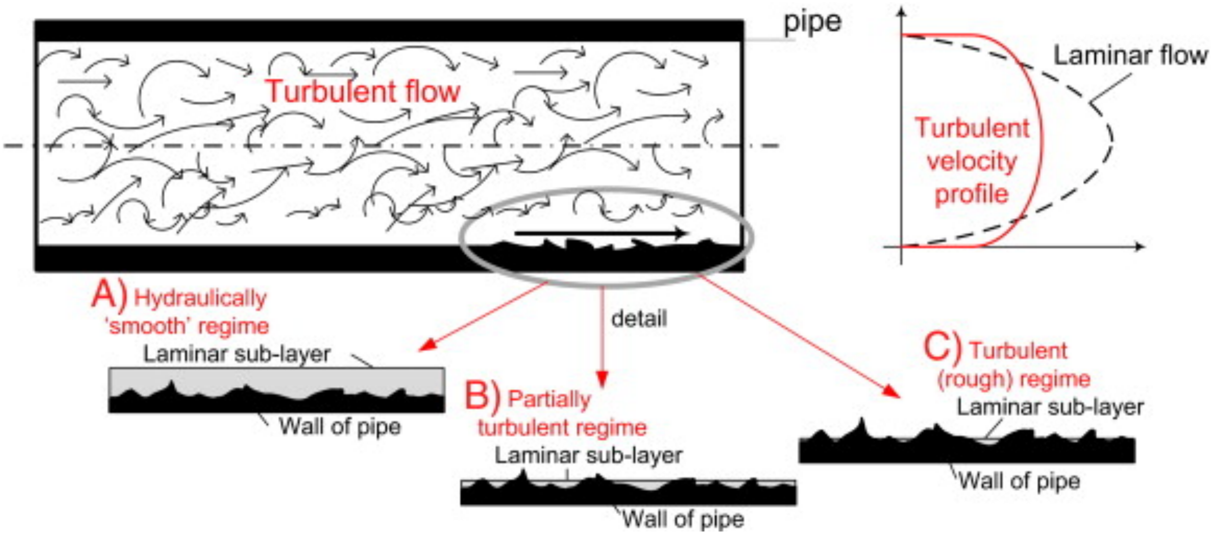



*Figure 8: Illustration of hydraulic regime (Brkić, 2011, p. 35)*

## 2.5 Roof Designed for Snow Conditions

"The design of building in regions of cold and snow is a complex subject because freezing conditions and buildup of snow is an ever-changing phenomenon hard to simplify." (Hjorth-Hansen, Holand, Løset & Norem, 2000, p. 213). Snow and ice can change characteristics in a very short period of time and falling snow can rapidly change from large dry snowflakes into ice bullets or small crystals. Climate changes influences the design of structures and the EU's strategies are adapting to withstand it and to be ready for its impacts, especially for vulnerable key sectors like buildings, characterized by a long-life cycle and high costs (European Commission, referred in Delpech & Thiis, 2016, p. 74).

The different geometry of roofs we find on buildings today are countless, however, they often originate from a handful characteristic roofs. Among the most common roof design is gabled, arched, shed and flat roofs, which all have different properties in presence of snow and cold conditions (Figure 9). The predicted pattern of snow accumulation and critical snow loads are given in standards such as International Standardization Organization (ISO) and European Organization for Standardization (CEN). The standards have an informative approach to snow loads on roofs, but also uncertainty due to snow sliding off the roof. For instance, in Eurocode 1 (NS-EN 1991-1-3:2003) it is assumed that snow cannot accumulate at roofs with 60° inclination. Further it appears from Mackinlay et al. (referred in Hjorth-Hansen et al., 2000, p. 213) that some building codes will permit snow loads to be reduced as the inclination of the roof increases, which is not a reliable approach. The figure next page illustrates general snow load cases on four characteristic roofs. The upper load case at each roof (1) is without influence of wind (snow drifts) and for gabled roof and arched roof the following load cases (2 and 3) is due to snow drifts.

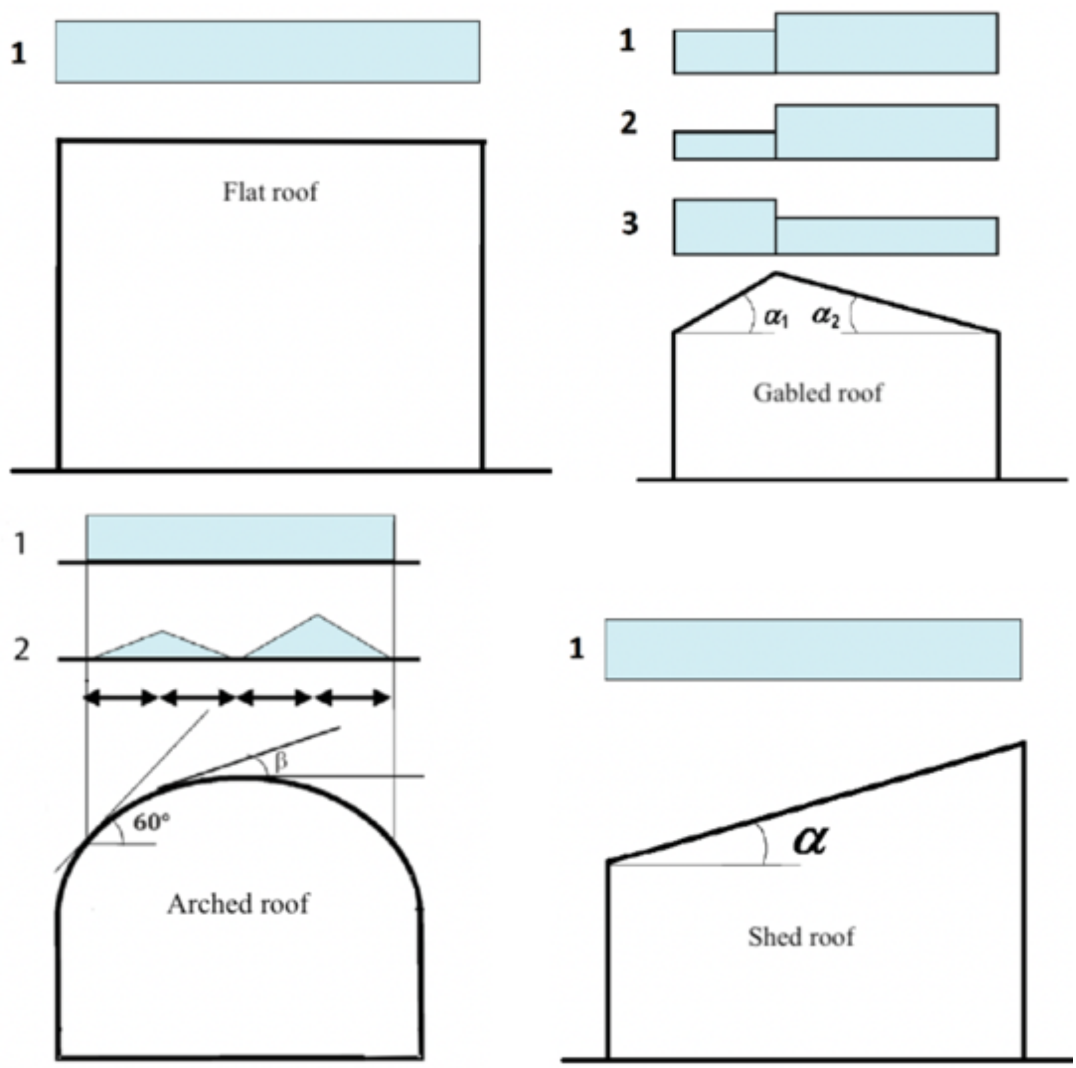



*Figure 9: Snow load cases on characteristic roofs (Standard Norge, 2003, p. 14-17)*

### 2.5.1 Sloped roofs

Even slippery sloped roofs should not be relied on to slide the snow away from the roof. This assumption could be dangerous since snow can be held on the roof by objectives like pipes, vents or even standing metal ribs (the roofing itself) (Hjorth-Hansen et al., 2000, p. 215). A recent incident concerning slippery sloped roof collapsing due to excessively snowfall occurred in Karasjok municipality, located at the inland of northern Norway. The building that collapsed was a barn with inclined tin roof (Figure 10). The owner of the building stated in the newspaper that they have never had any problems with the snow on top of their roof before. Further she also said that the snow normally just slides off the roof, but this winter, for some reason, it did not happen (Svala, 2020).

*Figure 10: Collapsed barn in Karasjok, northern Norway (Svala, 2020)*

Considering the heavy snowfall this winter, it could be an example of roof objects holding back the snow that usually slides off. The snow cover at the roof can be held on the roof as a result of frequent thaw and refreezing cycles. Figure 11 next page, is from the same evening that the barn collapsed. From the graph it seems likely that the density of the snow increased enough to break the roof when the temperature peaked at the evening when it collapsed. The sudden rise in snow load is considered to be the triggering event in this particular case, which can be a more frequent sight in the future years. As it appears from Strasser (2008, p. 1), an increased winter precipitation in areas where temperatures still remain below zero, will experience heavier snowfall with increased variability. If the temperature oscillates around zero – combined with heavier snowfalls – the rainfall may be stored in the snow cover, causing even greater snow loads.

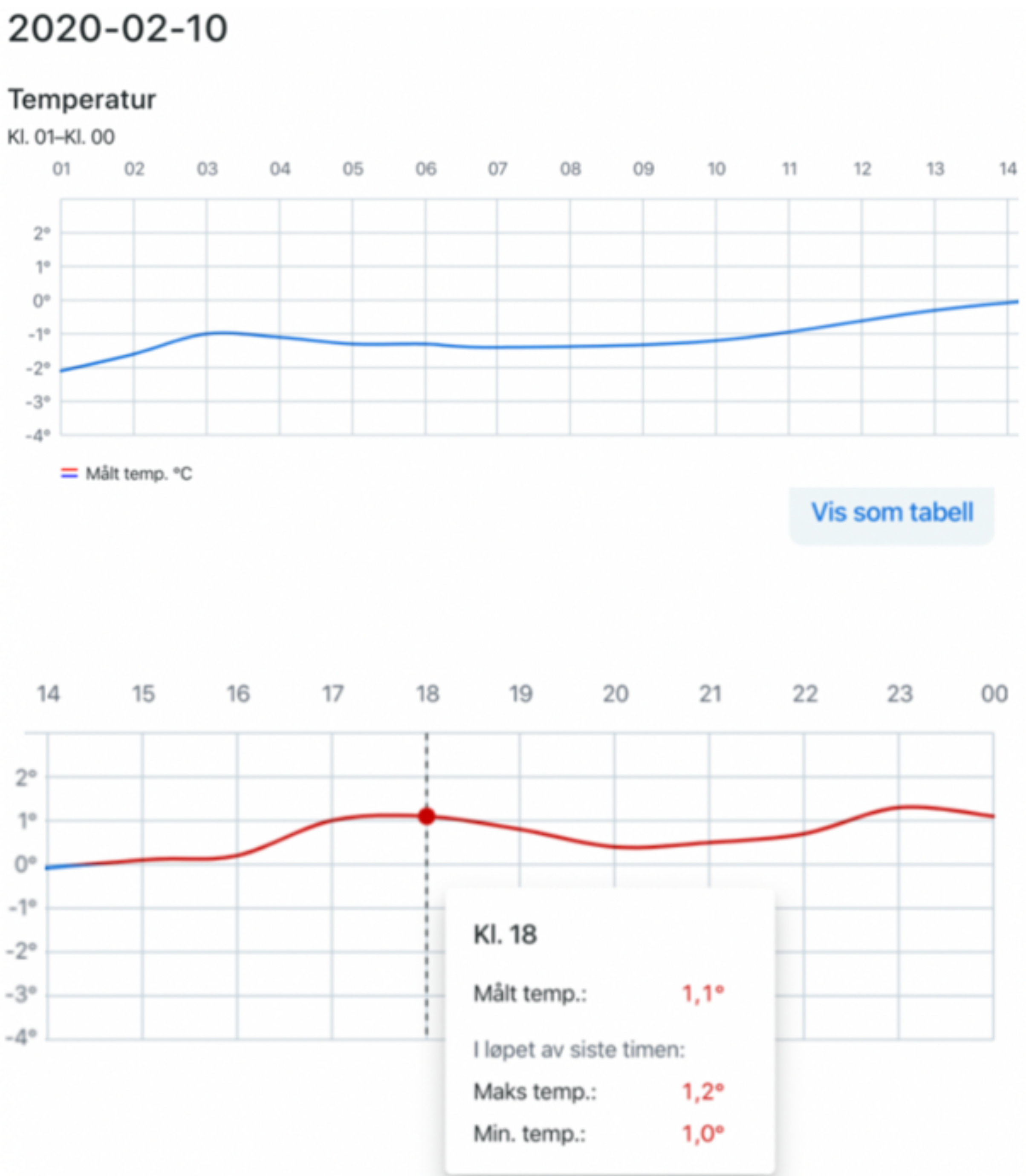



*Figure 11: Weather report at the incident day in Karasjok (yr.no)*

Another possible explanation is refreezing meltwater. Building heat or solar radiations can cause the snow to melt. When the melt water drains through the snow and runs down the roof, it can refreeze behind projections or at the edges of the roof when it meets the cold air again. The refreezed water underneath the snow can held it from sliding off, but it can also greatly increase the load on the roof or result in serious leakages. Another example of slippery sloped roofs where snow - against presumptions - have accumulated, is from Mackinlay et al. paper at the 4th International Conference of Snow Engineering (Figure 12) (Hjorth-Hansen et al., 2000, p. 214-215).

*Figure 12: Slippery sloped roof failing to slide off snow (Hjorth-Hansen et al., 2000, p. 214)*

Complex roof geometry and valleys greatly increases the damaging consequences of snow on roof. Slippery sloped roofs above lower level roofs could also be destructive, if large amount of snow accumulate before sliding off. The site orientation of the roof is imperative with respect to dominant wind direction and sunlight. As seen in subchapter 2.3, snow deposition is strongly dependent on the wind direction relative to the roof and for buildings in the high north this have to be given particularly attention, as the sun melting is absent for months (Hjorth-Hansen et al., 2000, p. 215).

### 2.5.2 Flat roofs (low sloped)

As with sloped roofs, flat roofs (low sloped) have their unique design parameters. Flat roofs are generally considered to have about 70% of the reference ground snow load in its area, this is because it relies on the wind to blow away some of the snow. This is a fair assumption in most cases, but for sheltered roofs, the amount of snow could be equal or even greater than the ground snow load. In this case, sheltered means either by terrain or taller buildings nearby. With flat roofs, problems related to snow sliding off the roofs is not of any concern. However, in the occurrence of wind, snow cornices are a very common sight at flat roofs. Even though such cornices are relatively easy to remove - if they are reachable - they can cause material damage or serious injury to people or livestock. The figure below shows massive snow cornices from a town in northern Japan in 2012.

*Figure 13: Massive snow cornices at buildings in northern Japan (360niseko.com, 2012)*

## 2.6 Reliability in Cold Climate

The main purpose of reliability engineering is identifying potential failures and preventing them from occurring. With a supposedly ever-increasing growth of mechanization and automation, reliability and availability has gradually also become important key factors in a large number of sectors, including building management (Moubray, 1997, p. 3). Rausand & Høyland (2004, p. 73) denotes subsystems and components of a functional system as functional blocks. Further they use the following definition of a functional block failure: "The termination of its ability to perform a required function" (Rausand & Høyland, 2004, p. 73). Markeset & Kumar (2001, p. 3) defines reliability in a product design context as "[…] the probability that the equipment can perform continuously, without failure for a specific period when operating under stated conditions". The reliability is a function of design; Once the system or parts are designed and sent to manufacturing, the achieved reliability is already determined and cannot be adjusted without redesign (Niebel, 1994, p. 230).

With the definitions in mind, it is important to identify the relevant functions of a system or a product and the performance criteria for each of these functions. In cold climate conditions, examples of such performance criteria - for an outdoor technical system - are; operating temperature, wind conditions, MDSD, snow load, ice accretions, snow characteristics, etc. For system reliability analysis, there are several different methods which can be used, e.g. FMEA/FMECA, cause and effect diagrams, event tree analysis, fault tree analysis, reliability block diagram etc. As the main purpose of this thesis is to study the feasibilities of airflows to prevent snow accumulations, a thorough analysis regarding system reliability will not be conducted. Nevertheless, a simplified analysis is conducted in order to highlight the importance of reliability engineering in a system operating in cold climate conditions.

### 2.6.1 Reliability and maintainability (R&M)

Maintainability characteristics are greatly influenced by reliability and availability of a system. It is important to differ between maintenance and maintainability, where "maintenance is the act of repairing or servicing equipment, while maintainability is a design parameter intended to minimize repair time" (Markeset & Kumar, 2001, p. 3-4). In other words, maintainability refers to measures taken in order to reduce maintenance as well as the time, tools, skill level, facilities required when maintenance is to be conducted. Life cycle costs (LCC) of systems and products are greatly influenced by maintenance costs, hence, both R&M parameters.

According to Markeset & Kumar (2001, p. 1) while designing a product, one has to decide either to *design out maintenance* or *design for maintenance*. As perhaps implicitly stated, "design out maintenance" will require very high reliability, which in most cases are either related to high costs or impossible due to technological limitations. Hence, most systems and products are designed for maintenance. The *design for maintenance* concept is illustrated in Figure 14. An important relationship in this figure is reliability and maintainability; if the reliability is too low, the maintainability parameters needs to be improved, and vice versa. There will always be a trade-off between R&M.

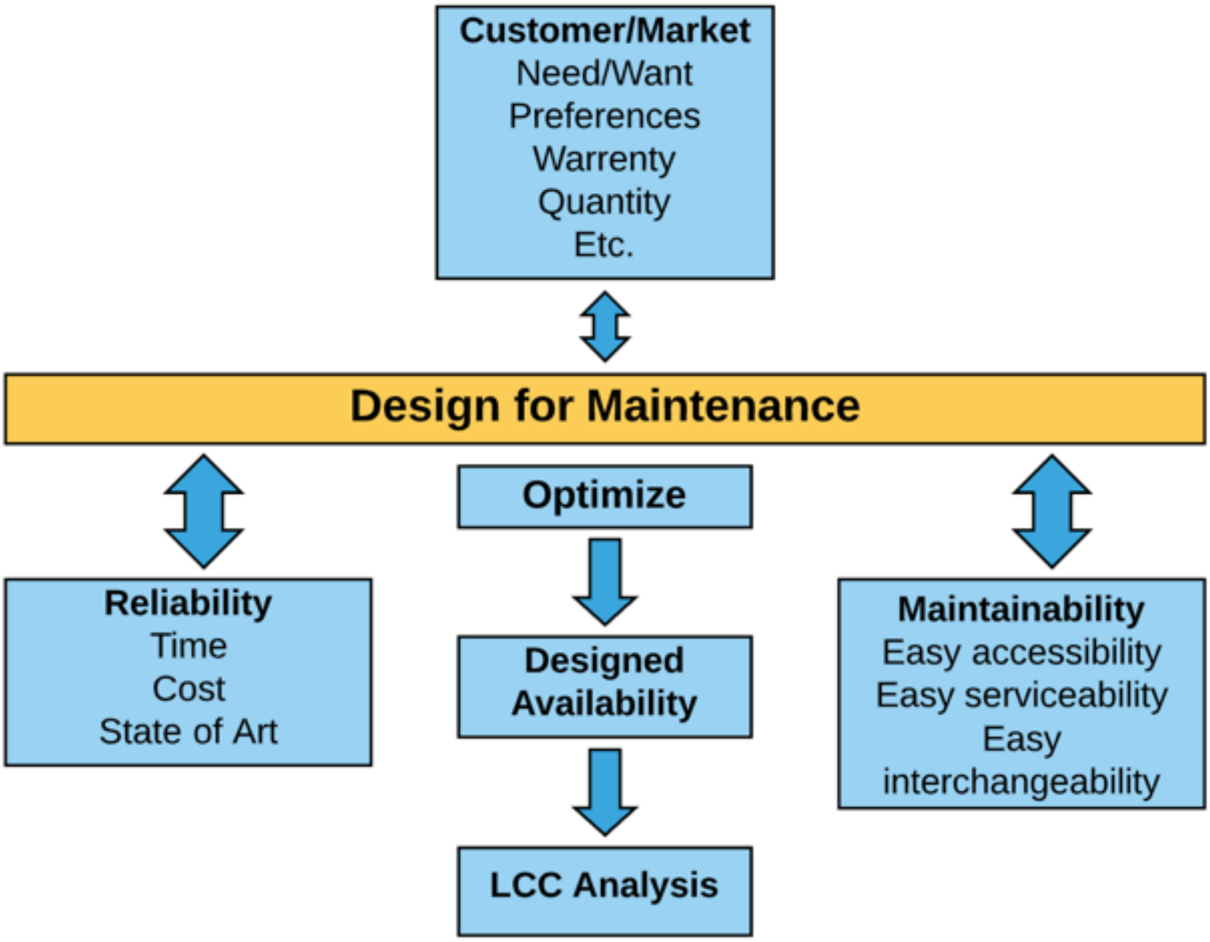



*Figure 14: Illustration of "design for maintenance" by Markeset & Kumar (2001, p. 4)*

## 2.7 Risk Management

The concept of risk has no unambiguous definition. Risk assessments and management began in the 1960s, in the aerospace and nuclear industry, and have since then become a key factor for success in many disciplines and industries (e.g. Engineering, oil and gas, finance, medicine, biology etc.) (Calixto, 2016, p. 554). In the risk literature, there are several different ways to relate and apply the concept of risk, in this thesis, Aven and Renn's (2010, p. 8) proposed new risk definition is preferred: "Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value". In this context severity refers to different measures of magnitude (intensity, size, extension, scope, etc.), with respect to something of humans value (e.g. lives, environment, economic aspect etc.).

Everyone is affected by the concept of risk and some more than others. By walking to the grocery store in Tromsø city at wintertime, is a suitable example relevant to this study. Usually there are huge amount of snow in Tromsø in the winter and commonly a lot of the snow is accumulated on roofs, often causing snow cornices and icicles. By walking underneath these roofs, you are affected by the concept of risk. There is a certain probability that the cornices or ice will break off or slide down at the exact time when you are walking past it. We know with certainty that the consequences could be severe if one is struck by the falling ice or snow, however, it is uncertainty related to the probability that it actually will occur. The combination of uncertainty, probability and consequence gives us an estimate of the experienced risk level.

Risk management is all about prevention or reduction of the risk. The risk management process starts with reviewing all relevant information, followed by categorization and evaluation, which forms the basis for risk management options selected. From this initial phase, three potential outcomes (acceptance criteria) are presented (Aven & Renn, 2010, p. 121):

- Intolerable situation: risk source is not acceptable and needs to be replaced or - if not possible - reduce vulnerabilities and restrict exposure.
- Tolerable situation: the risk is not critical but have to be reduced or handled within limits of reasonable resources. The risk has to be reduced to a level which is as low as reasonably practicable (ALARP).
- Acceptable situation: the risk is insignificant, sometimes negligible, because of extremely low probability or consequence or a combination of the latter. Risk reduction

is not necessary in this case. However, on a voluntary basis, pursuing further risk reduction is not wasted time.

### 2.7.1 Risk assessment

Risk assessment is often referred to as "risk analysis", both terms are used to describe the same process. In this thesis, risk assessment is the preferred thermology, as "risk analysis" has a vast number of different interpretations. Risk assessment is always a proactive approach since it exclusively concerns potential hazardous events. This is opposed to accident investigation as it seeks to identify causes and circumstances of unwanted events that have already occurred (Rausand, 2011, p. 7). Risk assessment consists of three main steps, often including answering related questions (Markeset & Kumar, 2001, p. 3; Aven & Renn, 2010, p. 75):

- Identification of threats, hazards, opportunities or unwanted events: what can go wrong, which could lead to system failure?
- Cause and consequence analysis: how likely is it to occur? And if it occurs, what are the consequences?
- Risk description to produce a risk picture: what is at stake? And how is the relation between probabilities and uncertainties for (un)wanted consequences?

To summarize the risk management process, Figure 15 illustrates the main steps.

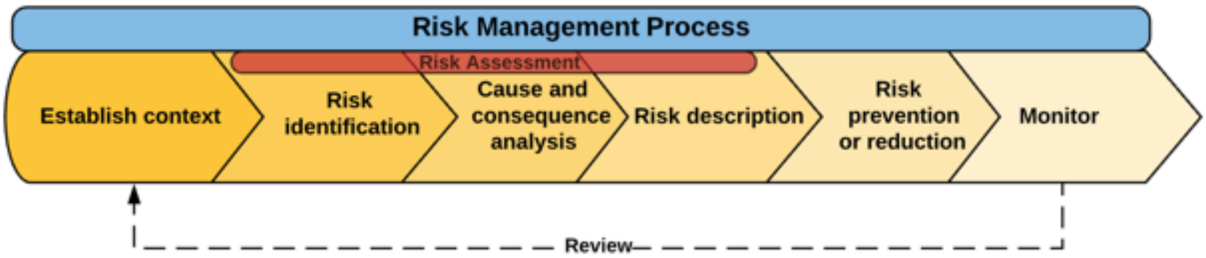



*Figure 15: Risk management process (general overview)*

To make the risk picture clearer, a risk matrix is often applied to show the correlation between likelihood (probability or frequency) and severity (consequence or costs). Risk matrix is a simple tool to increase the visibility of risks and helpful during identification, prioritizing and managing the risk level for a given system or project (Basu, 2017). At the next page we see an example of a risk matrix; the colors refer to the level of actions required, or acceptance criteria as explained at page 41.

- Red = unacceptable risk (intolerable situation) - requires risk reduction
- Yellow = ALARP (tolerable situation) - risk reduction should be done
- Green = acceptable risk (acceptable situation) - risk reduction is not required

*Table 1: 5x5 risk matrix*

| Risk Matrix | | | Consequence | | | | |
|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | E |
| | | | Negligible | Minor | Moderate | Major | Catastrophic |
| Probability | 5 | Frequent | | | | | |
| | 4 | Probable | | | | | |
| | 3 | Occasional | | | | | |
| | 2 | Unlikely | | | | | |
| | 1 | Very unlikely | | | | | |

All the probability and consequence categories have to be defined relative to the state of art. This means that e.g. consequence category E could refer to a huge natural catastrophic incident in one analysis, and in another analysis, it could refer to an explosion in a gas tank. The highest level in the consequence ranking is often adopted as; "Any failure that could result in deaths or injuries or prevent performance of the intended mission" (Rausand & Høyland, 2004, p. 94). The lowest level of consequences is often referred to as a failure that does not degrade the system or affect the overall performance. Although it is relative to the particular case or system, one has to identify the consequences first and then determine the probabilities of their occurrence. Further, the acceptance criteria or risk tolerability has to be defined at an initial phase. As Henry Ozog (2009, p. 1) stated; "Without adequate consideration of risk tolerability, a risk matrix can be developed that implies a level of risk tolerability much higher than the organization actually desires".

### 2.7.2 Bow-tie diagram

The bow-tie analysis method is beneficial to illustrate both conception and assessment of risks (Rausand, 2011, p. 6). In more detail, it shows the relationship between an identified hazard, its causes (triggers), consequences and barriers (Figure 16). The barriers can be divided further into proactive, reactive, active and passive barriers (see definitions page 5). The barriers either reduce probability of the hazard or mitigate its consequences. The method has been frequently used and also enhanced by the oil company Shell in the early 1990s. The appearance of the diagram looks like a bow tie and thereby it has its name (Rausand, 2011, p. 119).

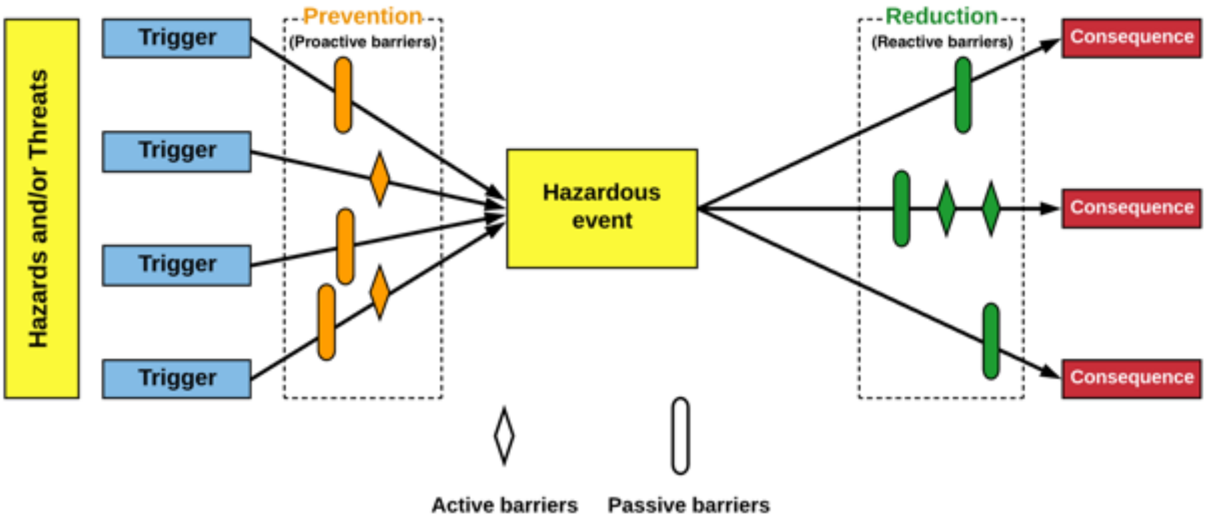



*Figure 16: Bow-tie diagram*

From the bow-tie diagram we see a hazardous event in the center, this is often referred to as the top event. For the top event to occur, there has to be one or several initial events, denoted as "hazards and/or threats". The initial events are often dependent on other events or conditions (triggering events) in order to induce the top event. In other words, the diagram illustrates potential "paths" from identified threats to consequences through series of events. The diagram has only one top event in focus at the time, which means that a separate diagram has to be established for each hazardous event (Rausand, 2011, p. 119). The bow-tie diagram is not designed to identify hazards or threats, which is why it is combined with preliminary hazard analysis (PHA) in this study.

The diagram gives particular attention to barriers, where barriers are either full or partial barriers – in addition to the mentioned types. A full barrier prevents threats from developing into consequences, when functioning perfectly. This is however limited by the reliability of the barrier. Separated driving files by fences are examples of full barriers in the traffic. Partial barriers on the other hand cannot fully prevent consequences from a threat, even when working perfectly. A fire alarm is an example of such barrier (Rausand, 2011, p. 369).

### 2.7.3 Preliminary hazard analysis (PHA)

This analysis method is used to identify potential hazards, threats, and hazardous events at an early project or design phase. The method is basically a review of where hazardous material or energy can be released uncontrollably. It is called preliminary because it usually is combined with other risk analysis methods. The requirements for conducting this analysis method is convenient for this study as it demands understanding and experience of the system in question.

It is also beneficial since the analysis can be carried out by one engineer, preferably with background as safety engineer (Rausand, 2011, p. 231). Table 2 below is an example of a PHA worksheet with explanations.

*Table 2: Preliminary hazard analysis*

| **Hazard/ Threat** | **Triggering event(s) (Cause)** | **Nr** | **Hazardous event (top event)** | **Potential Consequence(s)** | **Risk** | | | | **Existing barriers** | **Risk updated** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **F** | **Cate-gory** | **S** | **RPN** | | **F** | **Cate-gory** | **S** | **RPN** |
| | | | | | 4 | Human | **E** | **9** | | 1 | Human | **D** | **5** |
| | | | | | | Assets | **B** | **6** | | | Assets | **B** | **3** |

| | |
|---|---|
| Hazard/threat | Identifying hazardous events and threats which are given a number to make it easier for risk matrix analysis. Numbering the hazards are also helpful in order to separate them and practical for further analysis. |
| Triggering event (Cause) | Determining the main causes or triggering events for the identified hazards. |
| Nr | Hazard/threat are divided into hazardous events (unwanted events), which are given a number, mainly to make the risk assessment more effective and systematic. |
| Hazardous event | The hazardous events are the activities we will assess and try to reduce in terms of both probability and consequence. |
| Consequence | Determining the consequences or outcomes of the identified hazards. |
| Risk | Risk is divided into frequency (F), severity (S), category and risk priority number (RPN). RPN is also referred to as risk index (Rausand, 2011, p. 103). The purpose of this subdivision is mainly to make it more convenient to plot it in a risk matrix and to see which parameters of the RPN that is reduced after mitigations. The risk and severity are also divided into human and assets, because the consequences can be vastly different in a human or asset aspect. The frequency is not divided in categories, because this is related to the occurrence of the hazardous event, which is the same regardless of human or asset aspects. |
| Assets | Asset in this case concerns equipment and devices damaged (e.g. gutters or an outdoor light). It also concerns assets in a bigger picture, categorized by higher costs and social value, hence, roof, building, cars etc. |
| Human | As in the risk of a hazardous event and how it constitutes to risk for humans, either arbitrary people walking underneath the roof or people climbing on roofs in attempt to do risk reducing measures. |
| Category | Different aspect affected by the hazards. These categories will also visualize the effect of any identified and proposed mitigations or safeguards. |

| | |
|---|---|
| Existing barriers | Identified barriers and mitigation measures to reduce either probability (preventive) or consequence (reductive) of the hazards. |
| Mitigations | These are the proposed prevention and reduction measures. The bow-tie diagram is used to identify these measures in this thesis. |
| Risk updated | Updated risk is simply the new risk picture after mitigations measures. |

The "existing barrier" column is usually seen in HAZOP or SWIFT analysis methods. It is included here to better illustrate the effect of proposed new barriers. HAZOP is based on similar concept as PHA, although it is a more in-depth risk analysis method. Inspired by Calixto's (2016, p. 571) HAZID analysis, severity and RPN is divided into categories. HAZID is also closely related to PHA. The categorization makes it easier to see how the barriers affects different aspects.

**Advantages** (Rausand, 2011, p. 231-232):
- It is simple to use and requires limited training;
- It is a necessary first step in many risk analyses;
- Identifies and logs hazards with their respective risks;
- Sufficient to use in an early project phase, that is when design changes are still possible.

**Limitations** (Rausand, 2011, p. 232; Calixto, 2016, p. 566):
- It could be difficult to illustrate the effect of safeguards or mitigation measures and prioritizing safeguards;
- Cannot be used to assess risks of combined hazards;
- Difficult to represent hazardous events with a myriad of potential consequences;
- If used as a qualitative analysis, it could result in underestimation of risks, leading to lack of implemented safeguards.

To compensate for the first limitation listed, the "existing barriers" column is added as mentioned. In attempt to improve weaknesses with the method, the analysis is conducted semiqualitative. This is done by including the RPN in the analysis. As Rausand (2011, p. 121) states, in relation to semiqualitative: "The objective is to produce a more detailed prioritization than may be achieved in a qualitative analysis, not to suggest any realistic values for the risk, as is attempted in a quantitative analysis".

### 2.7.4 Risk associated with snow clearing on roofs

Snow accumulations on roofs are the cause of several risk aspects, either related to structural damage or personal injuries. As we have already seen, snow loads can cause serious damages or even collapses of buildings. Moreover, severe injuries occur every year as a consequence of snow clearing activities on roofs. Most of the injuries appear during leisure time at residential homes. According to Bylund et al. (2016, p. 105) these injuries are strongly related to snow depth. The study by Bylund and his colleagues was conducted over four winter seasons in Sweden, from 2007 to 2011, where in total 95 people was injured. All 95 cases of injuries resulted in hospital care. Nearly half (48.4%) of all injuries was categorized as fall off roof and the second most common injury mechanism was falling of ladders (35.8%).

Close to 60% of the injuries had moderate or serious injuries, where moderate was categorized as e.g. concussion with the loss of consciousness and serious injury as e.g. fracture of the femur. It appears that the risk of injuries occurrence increases as snow depth exceeds 30 cm, one can interpret that this is when people start considering removing snow from their roofs. Similar results regarding snow depth was implied in a study conducted by Pipas et al. (referred in Bylund et al., 2016, p. 108) in the U.S. Bylund et al. (2016, p. 107) concludes that "[…] injury incidences from snow-clearing activities increases when there is a heavy snow season". If these results are transferable to locations where it is predicted positive trends in snow depth, we cannot say for sure, but proactive risk mitigations should be done.

## 2.8 Existing Measures

Mitigations due to the adverse effects of falling or sliding snow are varied, ranging from melting the snow to roof clearing techniques and keeping the snow at the roof. Snow load challenges is in most cases more complex than wind load problems, which is reasoned by all the additional factors to take into consideration (Delpech & Thiis, 2016, p. 206). The snow loading problem can be viewed as a chain, as seen in Figure 17.

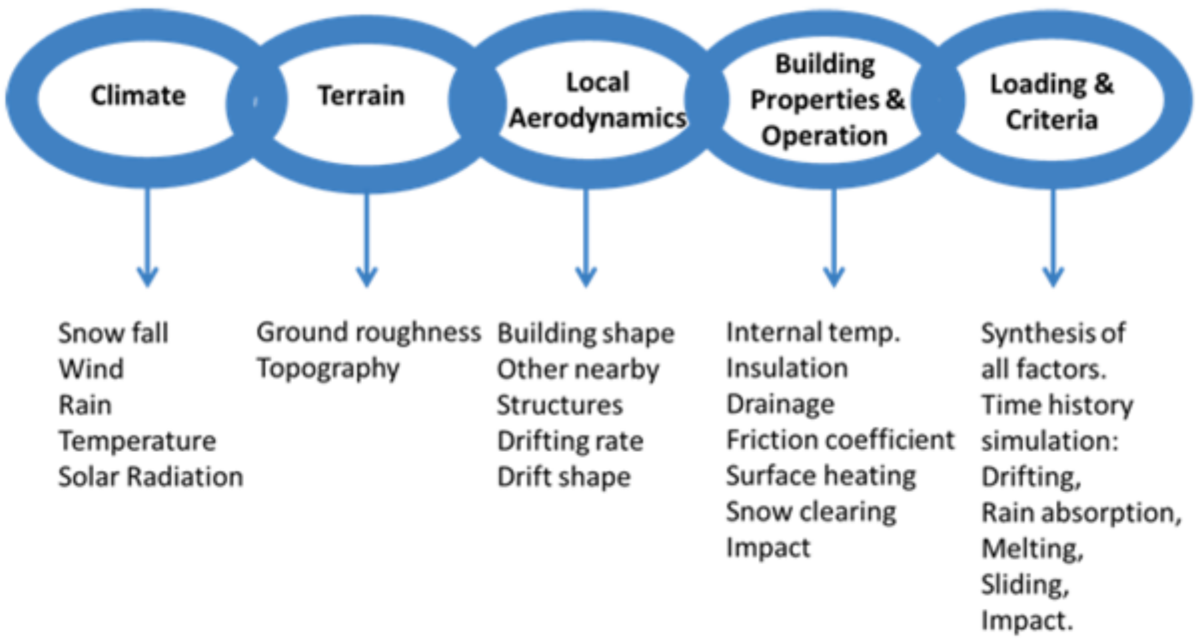



*Figure 17: Snow loading viewed as a chain (Irwin, referred in Delpech & Thiis, 2016, p. 206)*

It is not unusual to see people climbing on top of roofs with shovels or snowblowers either with or without fall protection to clean the roofs from deposited snow (Figure 18). The risk involved with climbing on snow-covered roofs with possibility of underlying ice covers, could be severe. In some cases, where no other measures are available, this is the only way to remove critical load or reduce the risk of avalanches. It is the owner of the buildings responsibility to maintain safety from avalanches from their roof, and the employer's duty to ensure safety of workers removing snow from roofs. This combination of regulations often leads into unfortunate situations. As the two first pictures at the figure next page shows, neither of the people on the roof are using any fall equipment. In a work-related context this would be a major violation on safety rules according to regulations concerning work at height § 17-25 (Regulations concerning the Performance of work, 2011; TEK17, 2017, §10-3).

The last picture in the figure below shows a creative technique to remove snow from a roof using wire. This method is also risky for both the people standing underneath and the building. One of the persons behind the video estimated the weight of one snow block to be around 15 tons, which would kill any persons unluckily standing under it. Considering the weight of one single block, the building could also be damaged due to unequal loads on the roof while removing it. Severe instabilities could occur due to unevenly removing pattern, which could damage the construction (Bjørhusdal & Lundind, 2018; Gray & Male, 1981, p. 572).


*Figure 18: Risky snow removals from roofs (Pellicer, 2010; Hagen, 2012; VGTV, 2018)*

Avalanche snow removal using a long steel rod with a plastic sheet to remove snow is another method, which is a relatively new invention. The snow slides down from the roof due to the low friction at the sheet (Figure 19). The same problem as for the previous measures could arise from this removing technique as well. Rather more inconvenient would irregular roofs, tall buildings and poor accessibility be considering the avalanche removal rod.

*Figure 19: Avalanche snow cleaner (www.Solbua.no)*

Thiis (2003, p. 23) did research towards an alternative way of sheltering areas from snow drift formations (Figure 20). In essence, different variants of "snowflushers" where tested to prevent snow accumulation on top and around buildings. These devices depend on sufficient wind blowing into it while it is snowing. It was concluded, among other things, that the snowflushers, despite removing snow, created new snow drift formations where it previously was not any snow. It is also obvious that these snowflushers take up a lot of space, characterizes the aesthetics of the buildings and are inefficient in lack of wind.

*Figure 20: Snowflushers (Thiis, 2003, p. 16)*

Thiis and Frimannslund (2019, p. 94) has also published a research article about the feasibility with a new photovoltaic system combining electrical power production with snow mitigation. The system seems however to be more sufficient to warmer climates occasionally experience heavy snowfalls, rather than colder climates with longer winters. A challenge with this method is refreezing melt water and water saturation of snow which can prevent a sufficient load reduction. Another problem using photovoltaics to melt deposited snow is the lack of sunlight during the periods with the most frequent snowfall, especially in the high north (Granås, 2019).

Figure 21*: Photovoltaic snow removal for illustration (www.gocamsolar.com)*

# 3 Methodology

To give an understandable presentation of the results and a proper discussion of these, the methodology behind the empirical method, simulation set-up and experiments are described in the following. Further, a preliminary study prior to this thesis was conducted in order to explore the impact of snow deposition on structures and the related safety challenges. The behavior of snow crystals by the influence of wind and drag force was among the phenomenon studied in this initial study. The research methodology is thoroughly explained in the first subchapter, followed by empirical method, simulation set-up, preliminary study and finally experiment set-up.

## 3.1 Research Methodology

This study contains four aspects (Figure 22) and is partly *exploratory* and *descriptive*, which is explained in the following. As stated in the title of the thesis, this study contains exploratory experiments, meaning that this part is an exploratory research study. Further, the research is based on an *experimental design*, as it constitutes that experiments are conducted in a systematic way in e.g. a natural setting (Wilson, 2014, p. 165). There is little literature published regarding applied airflows to prevent snow accumulations – at least to the extent of the authors knowledge - hence, the experiments are conducted in an exploratory way. Exploratory research study follows an inductive approach and aims to develop better insight into a particular topic (Wilson, 2014, p. 159). It is partly descriptive as well, because of the empirical method and numerical simulations conducted in this study. Descriptive research is characterized by attempting to describe existing phenomenon by using observations (Wilson, 2014, p. 160).


*Figure 22: The four fundamental aspects of this study*

Throughout this study it is used both deductive and inductive research approach, the combination is also known as *abductive approach*. Usually one chose either inductive or deductive, but with a *pragmatism research philosophy* – as is the paradigm in this study – it is common to go back and forth between the two (Wilson, 2014, p. 67).

*Deductive approach*, which in this case means that a hypothesis is stated and then the research strategy is developed in order to test the hypothesis. In a deductive approach, we go from theory to empiricism and back again. This approach is associated with quantitative research and widely used in areas with advanced knowledge (Wilson, 2014, p. 61), i.e. the field of fluid dynamics and drag force in our case. The empirical and numerical method follows a deductive approach.

*Inductive approach* is often chosen when studying areas with little or no prior knowledge, as is the case for the experimental part of this study, hence, the inductive approach is beneficial. It is also commonly used when seeking observations about your research and is associated with qualitative research strategy (Wilson, 2014, p. 61). As mentioned in the literature review subchapter 2.2.2, there are still physical mechanisms related to formation and behavior of snow crystals, that are not fully understood, even after centuries of study.

It appears from Greene (referred in, Wilson, 2014, p. 59) that a pragmatism philosophy is suitable for mixed methods (multi-strategy), which is the case in this study. Qualitative because of the experiment part and the quantitative is related to CFD and empiricism. A Pragmatism philosophy places the research questions and problem in the center of the study. In essence, this means that the most suitable way to give significant insight into the research problem is chosen (Wilson, 2014, p. 59). Further, since the data collected from the experiments is only through observations, the data analyzed is conducted by visual analysis (Wilson, 2014, p. 320). This means that the analysis of the experiments is mainly interpretations of video and images material from observed falling snow behavior by the influence of airflows. On the other hand, the data from the CFD simulation and hand calculations, are quantitatively analyzed, following a descriptive data analysis technique, as shown in the results from preliminary study (3.4) for instance. The research methodology presented in the past few paragraphs is may a bit dense and it can be complex to put it all in context, which is why the "honeycomb" is a useful tool to get an overview. Figure 23 illustrates the different segments and recognizes that it does not need to be a linear process.

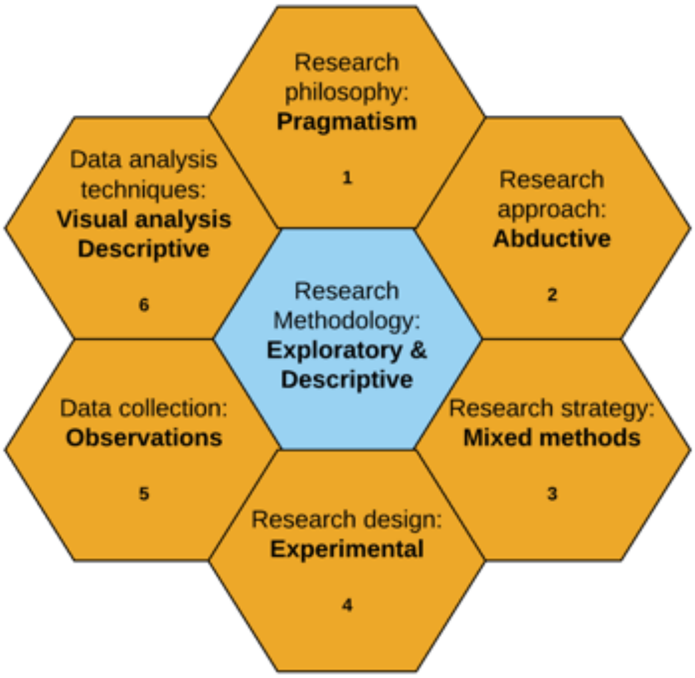



*Figure 23: "The Honeycomb of Research Methodology" adopted from Wilson (2014, p. 57)*

## 3.2 Empirical Method

Prior to both the simulations and the experiments, different initial conditions need to be calculated. One of the relevant initial condition for this study is the drag force at the different snow crystals. The purpose of this exploratory study is to avoid snow from accumulate on roofs by blowing it away before it reaches the surface. To accomplish this, the snow particles need to maintain airborne until they are out of reach from the surface of the roof, and thus $F_D$ has to exceed the gravity force from the particles ($F_D > F_G$) (Figure 24). In order to calculate the drag forces, two different equations were used, Equation 15 and Equation 16. The first equation considers the mass of the snowflake combined with various velocity parameters. The second equation consider the diameter of the snowflake instead of the mass, combined with a drag force coefficient and the air density. The remaining parameters included in the two equations are listed consecutively under each equation. The main reason for applying two equations for the calculation of the drag force is to have a more accurate estimate of the real drag force

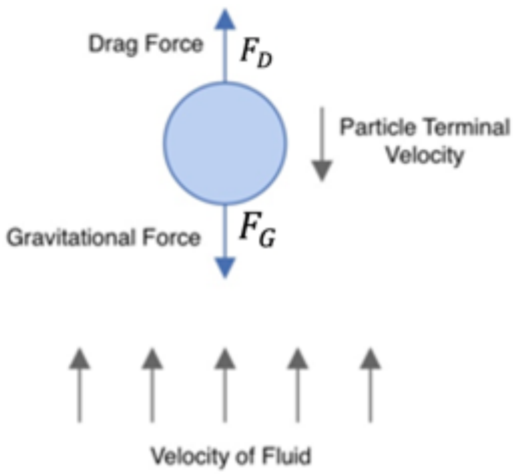



*Figure 24: Forces on a particle (Neutrium, 2013)*

experienced during the experiments. Furthermore, by considering both approaches, a stronger validation of the results could be achieved.

*Equation 15: Drag force (Moeslund, Madsen, Aagaard & Lerche, 2005, p. 4)*

$$F_D = \frac{U_{fluid}^2 \cdot m_{snow} \cdot g}{U_{max}^2} \tag{15}$$

Where $U_{fluid}^2 = (U_{wind} - U_{snowflake})^2$

$U_{fluid}$ – velocity of the air moving by the snowflake in the same direction as $F_D$
$U_{wind}$ – velocity of the wind interacting on the particle
$U_{snowflake}$ – velocity of the snowflake
$U_{max}$ – maximum vertical velocity taking wind resistance into consideration (terminal velocity)
$m_{snow}$ – mass of the snowflake
g – gravity constant

*Equation 16: Drag force (Huang, Sang & Han, 2011, p. 2)*

$$\overrightarrow{F_D} = -\frac{\pi}{8} \cdot d^2 \cdot \rho_f \cdot C_D \cdot w \cdot \vec{w} \tag{16}$$

Where $w \cdot \vec{w} = v^2$

d – particle diameter
$\rho_f$ – air density
$C_D$ – drag coefficient
$w$ – relative velocity scalar of a particle
$\vec{w}$ – relative velocity vector of particles
v – velocity

## 3.3 CFD Simulation

ANSYS® software was used to simulate the airflow profile in 3D. First the model was sketched as a flat surface with an additional plane parallel to the xy-plane. In this simplified model, the flat surface at zero offset in z-direction, corresponds to a section of the roofs surface. The inlets on the longitudinal sides are made for airflows (green holes in Figure 25). The model is shaped like a box to state the boundary conditions for the simulations of the flow field. This means that we are interested in the flow field inside the box shaped CFD model. This simulation was done with ten outlets at each side. When conducting the experiments, it turned out that ten outlets at each side was too many while using compressed air. Corrections related to the scaling of the experiments will be made clear in chapter 3.4.

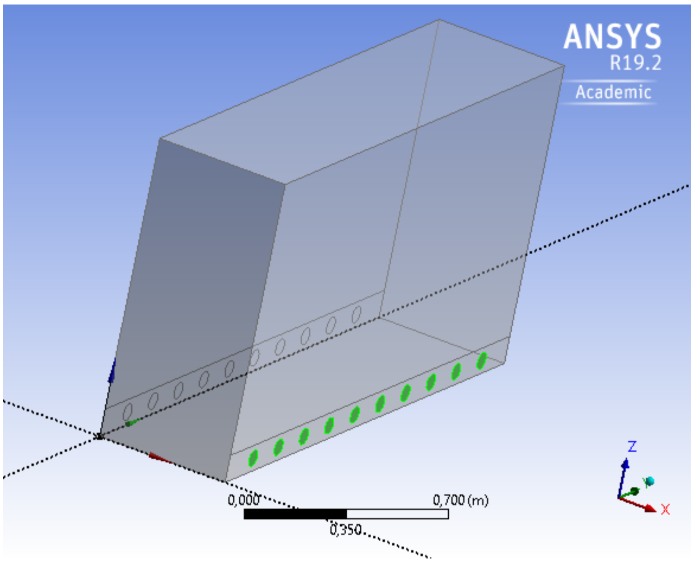


*Figure 25: Sketch of CFD model*

The mesh density was the next step in building the model. Mesh density considers both the number of elements and nodes. In order to implement a simulation which is as close to the reality as possible, one need to make some important assumptions considering mesh density. If the mesh density is too low (i.e. too few elements and nodes), the simulation would not be transferable to reality. On the other hand, if we make the mesh density too refined, the solving time is increasing rapidly.

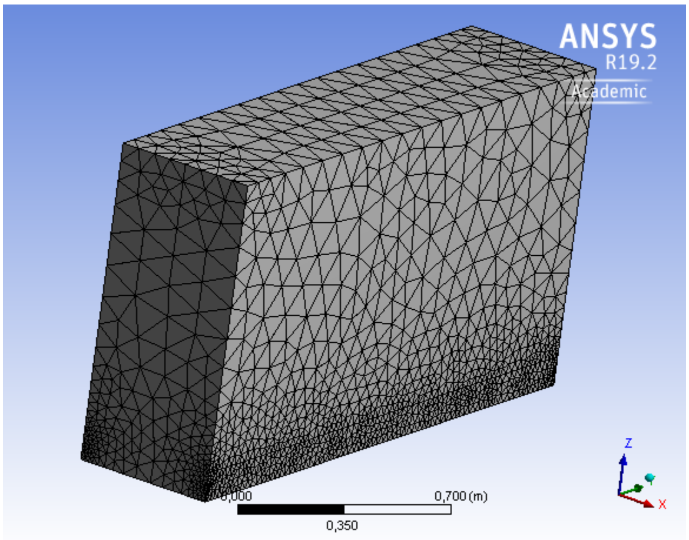


*Figure 26: Mesh density*

At this point the convergence study and engineering judgement becomes important, both to reduce solving time and to get sufficiently reliable results which can be used in an experiment. The purpose of convergence study is to find where the values (residuals) stabilizes. With too poor mesh density, the residuals will not converge and keep oscillating. If the results from a mesh refinement does not change the residuals substantially, one can assume that the result has converged. The mesh density used in the simulations where set to 8 (number of divisions). The element order is quadratic, which means that every element has an extra set of nodes compared to linear element order (Figure 26). In this case the residuals did not converge entirely, however, the errors were quite low and considered acceptable in the final simulations (Figure 27).

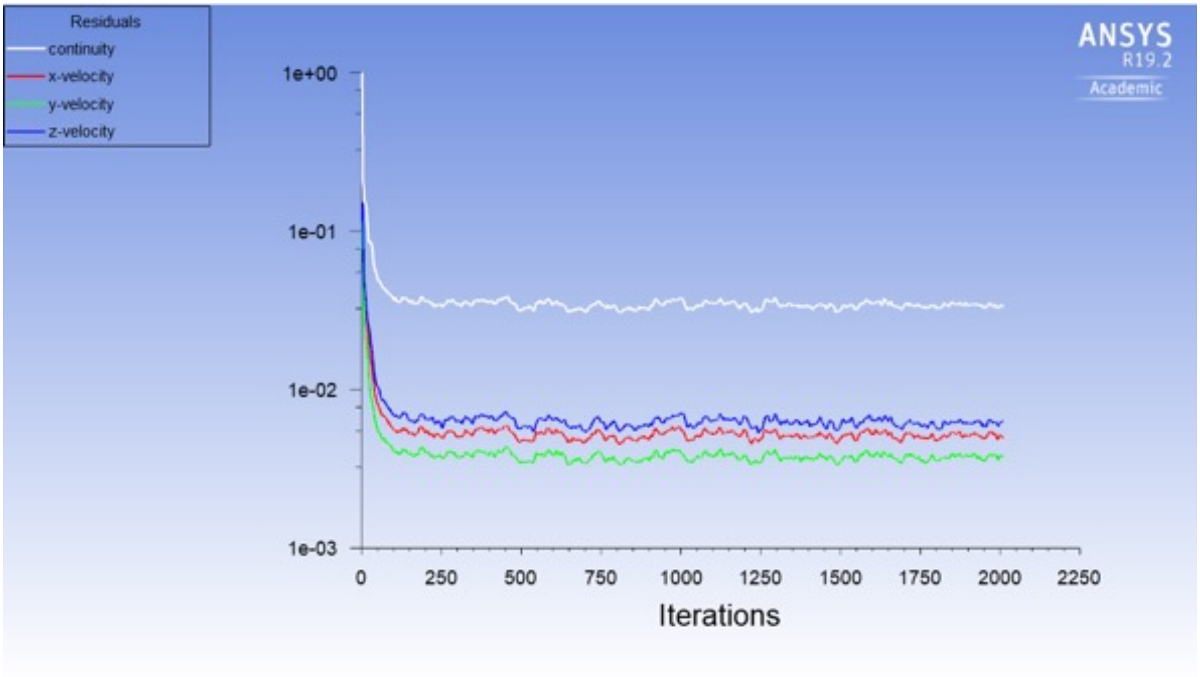



*Figure 27: Residuals convergence*

After the mesh is done the initial conditions of the simulation need to be stated. The air flows towards the center of the flat surface from both sides with an inclination to create a "wall of air" to prevent the snow from depositing and to keep the particles airborne. Different width between the two sources of airflow where tested at this stage to find the most convenient distance with different air velocities. A distance of 0.5 meter was chosen for the distance between the boards of airflows. After trying different inclinations for the flow, an angle of 45 degrees was the most stable and also most sufficient in terms of creating a wall of air (Figure 28). Since the airflow is leaving the outlet with an inclination to the base plane, one has to define the velocity in x- and z-direction in order to obtain a resultant velocity at the predetermined magnitude. The resultant can easily be found by using e.g. the law of sines.

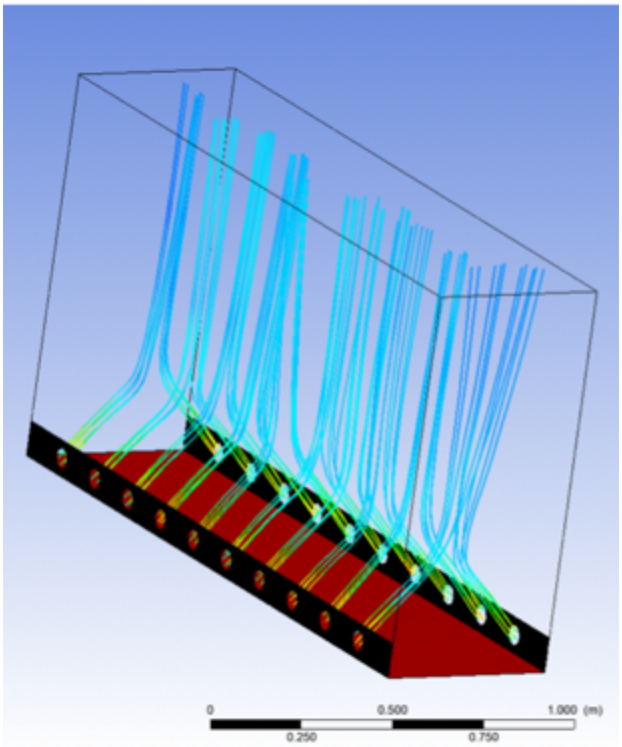


*Figure 28: CFD model with airflow trajectories*

## 3.4 Preliminary Study

The preliminary study for this master's thesis focused on simulation and initial calculations regarding the drag forces acting on different type of snow crystals. In the pre-study, it was made a rough plan for the experiments conducted in this thesis. The first draft of the experiments was based on a leaf blower as the source of the airflows, which was later replaced, as it is thoroughly reviewed in the following experiments chapter 3.5. The preparatory work from the preliminary study was important in order to conduct the experiments in this study, and some relevant results from this pre-study are presented in the following subchapter.

### 3.4.1 Preliminary empirical results

By using the two drag force equations presented earlier with various conditions and scenarios, the amount of data quickly became vast. Hence, the values compared to each other and presented in the same graph, are the ones found most relevant for this study. There was made a few assumptions through the process, which will be highlighted. First of all, the air velocities used in the calculations were set to be 3 m/s or 27 m/s throughout the calculations. The reason for using 3 m/s is that it appeared that the average velocity to keep the snow particles airborne is close to this value, when using Equation 15 (Figure 29). The average from Equation 16 is closer to 2 m/s, but with larger deviations (Figure 30). The value of 3 m/s is arbitrary picked to be just over the average from both equations. This is mainly done to have a value for drag force close to the snow crystals gravity force, as it will give us the minimum velocity needed to reject incoming snow crystals. The reason why 27 m/s is used in the calculations is because of an early experimental assumption. Due to several unforeseen obstacles, the actual velocity obtained in the experiments were quite lower, which is detailed explained in the experiments chapter 3.5.

In the graph below, we distinguish between the most common snow crystals. The terminal velocity ($U_{max}$) is dependent on wet or dry snow crystals. The real drag force will most certainly be somewhere in between those two characteristics of the snow crystals, however.

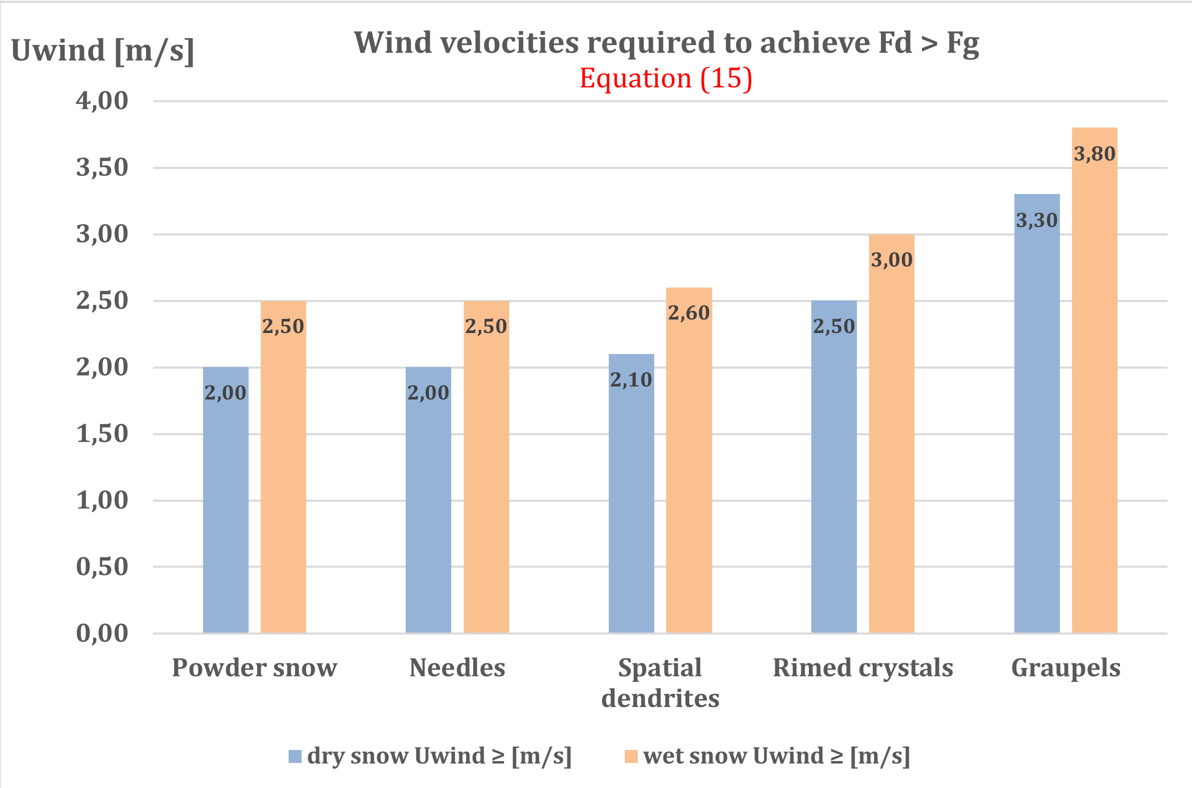



*Figure 29: Required wind velocities to maintain airborne snow (Eq. (15))*

The next graph is equivalent to the previous and relies on the drag coefficient rather than wet/dry conditions. The mean value for $U_{wind}$ from Eq. (16) is smaller than for Eq. (15). However, there is larger deviations using Eq. (16). This indicates, that shape of the crystals (related to Cd) makes a larger impact on the drag force than wet/dry conditions of the crystals.

An explanation could be found by exploring the drag coefficient further. First of all, the shape of an object has a huge impact on the amount of drag experienced. This is because as a fluid moves by an object, the molecules close to the object are disturbed and starts moving around the object in the direction of the flow field, which makes the shape of the object (snow crystals) important (Hall, 2015).

In this study, Cd is assumed to be between 0.07 and 0.5, this is because the shape of the snow crystals has been simplified to spheres. The reason for the range of values for a sphere is because it is strongly dependent of the Reynolds number (Hall, 2015). Both extreme values for Cd has been included in the calculations from Eq. (16). Including the extremes for Cd are done in the attempt to make sure that the real drag force is somewhere in between.

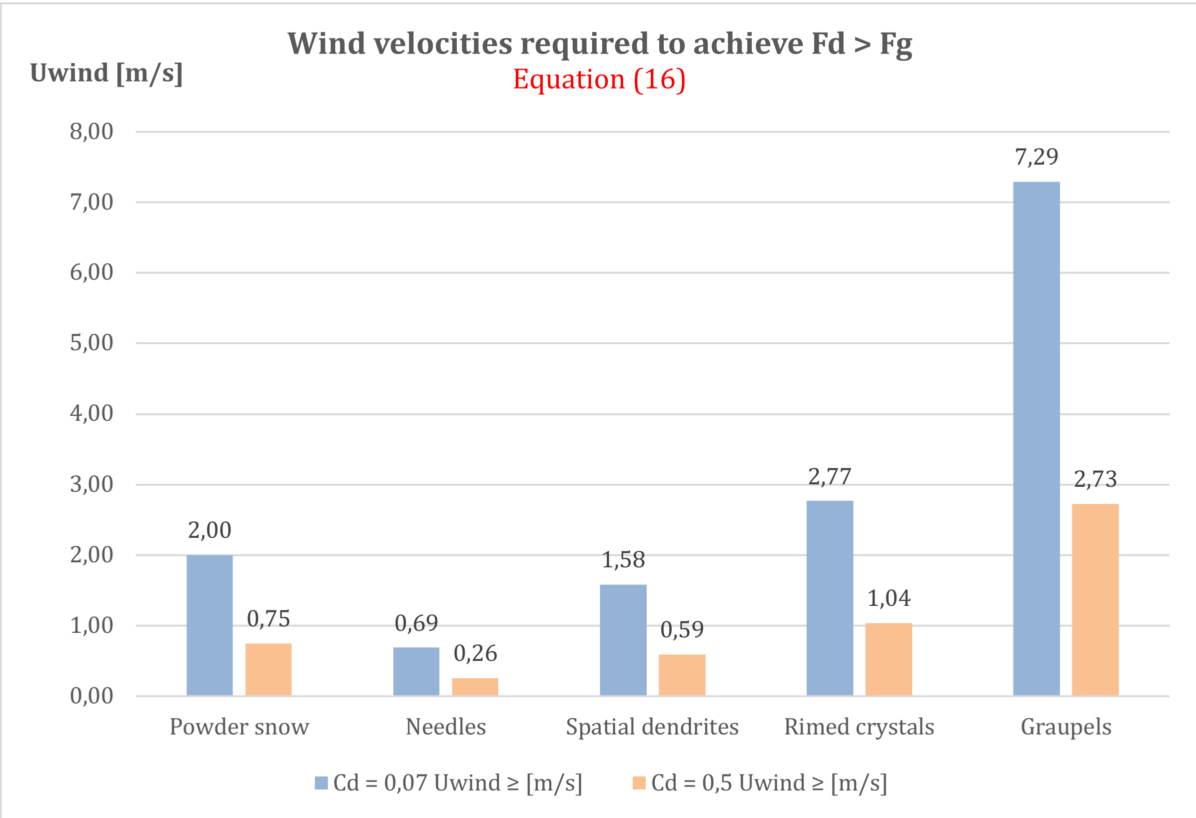



*Figure 30: Required wind velocities to maintain airborne snow (Eq. (16))*

In the next graph (Figure 31) the drag force from both 3 and 27 m/s wind velocities are compared to the gravity force of each type of crystal, respectively. Here it is important to clarify that the vertical axis is reversed logarithmical and the drag force is in milli Newton's (i.e. taller columns means smaller values). The result shows that the drag force for the snow crystals are larger than their respectively gravity force when air velocity is 3 m/s, except for graupels. From the average value determined in Figure 29, we knew that most of the crystals drag force would exceed its respective gravity force at this velocity. If we take a look at the drag force created from an applied airflow of 27 m/s, we notice that this force is significantly greater than its respective gravity forces. A similar graph for wet snow conditions and with 3 m/s is given in chapter 4.1.1. Wet snow conditions appeared to be more relevant in order to compare it to the experiments conducted in this study.

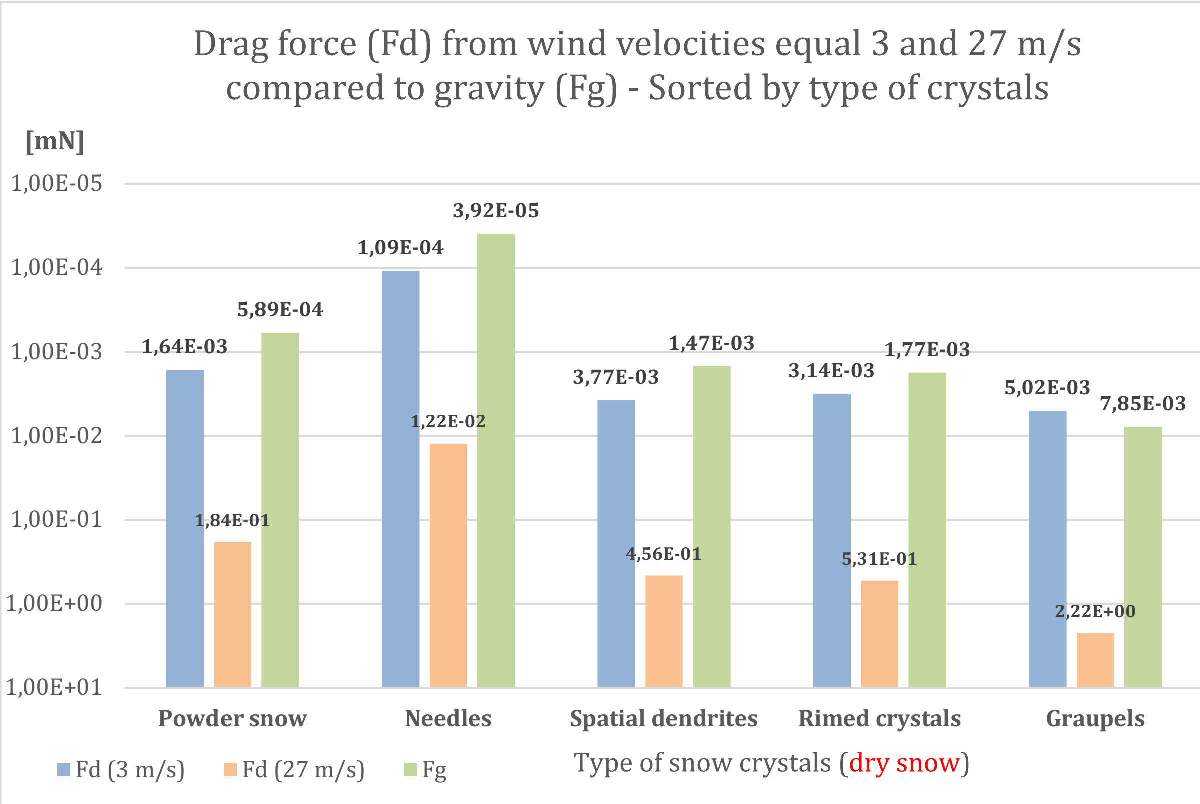



*Figure 31: Drag force and gravity force from dry snow conditions (Eq. (15))*

The last graph from the preliminary study concerns the average for all the snow crystals in various conditions for 27 m/s (Figure 32). The vertical axis is modified in the same way as the previous graph. From the graph we can clearly see that the average for all crystals, either wet or dry and with the extreme values for Cd, all greatly exceeds the average gravity force. What we can take with us from these results is that an air velocity of 27 m/s are sufficient to accomplish our fundamental criteria of drag force exceeding gravity force (Figure 24). In the discussion chapter (4.1.1), an almost identical graph is presented, the only difference is the velocity, which will be explained and discussed thoroughly there.

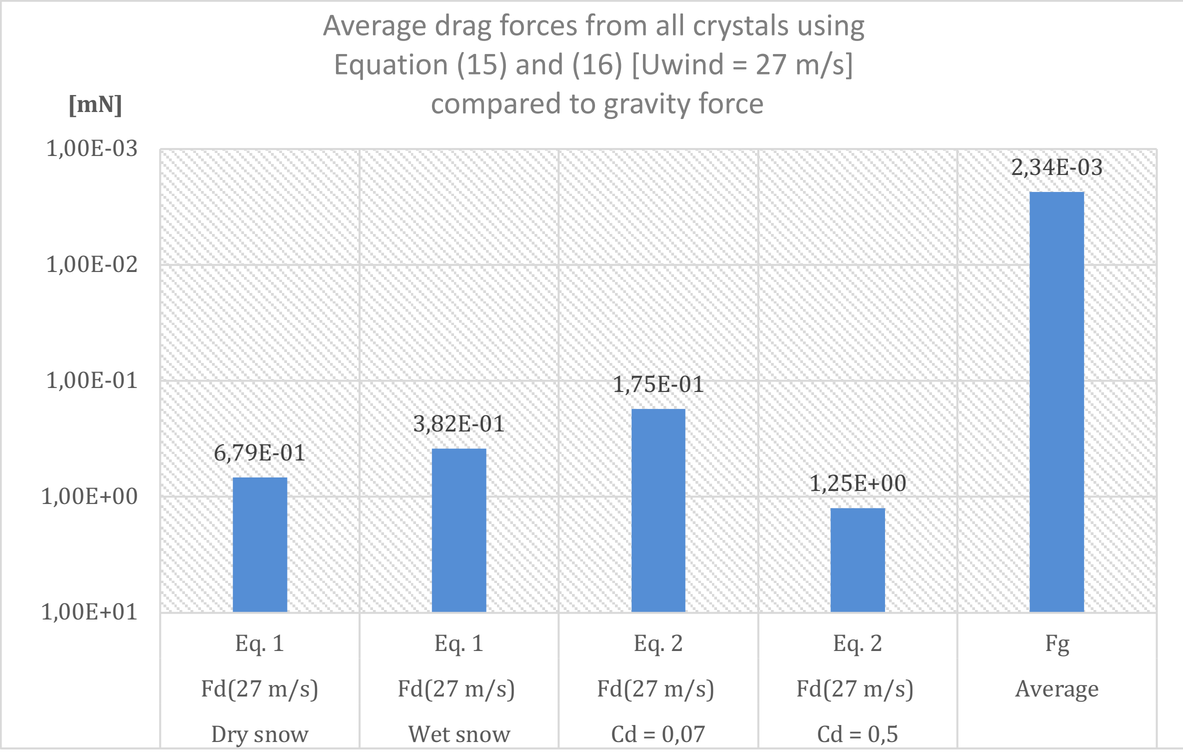



*Figure 32: Average drag from all crystals under various scenarios with 27 m/s (Eq. (15) & (16))*

## 3.5 Experiments

In order to prepare for the full-scale experiment, some preparedness needed to be done, this includes initial testing of equipment and experimental set-up. In this chapter all the details about planning, assumptions and corrections throughout the experiment process will be presented.

One fundamental change was made from the planning of the experiments towards the assembling of the test model. The source of airflows has been one of the most vital elements in planning, set-up and execution of the experiments. At first, the source of airflows was intended to be a leaf blower due to its high velocity and cubic feet per minute (CFM). Further, in favor of using a leaf blower, was the fact that one does not have to build a system with excessive use of customized parts, which likely would exceed both budget and time. To lead the airflows from the leaf blower to the outlets at the boards, standard garden hoses was intended to be used. The garden hoses were discarded as it was hard to find a sufficient way to connect them to valves, distributors and the outlet of the leaf blower itself.

The experiment design went over to pneumatics. It seemed considerably timesaving and simpler to use push-fit pneumatics from Festo® with corresponding valves and transitions. However, the pneumatic hoses were limited to a certain cross-sectional diameter, which resulted in problems regarding the source. In general, a leaf blower consists of a centrifugal fan with an impeller. These impellers are designed for the purpose of blowing leaves from the ground and not to build up pressure, which the pneumatic hoses are dependent on if we want to maintain the required velocities at constant flow. As the main purpose of the experiment itself is attempting to proof a concept, the most convenient way to achieve the same conditions as in the simulations had to be the prime focus. Hence, the leaf blower had to be replaced by another source as well. The reason for this decision relied on the implications related to the pressure requirements. The final solutions became to use compressed air.

### 3.5.1 Initial test of hoses and manifold

Testing the manifold and hoses was conducted as an initial test before assembling the full-scale experiment. The purpose of this testing was to measure the velocities from the hose outlets and to study the distribution of flow from the manifold and compare it to the empiricism consecutively before setting up the experiments. The manifold is produced at the University's workshop (Figure 33). To quality check the manifold, a test was necessary. Further discoveries throughout the first testing were the relationship between pressure loss (Δρ) and velocity loss (Δv), which is illustrated in Figure 34.

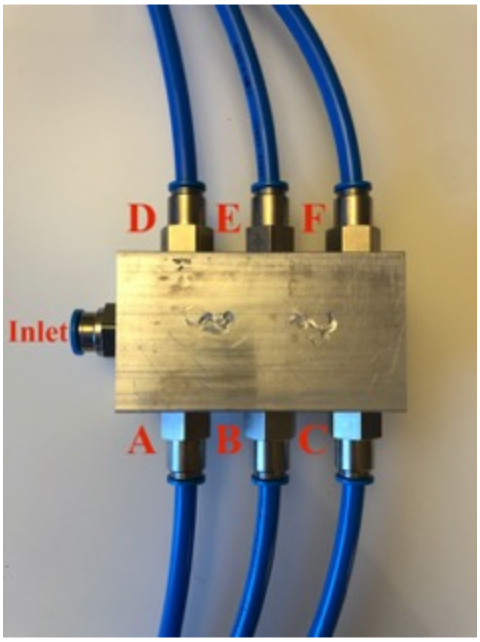



*Figure 33: Manifold*

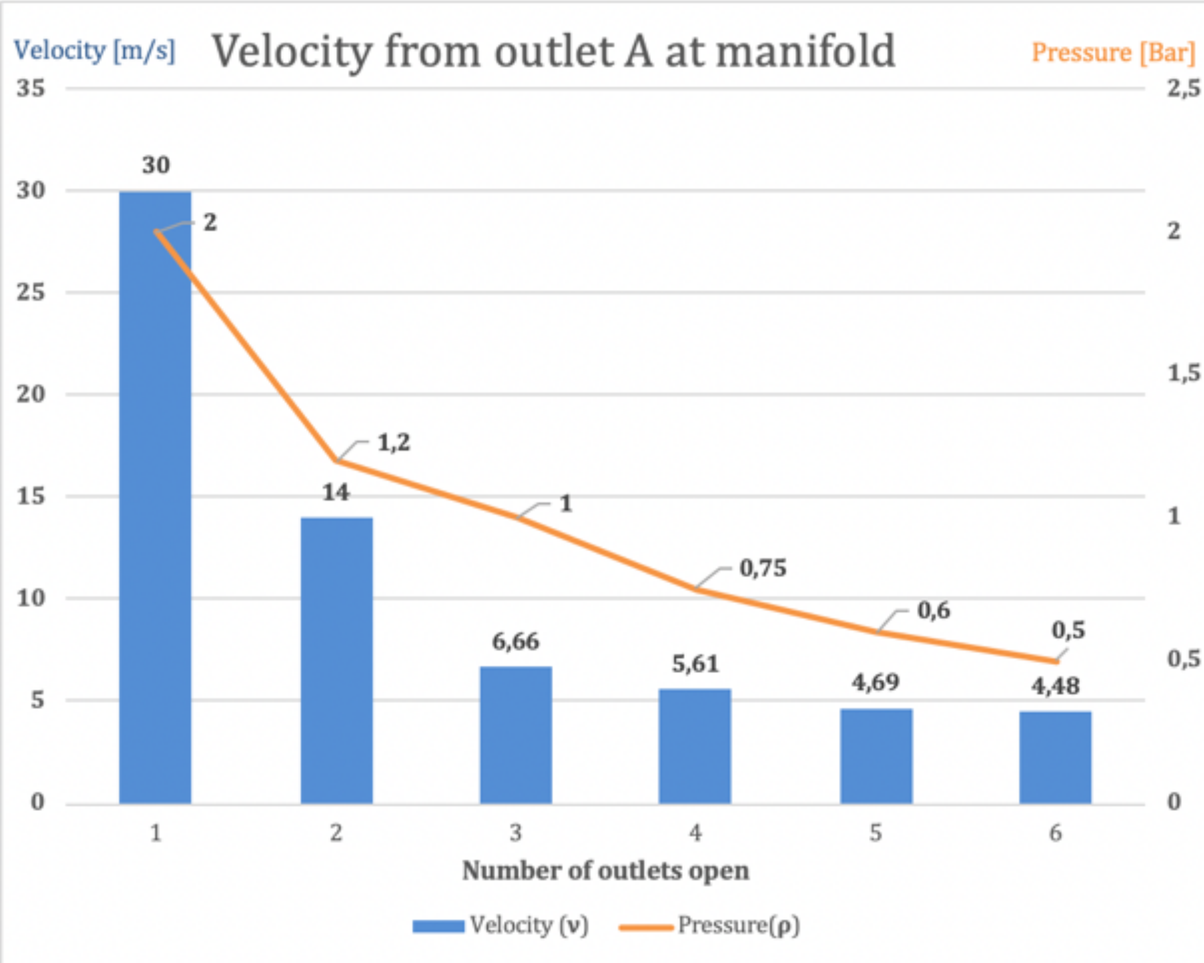



*Figure 34: Velocity from manifold outlet A*

A one-meter long hose, with 6 mm inner diameter, is connected to the outlet A on the manifold. The velocity is measured at a distance of 35 cm from the outlet. The reason for this specific distance is due to the geometry of the flow field from the CFD simulations. From the model (Figure 28) we saw that the boards where 50 cm from each other, and with an inclination of 45 degrees, the distance from the outlets to point where the flow fields meet is 35 cm. Further, we can compare the velocities achieved from the first test and the required velocities (Figure 29 & Figure 30) to keep the various snow particles airborne. We saw that the average required velocities from both Equation 15 and Equation 16 gave us about 2-3 m/s, excluded the graupels with the extreme drag coefficient. At the point where the flow fields meet, the achieved velocities are adequate in terms of precalculated requirements (given a manifold with six outlets).

The first test conducted with compressed air through the hoses were done with one manifold with six outlets. Outlet A and D ended up getting the lowest velocity when all six outlets were used simultaneously, which is a characteristic behavior of manifolds. As expected, the outlets further from the air inlet (outlet C and F), measured higher velocities since the pressure is higher at the opposite side of the inlet in the manifold (Zemlyanaya & Gulyakin, 2017). The measured velocities where done by using a rotating vane anemometer (TSI 5725). As shown in Figure 35 from the first test, the anemometer where mounted at the edge of the table and the hoses where attached to a 3D printed mount, in order to keep the flow field steady and perpendicular to the rotating vane. The 3D printed mount also made it easy to switch between the different outlets and operate the pressure valve at the same time. First the hose was connected to the mounting gear followed by completely opening the pressure valve and start logging air velocity.

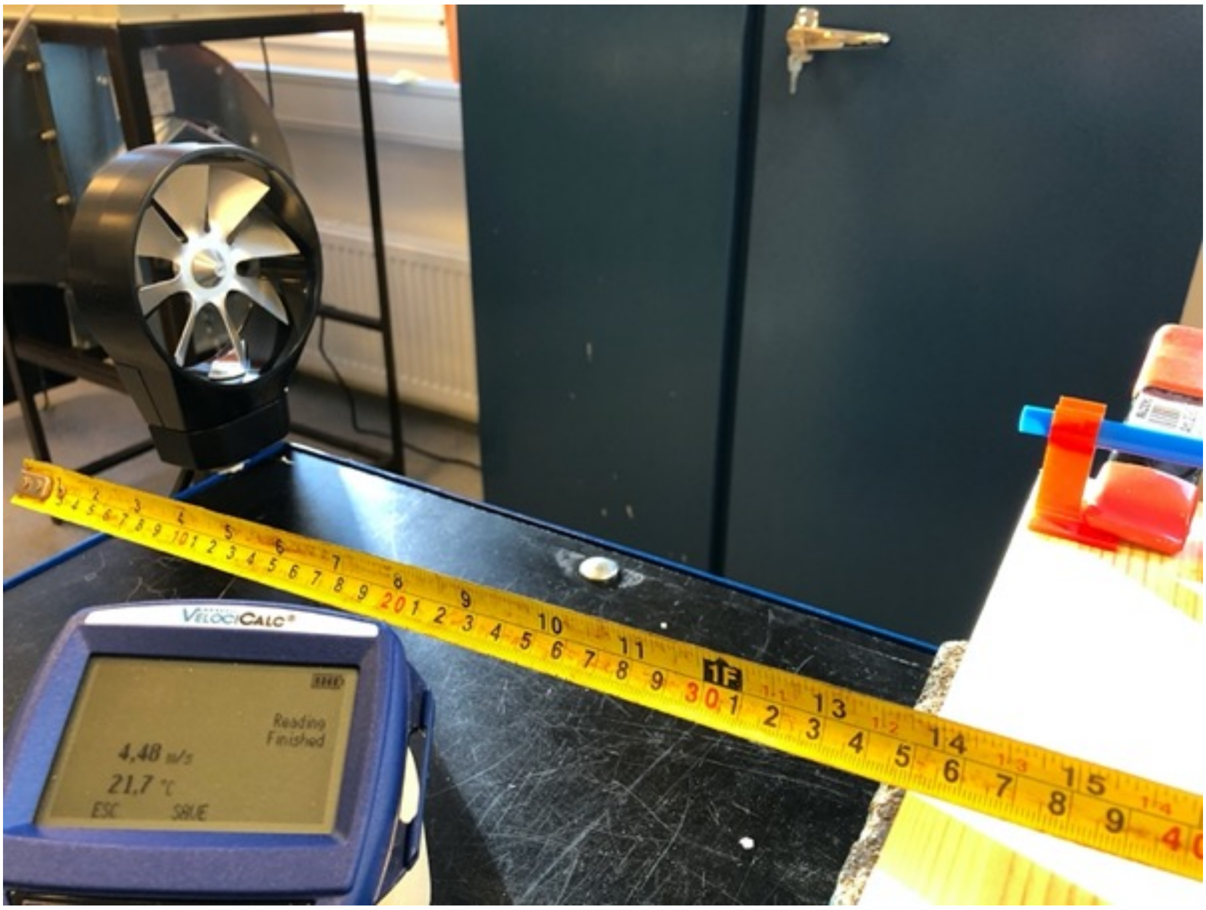



*Figure 35: Velocity from A with all six outlets open*

### 3.5.2 Experimental diffusion of airflows

In Figure 36 on the next page, the maximal velocity against distance from the outlets is plotted. The velocities were measured for 45 seconds at each distance, as it took about that time for the velocities to be constant. The behavior of the airflows was not quite as expected. The velocities tend to diffuse faster between 14 and 21 cm, compared to diffusion between 21 to 28 cm. It could be a lot of reasons for this result, e.g. different spread of the airflow in relation to the anemometer or vortices due to turbulent flow field. As the hose outlet gets closer to the anemometer, the airflow gets more concentrated and because of this the center of the air stream had to be pointed away from the center of the turbine. The reason for this is found by taking a closer look at the center of the turbine. The turbine blades stop a short distance from the center point, which means that the airflows will not rotate the turbine enough to measure the real velocities when the hose outlet gets too close. The distribution of airflows from the hoses was explained in Figure 5, where we saw, among other things, that the greatest velocities are found along the centerline of the flow, which is why the flow had to be steered away from the center of the anemometer. To deal with these potential errors from the measures, one could have used a pressure probe (pitot tube), which uses Bernoulli's equation along with the difference in static and total pressure to estimate the velocity (Benson, n.d.). Nevertheless, the results of importance in this case are the average values (green line in the figure below), which is higher than the required velocities to keep the snow particles airborne.

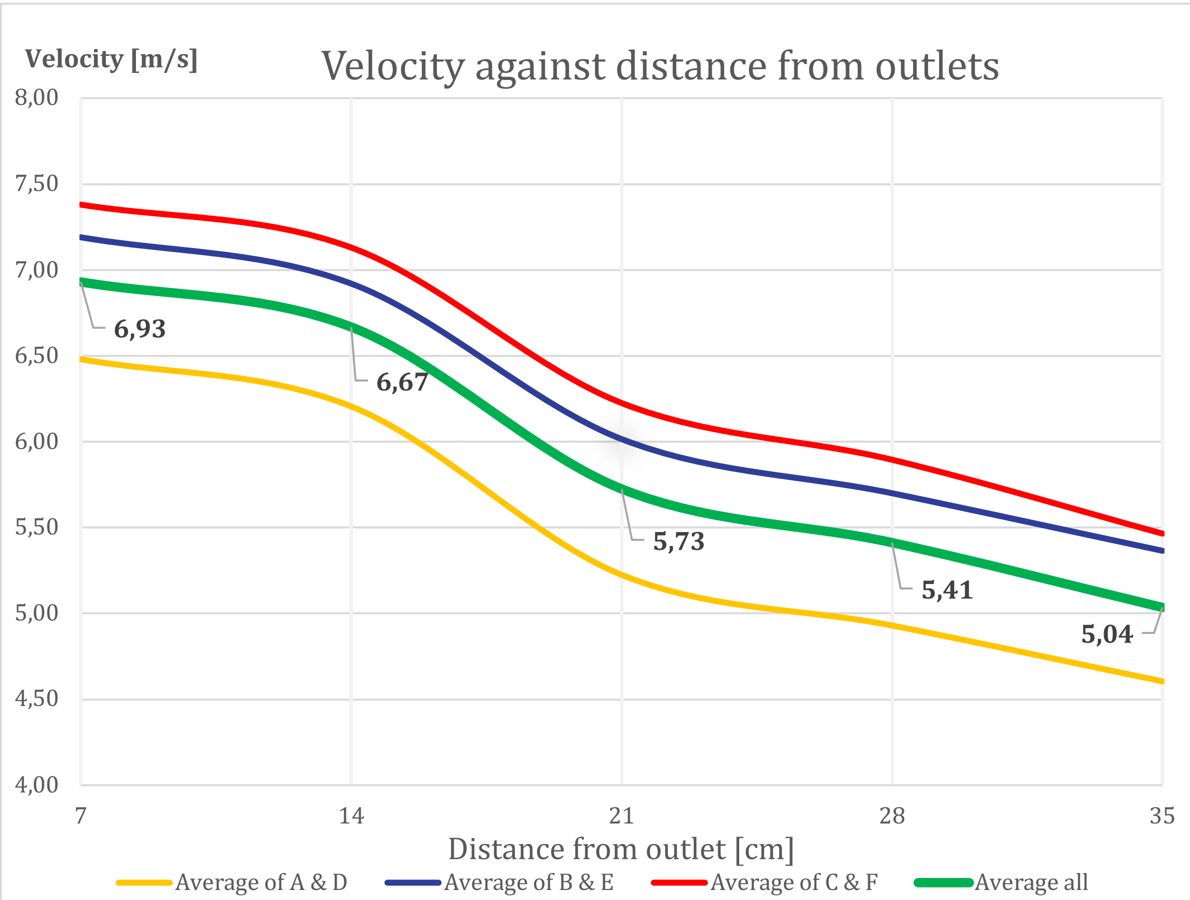



*Figure 36: Diffusion of airflows by distance from outlets*

The 7 cm intervals between the air velocity measurements are chosen due to the air streamlines from the CFD analysis. If we consider the CFD model in Figure 37, the distance from the outlets to the center of the surface is 25 cm (x-direction), which corresponds to 35 cm at the airflow trajectories above. Hence, for every 5 cm in x-direction the corresponding distance is about 7 cm at the streamlines.

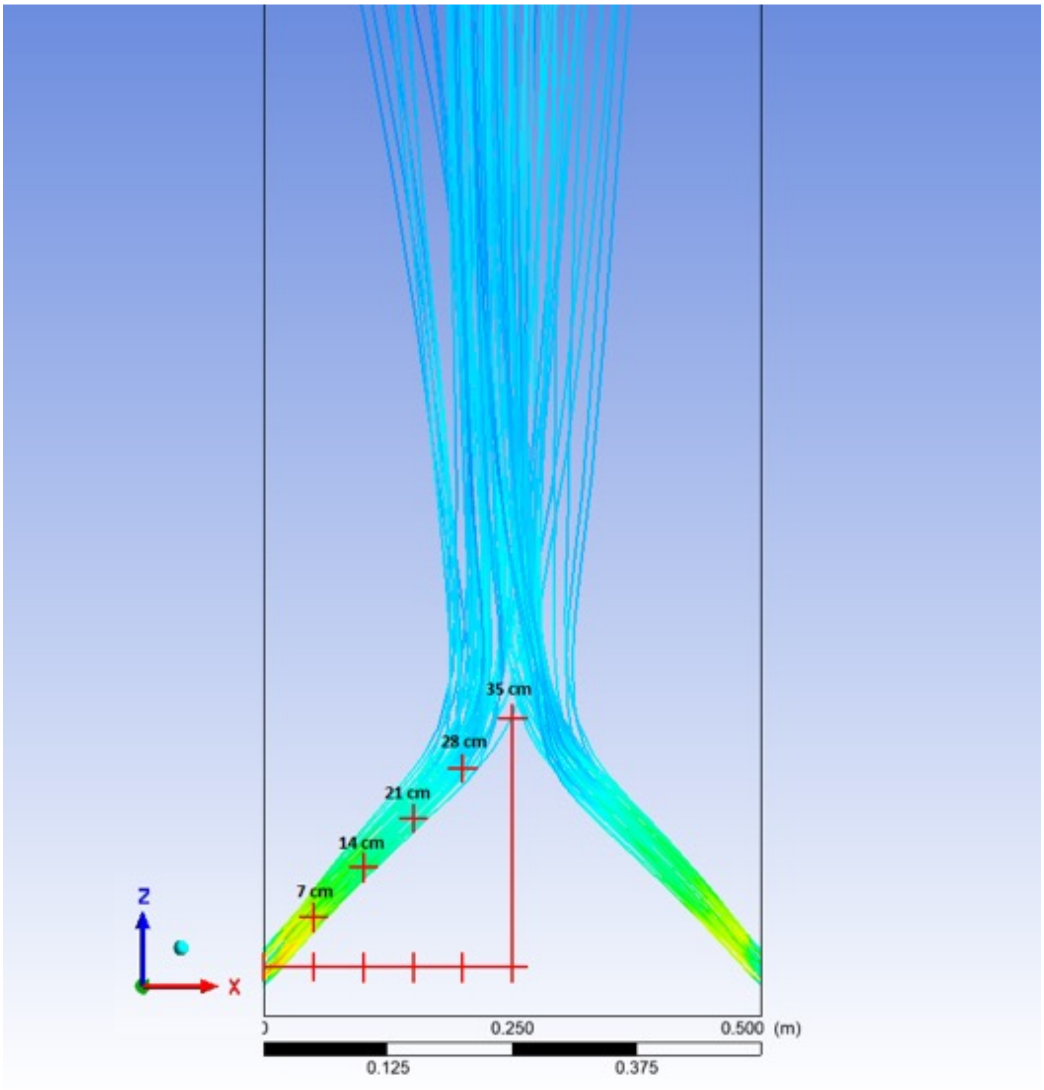



*Figure 37: CFD perpendicular airflow*

The purpose of determine velocity at different length from the outlet and velocity at various distances from the centerline of the airflow, is to use this information in the setup of the experiments. Since we know how the theoretically airflow will occupy the surrounding air and diffuse in the far field, we can correct the positioning of the outlets relative to capacity of the air source applied.

### 3.5.3 Experiment set-up

The set-up of the experiments is intended to be as close to the simulation conditions as possible. The inclination of the hose outlets is 45 degrees relative to the xy-plane (refers to the same coordinate system as seen in the simulation part) with a deviation of a few degrees for some of the outlets. Distance between the drilled holes is 7,7 cm from the center of each hole (Figure 38).

*Figure 38: Boards with drilled holes for outlets*

The distance between outlets at the board is because the manifold was chosen to have six outlets, and by drilling 12 holes – instead of six - at each board with equal distance from each other, we have the ability reduce the distance by half if needed. Further, we can also use every other outlet at each side, to see the difference between a perpendicular flow field (Figure 37) and a parallel flow field where the airflows passes each other in an "interlocking fingers"-pattern (Figure 39). The perpendicular flow is denoted after its 90-degree angle created at the meeting point of the two airflows (ideal flow). Consecutively, the parallel flow is denoted after the parallel behavior of the airflows, although this is also purely theoretical.

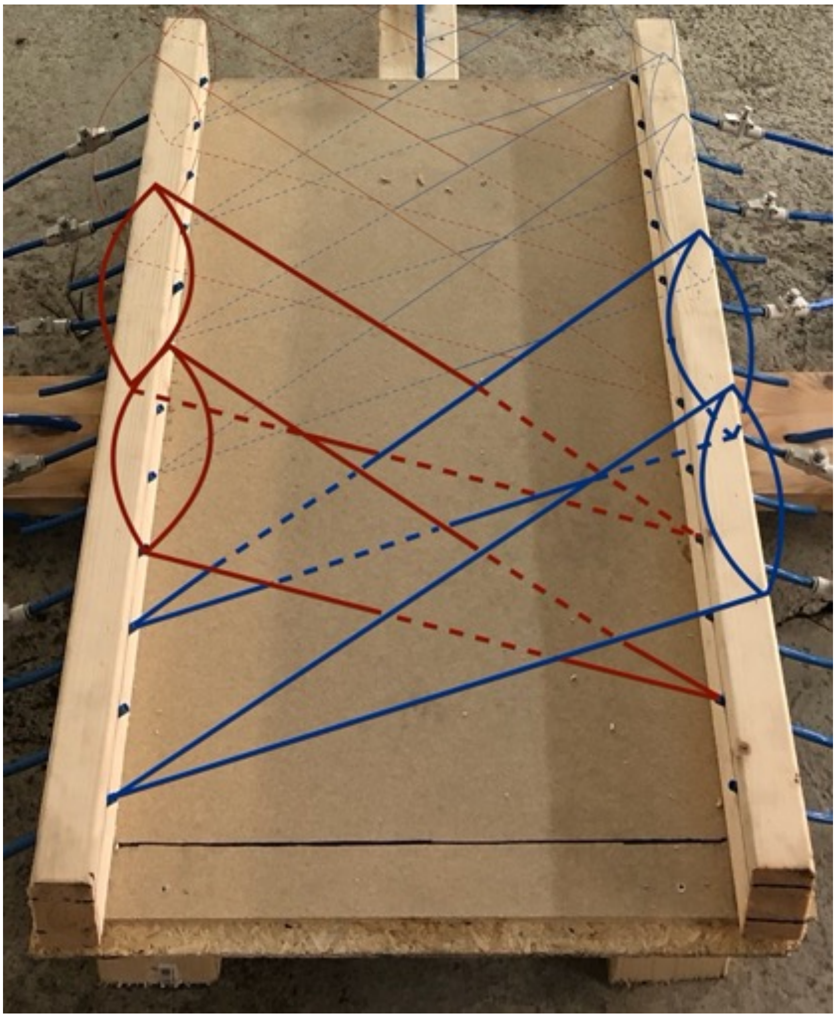


*Figure 39: Parallel flow field*

The experiments were supposed to be conducted at the university, where sufficient compressors and tools are available, but the whole university had to be closed off for over six weeks due to extraordinary circumstances. In lack of tools, compressor and workshop, this led to a few extra challenges in order to assemble the model and conduct the experiments. However, by renting a truck it was possible to borrow and transport most of the tools from the university laboratory, continued by assembling it in the back of the truck and buying the most suitable compressor within the budget.

The compressor was not able to sustain the same velocity as the compressor at campus, which affected the experiment set-up. The original set-up was designed with 12 hoses distributed from two manifolds (Figure 40).

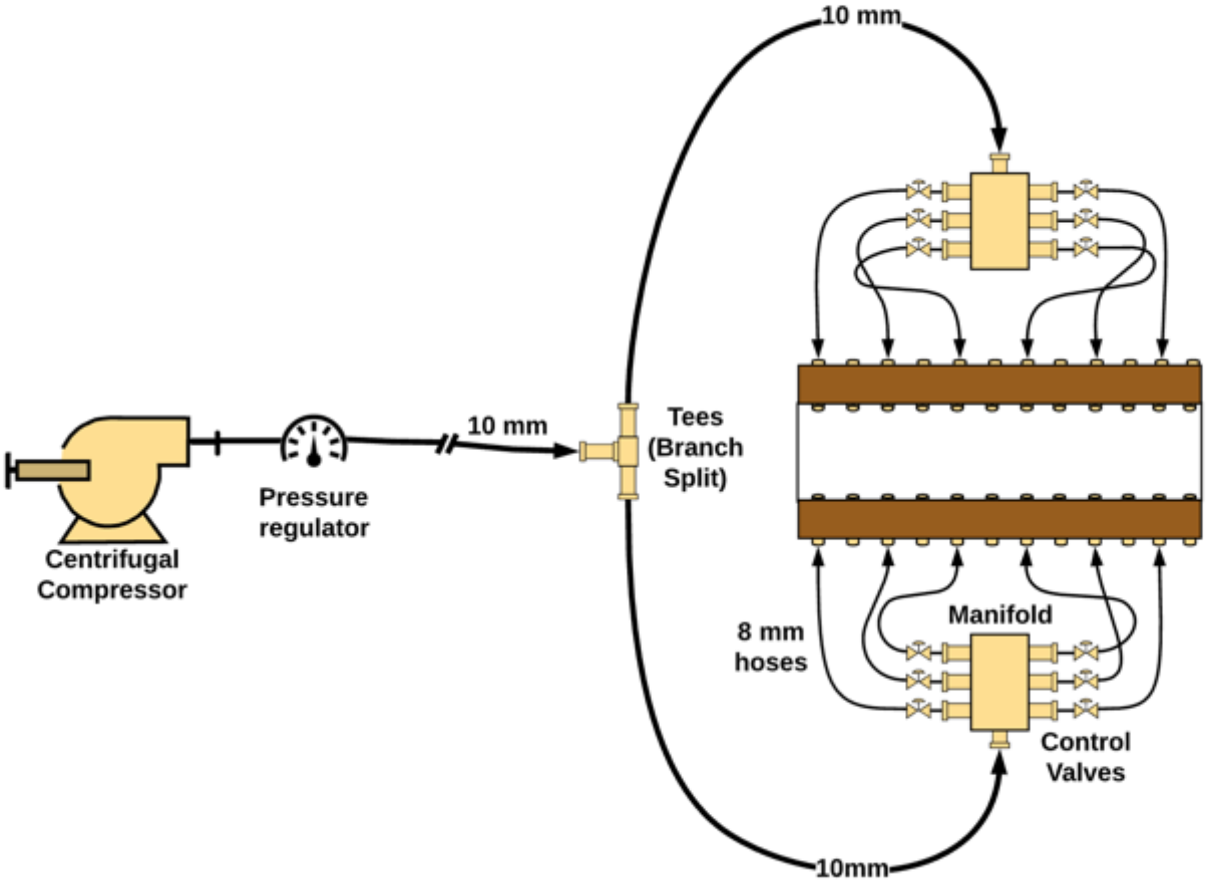



*Figure 40: Schematic view of the original experiment set-up*

This set-up was not possible to maintain since the velocities decreased to below 1 m/s. The solution became to scale the experiments down to one third of the original (Figure 41). The Meec tools® compressor used in the experiments is 2200 W electric, with 50-liter tank and delivers 392 l/m. After measuring velocity, it became clear that the compressor was only able to sustain adequate velocity for four hoses in total and even then, the velocities where barely acceptable in terms of the precalculated drag forces. Nevertheless, it should be possible to analyze and discuss the results, even though it had to be significantly down scaled.

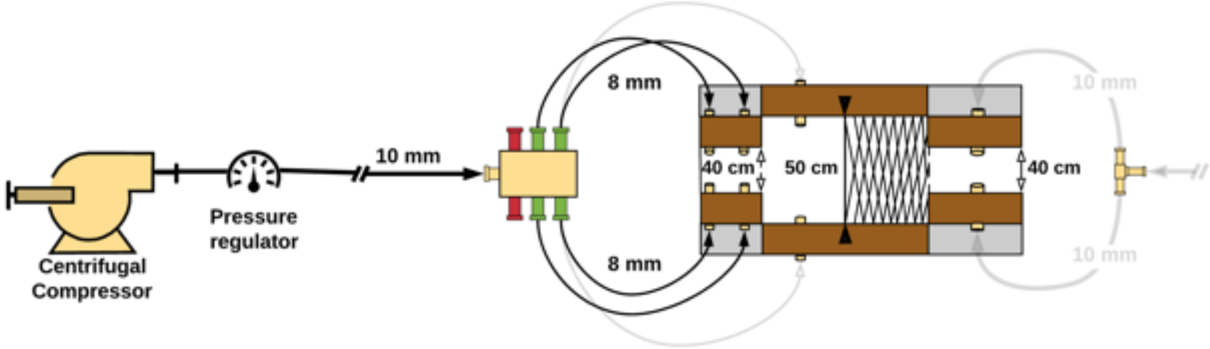



*Figure 41: Schematic view of the final experiment set-up*

### 3.5.4 Execution of experiments

The aim of the experiments is first of all to test the validity of the CFD simulation and the precalculated drag forces. The experiments are executed during snow weather and under different conditions through March. We cannot control the weather conditions, it is, however, fortunately common that all the various snow particle categories are present in Tromsø during this month and often several within a single day.

On the other hand, there are several conditions in these experiments which are modified and controlled. The first settings to be modified is to use every other outlet as mentioned earlier, even though it only could be done with four hoses due to the source limitations mentioned. Applying airflows from only one side will also be conducted if a dominant wind direction occurs during the testing. The relevance of testing the latter is to study one of the main principles of snow deposition, namely that snow will be deposited in "aerodynamic shadow zones", which possibly could be manipulated using airflows. Since the experiments had to be scaled down, extra tests will be conducted using 10 mm hose (8 mm inner diameter). This test will also be done in the same way as the 8 mm hoses (6 mm inner diameter). Further, the distance between outlets in both x- and y-direction will consecutively be modified if needed. In Figure 42 next page, we see the final modified test model with three different test ranges.

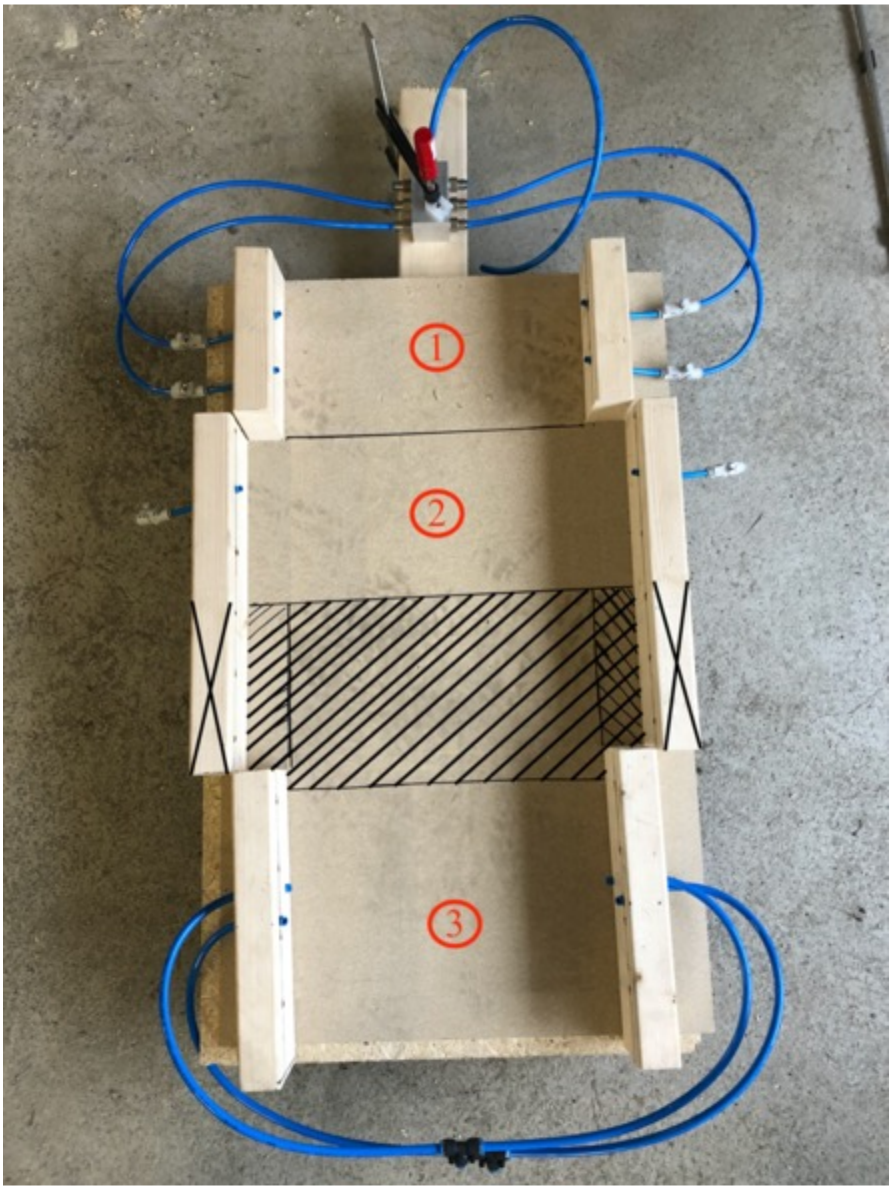
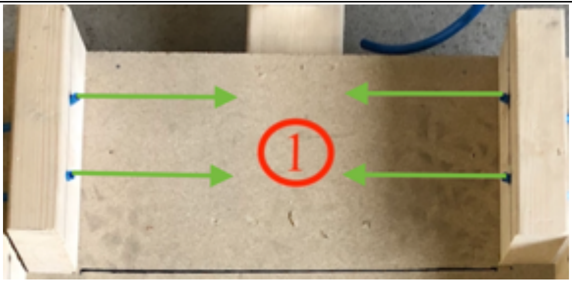
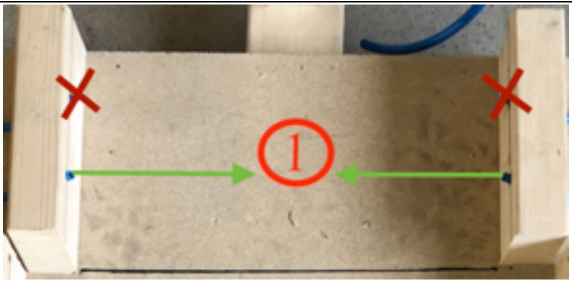
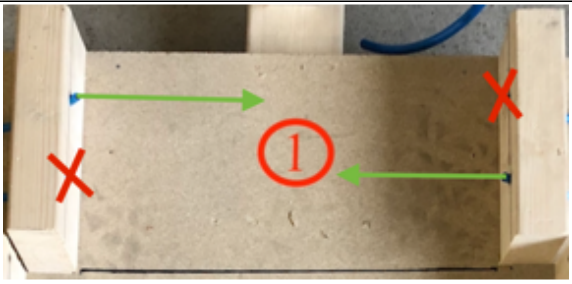
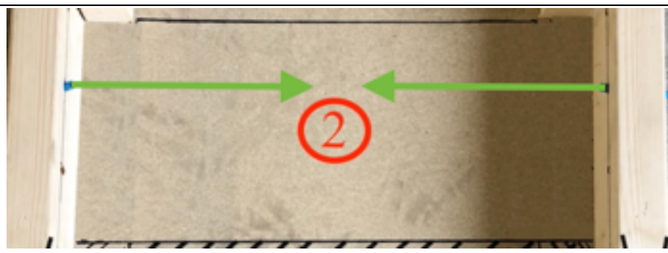
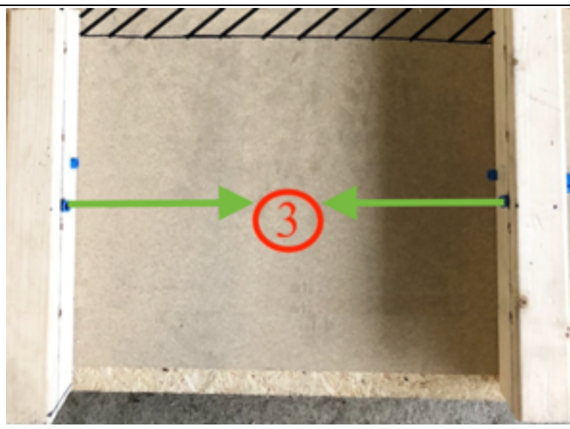



*Figure 42: Final experiment set-up with three test ranges*

The distance between the wooden boards in test range one and three is reduced by 10 cm from the original set-up. The distance was shortened to obtain the desired velocities when applying four hoses (test range one) and when switching to 10 mm hoses (test range three). At the test ranges, it is a total of five different test cases consisting of various distance and hose diameter configurations. At range one, the three first cases (A, B1 & B2) are tested, followed by one case (C) tested at range two and the last case (D) at range three. The overview of the different test cases is given in Table 3.

*Table 3: Case review*

| Cases ↓ | Details | Illustration |
|---|---|---|
| **A** | • 4 outlets<br>• 8 mm hoses<br>• Perpendicular flow<br>• 40 cm between boards |  |
| **B1** | • 2 outlets<br>• 8 mm hoses<br>• Perpendicular flow<br>• 40 cm between boards |  |
| **B2** | • 2 Outlets<br>• 8 mm hoses<br>• Parallel flow<br>• 40 cm between boards |  |
| **C** | • 2 Outlets<br>• 8 mm hoses<br>• Perpendicular flow<br>• 50 cm between boards |  |
| **D** | • 2 Outlets<br>• 10 mm hoses<br>• Perpendicular flow<br>• 40 cm between boards |  |

In absence of snow, an alternative method was used as a substitute. When the model was ready for execution, several hours waiting for snowfall led to the idea of using expanded polystyrene (EPS). EPS typically have a density of 11 to 32 kg/$m^3$, which make it suitable as an alternative for falling snow if crumbled it into snowflake sized particles (Australian Urethane & Styrene, 2010). The EPS made it easy to see the behavior of the airflows and some other interesting aspect. A few tests were conducted using EPS, which will be presented in the analysis and discussion chapter as well. The set-up for these "bonus" tests were the same as for the cases presented at the previous page.

# 4 Results and Discussion

In this chapter, the results from empirical, numerical and experimental methods, is discussed sequentially. Firstly, the results from the empirical method is presented and discussed, followed by the results from the CFD simulations in the next chapter. The third chapter consists of the risk and reliability aspects of the thesis. Fourth chapter considers the experiments, which is further divided into the different cases. The two last chapters is comparison of the three aspects of the thesis and discussion regarding the research questions.

## 4.1 Empirical Method

In this first subchapter of the results and discussion, the empirical results are discussed with respect to the experiment setup and cases. Firstly, discussion regarding drag force and how it is affected by wet snow conditions is conducted. Secondly, a few empirical results regarding the airflow from the hoses and source used in the physical experiments are presented and discussed.

### 4.1.1 Drag force on snow crystals

As promised in the review of the preliminary study, two similar graphs as the two last one in chapter 3.4.1, are presented here. From the first figure below, we see the drag forces generated by a wind velocity of 3 m/s in wet snow conditions. Unlike dry snow condition, wet snow have potentially higher terminal velocity ($U_{max}$), this results in smaller values for $F_D$. As a consequence, the decreased $F_D$ is closer to the gravity force from the falling snow crystals ($F_G$). For rimed crystals and graupels, the drag force generated will not be able to keep these crystals airborne.

Determining drag force from 3 m/s airflows appeared to be more relevant than 27 m/s for the experiments. Although the maximum velocity ($V_{xm}$) along the centerline of the airflow is greatly exceeding 3 m/s, it diffuses relatively fast in the free air. The high air velocities at the centerline diffuses rapidly with distance from the center, resulting in less than 50 % of the airflow maintaining ≥ 3 m/s. The latter is the reason why any velocity greater than 3 m/s is not given further attention in the empirical method. The next chapter is discussing the velocities and the area occupied by the airflows.

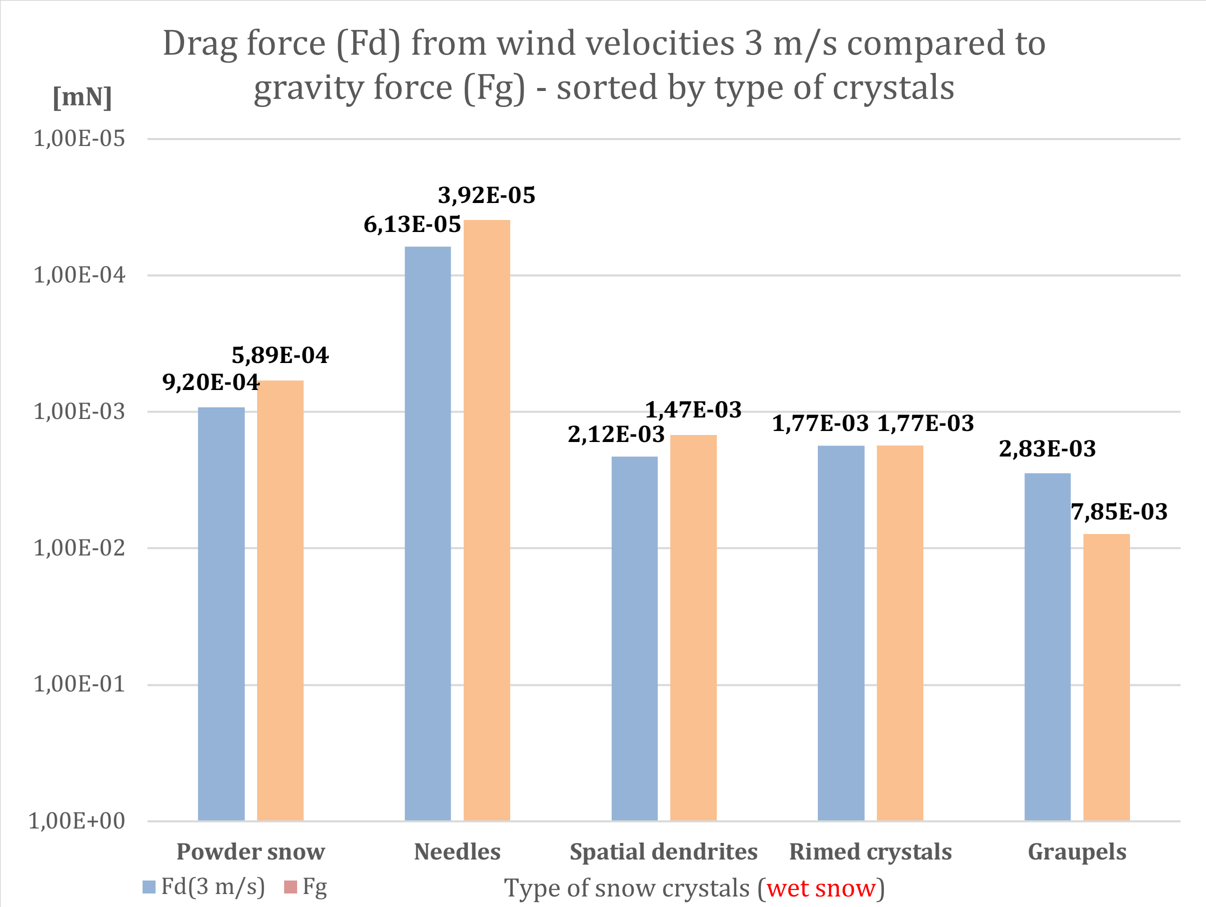



*Figure 43: Drag force from 3 m/s in wet snow condition (Eq. (15))*

The next figure compares various conditions using Eq. (15) and (16) along with 3 m/s velocity. Each bar is an average from all five snow crystal categories. From the results, we have two bars with red values, meaning that the average from wet snow condition and the lowest drag coefficient is less than the gravity force. On average, the velocities need to be greater than 3 m/s if we want to accomplish the criteria of $F_G < F_D$ , when exposed to wet and/or aerodynamically shaped snow crystals. The data behind these two figures and the ones presented in 3.4.1 are attached in Appendix C.

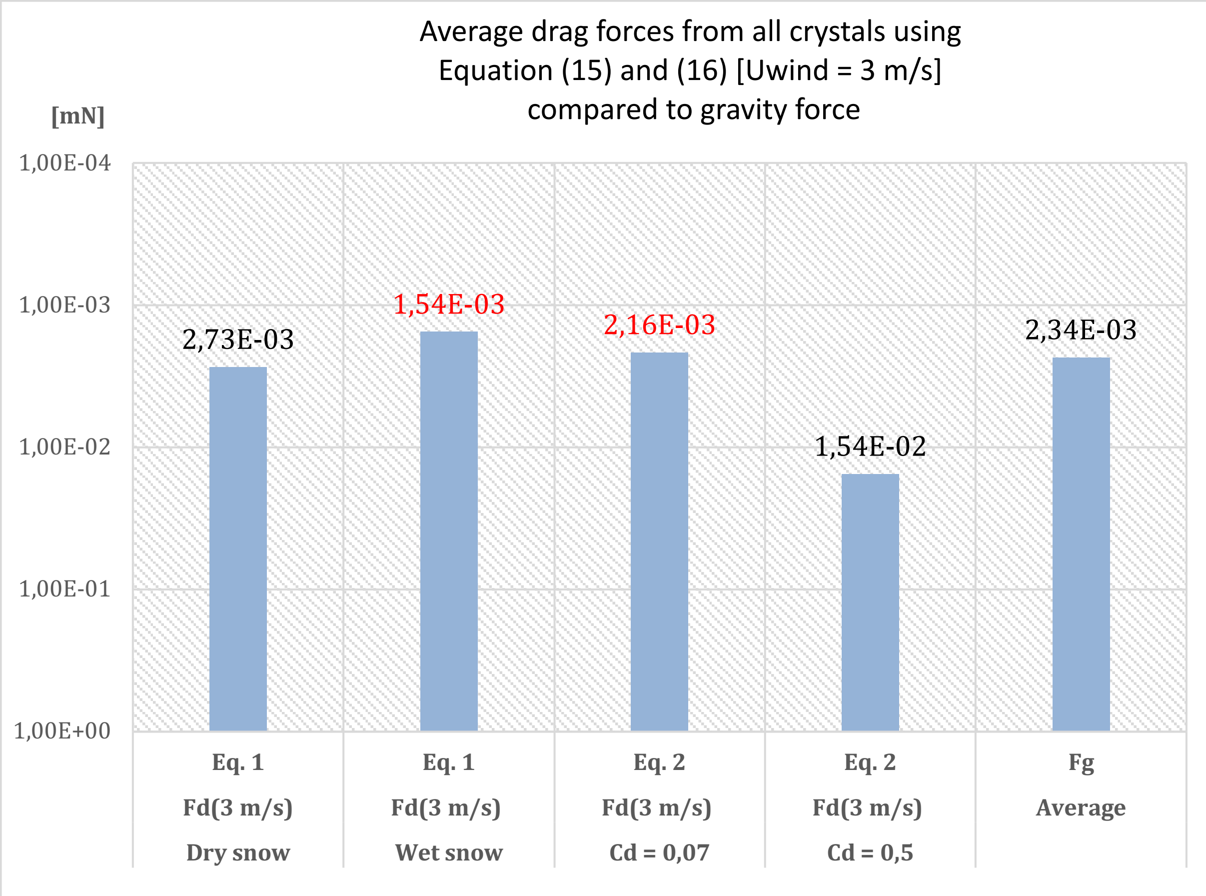



*Figure 44: Average drag from all crystals under various scenarios with 3 m/s (Eq. (15) & (16))*

### 4.1.2 Theoretical airflow

In order to have a better understanding of the results from the experiments, determine a theoretical airflow could be advantageous. From Figure 45 we recognize the characteristic cone formed airflow from Figure 5, but here most of the parameters and designations are removed.

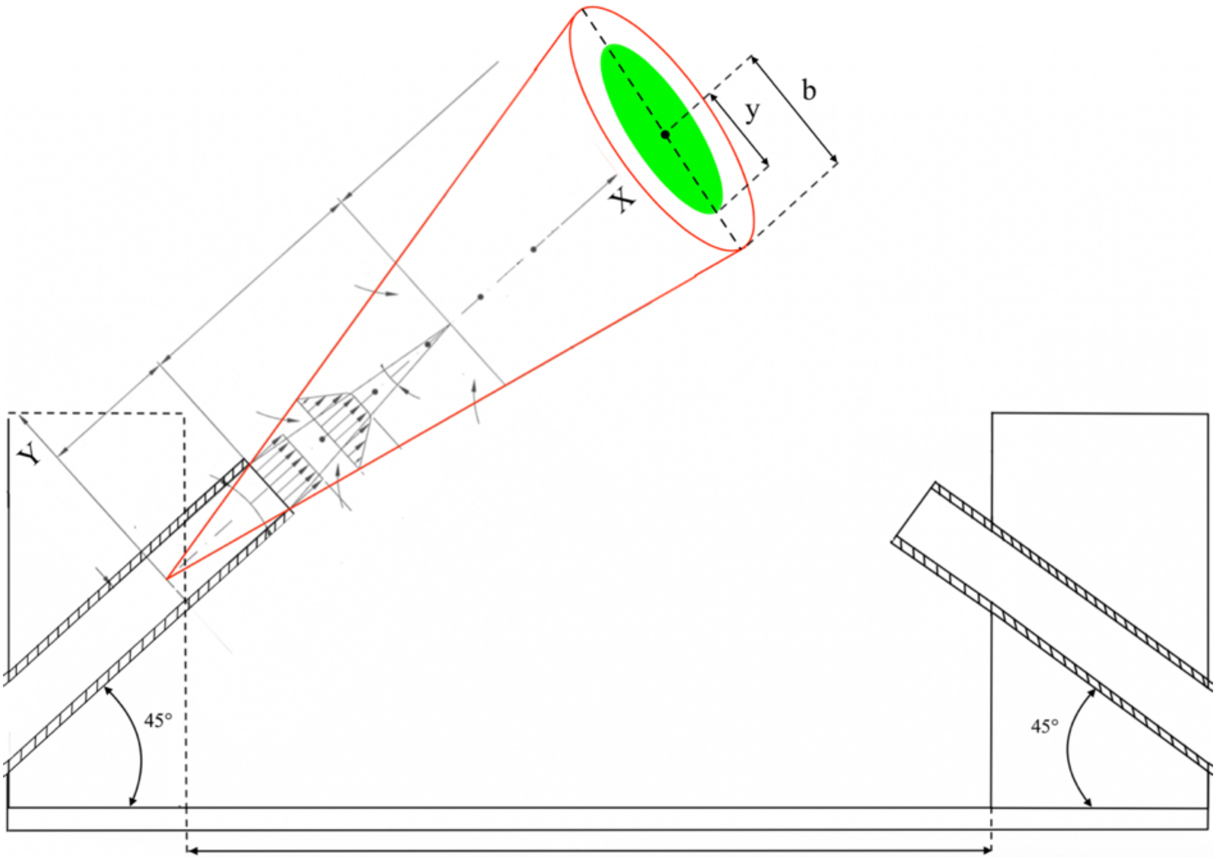



*Figure 45: Airflow from a circular cross-section*

The green ellipse illustrates the area where air velocity is greater or equal to 3 m/s, the area is calculated using Eq. (9) and solved for y. By solving for y, we find the distance from the centerline of the flow to the point where air velocities decrease below 3 m/s. The size of the green area is mostly influenced by $V_{xm}$, which we can see from Table 4 (next page). The green contour is at the theoretical cross-section where the airflows meet in case A, B1, C and D (perpendicular flows). For the parallel flow (case B2), the cross-section used for calculating the green contour is approximately where the flow passes the wooden boards at the opposite side of the model (Figure 39). As we remember from the literature review, the occupied area by airflows at a distance $X_d$ from the outlets have a radius of b, which can be calculated by using Eq. (5). The parameters b, y and $X_d$ are important to take into consideration, especially when visually analyzing the experiments. The latter is of great interest, simply because we are trying to accomplish that air velocities greater than 3 m/s covers as large areas as possible.

*Table 4: Diffusion of airflow in experiment cases*

| Cases | Distance to control cross-section $X_d$ (cm) | $V_0$ (m/s) | $V_{xm}$ (m/s) | y (cm) | b (cm) | Percent of the airflow ≥ 3 m/s at the control cross-section (green contour in Figure 45) |
|---|---|---|---|---|---|---|
| A | 28 | 57.8 | 8.4 | 3.7 | 6.8 | ~30% |
| B1 | | 115.5 | 16.7 | 4.7 | 6.8 | ~45% |
| B2 | 58 | 115.5 | 8.2 | 7.4 | 13.8 | ~29% |
| C | 35 | 115.5 | 13.5 | 5.5 | 8.4 | ~43% |
| D | 28 | 65 | 12.4 | 4.4 | 6.9 | ~39% |

We see from the table above that initial air velocity $V_0$ is relatively high in all cases and the velocities decreases to about one tenth at the point where they meet the opposite directed airflow. The initial velocity is based on the compressor's delivered airflow and by using Eq. (8) to calculate the velocity. Case D is the only scenario where 10 mm hoses where used and it stands out from the other 8 mm hoses by less decreased velocity over the same distance. Further, if we look at the percentages in the column to the right in the table above, we see that the covered area ranges from about one third to almost half of the total area at the given cross-section. Not surprisingly, the lowest value is the only case where it is used four outlets, meaning that the flow rate from the compressor have to be shared by more outlets. Case B1 is the case with the largest area of the airflow covered by 3 m/s or more. Note that the control cross-section for B2 is almost 60 cm from the outlet, which explains the large difference between the green contour area in B1 and B2. How to spread the airflow in order to occupy a larger area is discussed in chapter 4.4.4.

## 4.2 CFD Analysis

From the empirical calculations we saw that an air velocity of approximately 3 m/s were sufficient to exceed the gravity force and thus keep the snow crystals airborne. In reality, wind in combination with snowfall may disturb the flow field or larger snowflakes consisting of several crystals falls towards the surface. Diffusion of airflows will naturally decrease the velocity as well. Therefore, we have to design the flow field with higher velocity from the outlets, which is chosen to be minimum 27 m/s as previously explained. To investigate the velocity profile and how it diffuses far from the inlets, a contour within the boundaries are made. From Figure 46 below, the contour is placed in the xy-plane with an offset in z-direction of 0.1m. We then see that the max velocity is ca. 17 m/s at this profile.

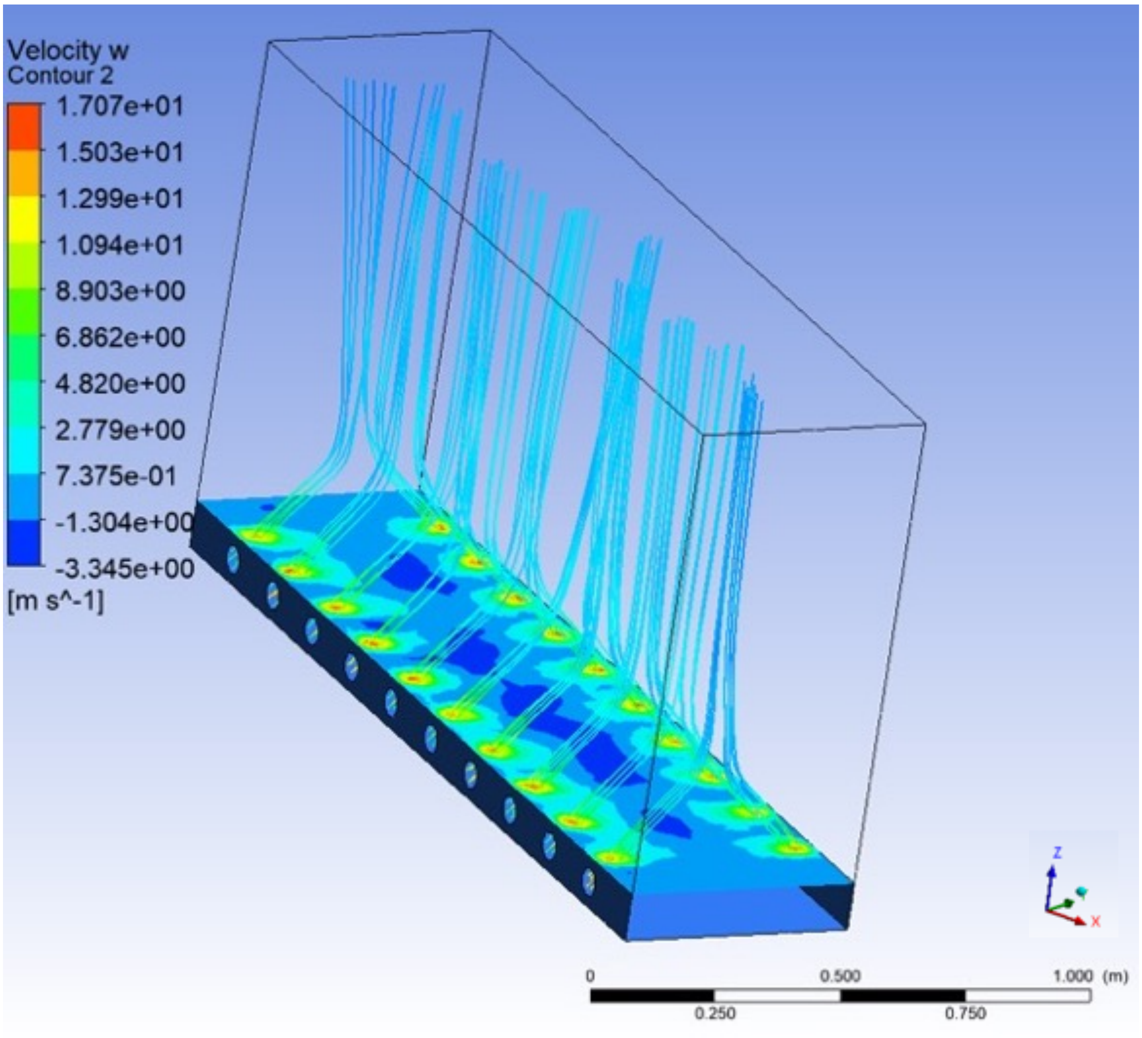



*Figure 46: Velocity profile at 0.1m offset*

The next contour is at 0.5 m offset (Figure 47), and we see how fast the velocity have diffused compared to the previous. The maximum velocity is just over 7 m/s at this height above the board. The contour shows that the velocity will be largest in the center of the flow field, and decay towards the boundaries. However, we see that a large part of the contour is covered with velocities greater than 3 m/s. At the areas with lower velocities, the snow will head towards the surface. Anyhow, the snow passing the flow field at 0.5 or 1 m above the surface will ideally be rejected by the flow field further down (between 0.1-0.3 m) as seen in the previous figure. From the discussion and analysis of the experiments, we will see if the snow passes through the contour-plane at 0.5 or 1 m and do not get rejected before reaching the surface. Given the latter scenario, the effect of a parallel flow field is compared to the perpendicular airflow in the chapter 4.4.

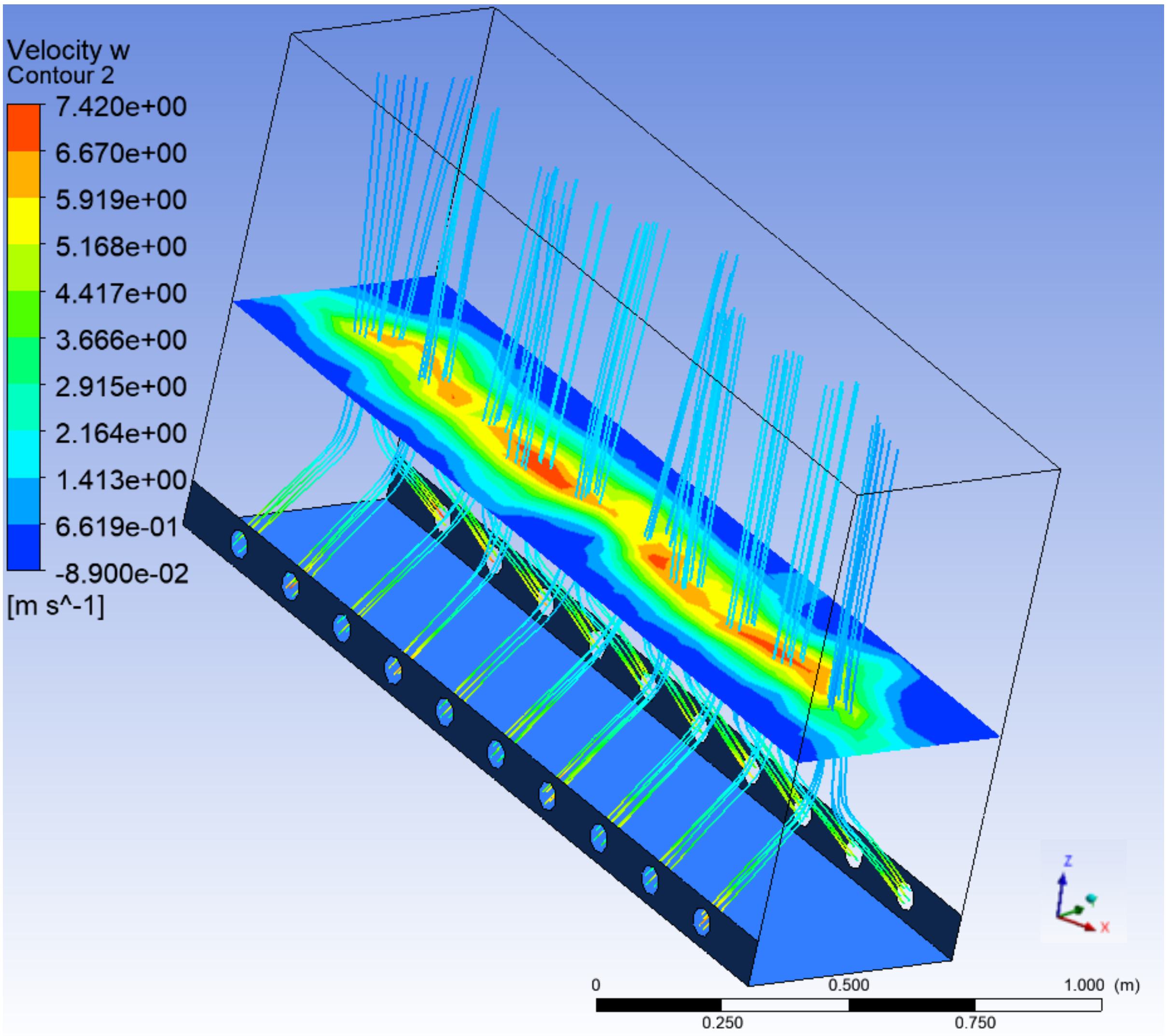



*Figure 47: Velocity profile at 0.5 m offset*

The last contour to be presented is 1 m above surface (Figure 48). The main differences observed at this height is that the flow filed is covering a greater area, as expected since the occupied area by the outflowing air is increasing proportionally to the distance from the outlet of the hoses according to Zawadzki (p. 26). As a result of this, the velocities larger than 3 m/s is also covering a greater area. The area covered by the maximum velocity at 1 m from the surface does not seem to change remarkable. On the other hand, velocities in the green color (2-4 m/s) expands in range and tends to constitute by an increasingly part of the velocity profile. We could have study the velocity profile further away from the surface, but for the purpose of this study, we are only interested in the area relatively close to surface. Therefore, how the flow field looks at the far field is not of concerns here.

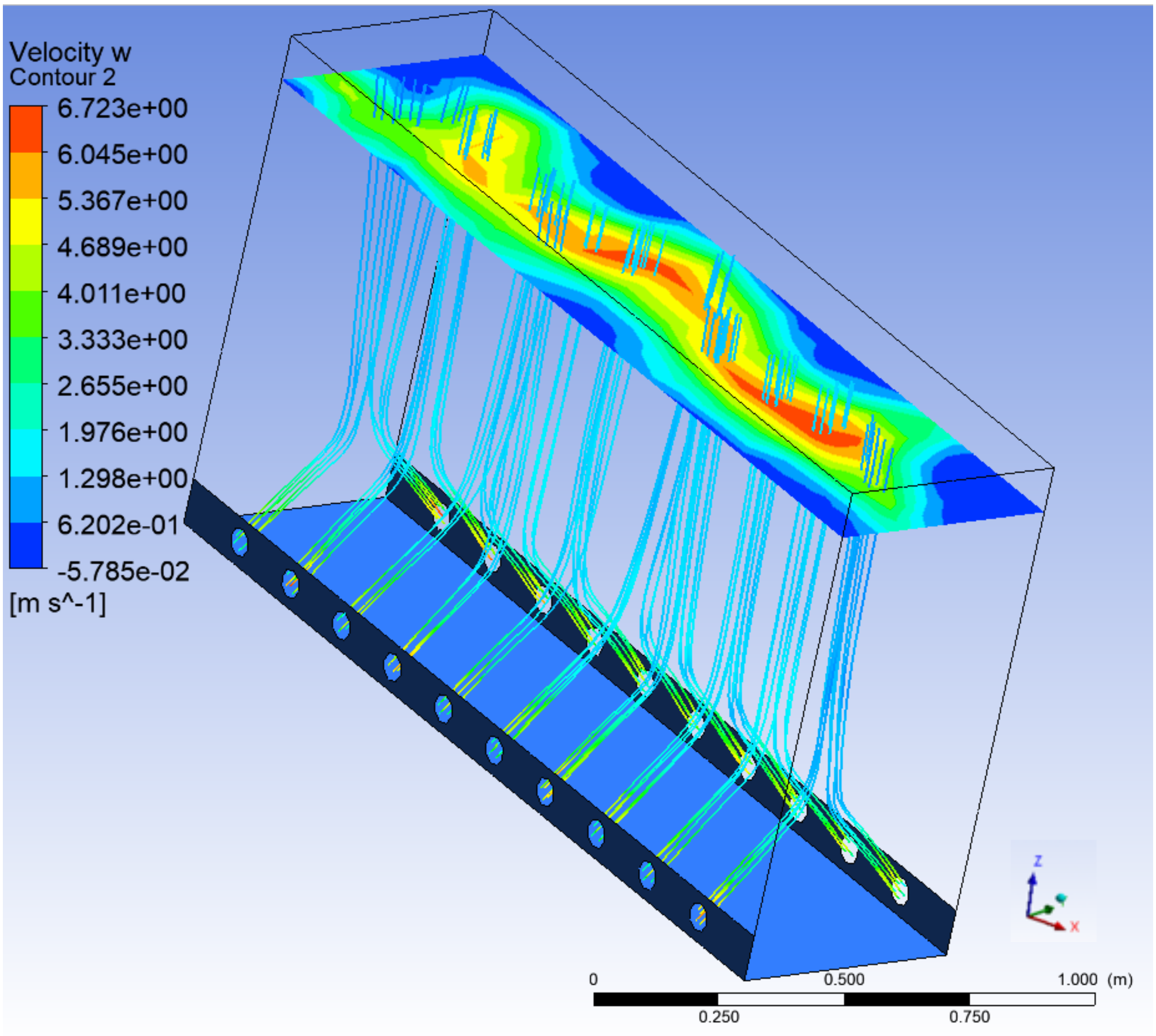



*Figure 48: Velocity profile at 1 m offset*

The reason we only consider velocity in the flow field and not pressure or energy aspect, is because we are only interested in drag force. Drag force is dependent on the velocity and not the pressure or energy. Hence, this is also the reason we only consider the convergence of velocities in the simulation part. Velocities are the first to converge, followed by pressure and at last we have convergence of energy.

## 4.3 Risk and Reliability

In this chapter, both the risk assessment and reliability analysis will be presented and discussed sequentially. As promulgated in the literature review, the risk assessment is conducted by using preliminary hazard analysis (PHA) combined with the bow-tie method and risk matrix. The bow-tie diagram is included in order to identify risk reducing barriers for all hazardous events and the risk matrices provides the overall risk picture from the risk assessment.

The PHA is divided into three sequences; pre-barrier, post-barrier and post-implementation, which establishes the whole fundament of the risk management process. Further elaboration of the sequences follows in the next subchapter. The complete PHA constitutes ten pages (Appendix D), thus, it had to be attached in the appendices. However, excerpts from the appendix with high risk priority numbers (RPN) is included, as they are not in the acceptable risk area. At last, a simplified reliability analysis, consisting of a few important principles, are presented and discussed.

### 4.3.1 Preliminary hazard analysis

This analysis method is considered to be the best suited as it is sufficient to use in an early project or design phase, where changes are still available. As this study consists of exploratory experiments, the need for adjustment are unavoidable, especially if a realization is to take place. A few elements are added to the classic PHA approach, such as an updated risk after applying the identified barriers and an updated risk after implementation of the airflow system. This will purposely provide a clearer picture of the barrier's effectiveness and also separating the three sequences mentioned earlier. In order to illustrate the positioning of the risks relative to the risk matrix, the same colors used in the risk matrices are included in PHA. Purposely the colors contribute to make the worksheet more productive, since the reader do not have to switch back and forth between PHA and different risk matrices while viewing the PHA table. The first sequence is estimated risk for each hazardous event followed by quantifying the risk by RPN (pre-barrier). Next sequence is the updated risk after identifying barriers (post-barrier) and the final sequence concerns the risk after implementation of an ideal airflow system (post-implementation).

To identify potential hazardous events associated with snow and ice accumulations on roofs, the hazards and threats are divided into eight categories. At first sight, we see from Table 5 that some of the categories could be either causes or consequence of each other and some of them are too, because one hazard could lead to another. Anyhow, the purpose of dividing it into these categories are to emphasize the context of the respective barriers and consequences. To elaborate this a little; particular consequences and barriers appears more than once in the PHA, but are caused by or reducing different hazards/threats.

*Table 5: Categorization of hazard/threat*

| Category | Hazard/threat |
|---|---|
| 1 | Snow avalanche |
| 2 | Falling icicles/ice blocks |
| 3 | People falling from heights |
| 4 | Emergency exit blocked |
| 5 | Roof damages |
| 6 | Roof leakages |
| 7 | Snow cornices |
| 8 | Extensive snowfalls |

The probability and consequence parameters are defined to calculate the RPN and to present the risk in the risk matrices. The consequences are divided into two different aspects, namely human and assets (Table 6). The consequences can be vastly different for human and assets, which is why it is viewed separately in the risk assessment. Ranking of the human consequences are inspired by the Abbreviated Injury Scale (AIS) from the International Injury Scaling Committee, referred in Bylund et al. (2016, p. 106). For assets, the ranking of consequences is considered with respect to the level of actions required. The probabilities are defined partly by qualitative document analysis (Svala, 2020; Hanssen-Bauer et al., 2015; Hjorth-Hansen et al., 2000; Pellicer, 2010; Hagen, 2012; VGTV, 2018; Eriksen, 2017) and partly through collection of statistics (Bylund et al., 2016; Kesser, 2018; 360niseko.com).

*Table 6: Definition of probability and consequence parameters*

| Probability (frequency) | | | Consequence (severity) | | | |
|---|---|---|---|---|---|---|
| 1 | Very unlikely | Once per year – A winter season can pass without any occurrences | A | Negligible | Human | Bumping into a wall or ladder, causing a small pain at the moment, but leaves no marks or harm |
| | | | | | Assets | Elastic deformation, with no need for service or maintenance actions |
| 2 | Unlikely | Once in six months | B | Minor | Human | Smaller wounds or bruises |
| | | | | | Assets | Wear and tear on the roof which does not need urgent actions or follow up |
| 3 | Occasional | Once every other month | C | Moderate | Human | Concussion and/or smaller bone fractions |
| | | | | | Assets | Tear on the roof or assets which requires actions (e.g. gutter ripped off, bended snow guards etc.) |
| 4 | Probable | Once per week | D | Major | Human | Serious head injuries, large bone fractures, internal bleeding |
| | | | | | Assets | Huge leakages, permanent deformation or destruction of critical/important equipment (require immediate actions) |
| 5 | Frequent | Daily basis - Almost certain of occurring | E | Catastrophic | Human | Critical or irreversible head injury or fatality |
| | | | | | Assets | Collapse of roof or construction |

#### 4.3.1.1 Pre-barrier risk matrix

It is identified a total of 25 hazardous events from the eight categories, where several of them constitutes risk for both human and assets. Since some of the hazardous events are divided into both human and assets risks, the total number of risks deliberated in the risk matrices are therefore 40. Numbers followed by the letters A and H is simply a way of separate risks concerning assets and humans, respectively. In the pre-barrier risk matrix below (Table 7), all the unwanted events are presented. Without any preventive or reductive barriers, majority of the events are in the intolerable section (red zone) and tolerable section/ALARP (yellow zone). As we know by now, the intolerable zone requires immediate risk reduction and events in the tolerable zone should be managed according to ALARP principle.

*Table 7: Pre-barrier risk matrix*

| Risk Matrix | | | Consequence | | | | |
|---|---|---|---|---|---|---|---|
| | | | A<br>Negligible | B<br>Minor | C<br>Moderate | D<br>Major | E<br>Catastrophic |
| Probability | 5 | Frequent | | **4.1A** | **5.2A** | **1.5A, 4.1H** | |
| | 4 | Probable | | | **1.4A, 3.2H, 5.5A, 6.4A,** | **1.3H, 1.4H, 2.1A, 3.1H, 5.1A, 5.5H, 6.4H, 7.3H** | **2.1H** |
| | 3 | Occasional | | **1.1H** | **1.1A, 6.2H, 6.2A, 7.1H, 7.1A, 8.1H, 8.1A** | **6.1A** | |
| | 2 | Unlikely | **1.2H** | **2.2H, 8.2H** | **1.2A, 2.2A, 8.2A, 8.3H, 8.3A** | **5.3H, 5.3A, 6.3A, 7.2H** | |
| | 1 | Very unlikely | | | | | **5.4H, 5.4A** |

### 4.3.2 Bow-tie method

Bow-tie method is applied to identify preventive and reductive barriers for all 25 hazardous events. The barriers derived concerns risk reduction for both human and assets aspects and are further distinguished into passive and active barriers (Table 8).

*Table 8: Barriers identified by bow-tie method*

| | **Preventive barriers** (Proactive) | **Reductive barriers** (Reactive) |
|---|---|---|
| **Passive** | 1. Internal drainage<br>2. Rows of snow guards<br>3. High friction roofing materials (e.g. granular faced asphalt composition)<br>4. Smooth roofing (slippery sloped roof) with low friction factor in order to restrict the buildup of potential energy, through sliding off smaller snow avalanches (e.g. metal roofing)<br>5. Single snow guards<br>6. Vents placed further from eaves<br>7. Cold sloping roofs (ventilates heat and moist from the building away from the surface of the outer roof)<br>8. Design: roof designed with particular attention to dominant wind direction for storms and average wind direction during winter months. This in order to reduce leeward sides of the roof<br>9. Design: Particular attention given to ultimate limit state (ULS) of the construction/roof<br>10. Design: Locate emergency exits in relation to local snow drift patterns (e.g. not at leeward side of the building)<br>11. Design: Particular attention given to prediction of snow avalanche trajectories<br>12. Design: Less complex geometry of the roof with few valleys<br>13. Design: Seams/ribs always head in same direction as potential snow avalanche trajectory<br>14. Design: Avoid signs and lights mounted at vulnerable positions where cornices are likely to form<br>15. Design: Air intake placed on a wall instead of on e.g. a flat roof<br>16. Design: Longer ventilation pipes | 1. Snow avalanche warning sign<br>2. Separated/closed off area directly underneath roof<br>3. Personal protective equipment (PPE)<br>4. Physical shielding<br>5. Fall protection belt/strap<br>6. Design: Redundancies in the construction, in this case meaning that the integrity of the building has to be maintained even if the collapsing roof tear apart supporting beams<br>7. Inwards inclined roof edges in order to reduce formation of cornices<br>8. Design: Emergency exit located where there are no adjacent higher roofs with potential of slide off snow in front of the exit.<br>9. Rows of snow guards<br>10. Single snow guard |
| **Active** | 1. Shoveling off snow from the roof<br>2. Heating wires located at eaves to prevent snow or ice accumulations<br>3. Job safety analysis (JSA) – motivated by prevention of hazards or unwanted incidents<br>4. Proper training in snow removal techniques<br>5. Heating mats to prevent meltwater to refreeze<br>6. Physically remove ice from eaves<br>7. Heating wires in front of emergency exits<br>8. Heated drainage system<br>9. Using snow removal techniques that does not require heavy equipment on the roof<br>10. Using avalanche snow cleaner (subchapter 2.8) if the roof has the required availability | 1. JSA – when the dominant motivation is to monitor/control safety through documentation (Solberg, Svensli & Albrechtsen, 2017, p. 7)<br>2. Use of lift or other machines to separate the trajectory of an avalanche from working position |

Several of the barriers identified from the bow-tie method appears in multiple events. A few barriers are acting as preventive and reductive at the same time, thus listed at both places in the table on last page. Snow guards are one of these barriers, if they are implemented to reduce the frequency of snow avalanches, they can reduce the consequences of an unwanted avalanche as well. The other barrier appearing two places is the JSA, as explained in the table, it depends on the motivation behind the usage of it.

#### 4.3.2.1 Preventive barriers

Most of the preventive barriers are passive, meaning that they are intended to reduce the frequency of the unwanted events without the need for human interactions. Some of the preventive barriers introduces new risks, such as the active barrier "shoveling off snow from the roof". This barrier was identified as a barrier to reduce the frequency of uncontrolled snow avalanches for instance, but it introduces probabilities of other hazardous events like falling from heights as well. The fact that one risk reducing barrier also can be the cause of another identified hazard, is paradoxically and indicates that the benefit may be less than the risk associated. Another example of such barrier is in this case the snow guards, if MDSD or snow load capacity is not thoroughly considered, excessive snow loads restricted from sliding off a sloped roof can end up damaging the roof. The latter is a realistic scenario for places with low enough temperature for the predicted increase in annual rainfall to be solidified (Hanssen-Bauer et al., 2015, p. 12).

#### 4.3.2.2 Reductive barriers

One quite vital reductive barrier is the "fall protection belt/strap" when conducting snow removal activities on the roof. This is, however, not frequently used by residential owners (Bylund et al., 2016) and accordingly the usage of this barrier does not seem to be more frequent for public buildings either (Pelicer, 2010; Hagen, 2012). Closing off or separate the area directly underneath roofs combined with warning signs are almost a certain winner if the goal is to avoid people getting injured by snow or ice falling from a roof. The evident disadvantages or inconvenient effects of these combination of barriers are the fact that larger areas often have to be closed off several weeks during winter season. Sometimes – from the authors experience - a whole sidewalk has to be closed off to achieve the reduced consequences by using the latter barriers.

#### 4.3.2.3 Post-barrier risk matrix

After implementation of both preventive and reductive barriers, the risk picture is considerably different (Table 9). It is important to emphasize that this risk picture is conditional to the application of all the listed barriers for the respective events and that they work as intended. Most of the events are now in the acceptable section of the matrix (green zone). However, there are still three unwanted events located in the ALARP area.

*Table 9: Post-barrier risk matrix*

| Risk Matrix | | | Consequence | | | | |
|---|---|---|---|---|---|---|---|
| | | | A Negligible | B Minor | C Moderate | D Major | E Catastrophic |
| Probability | 5 | Frequent | | | | | |
| | 4 | Probable | | | | | |
| | 3 | Occasional | | | **3.1H** | | |
| | 2 | Unlikely | **2.1H, 2.1A** | **1.1H, 1.4H, 1.4A, 1.5A, 3.2H, 5.5H, 5.5A, 6.4H, 6.4A** | **1.1A, 1.3H, 5.2A, 6.2H, 6.2A, 7.1H, 7.1A, 8.1H, 8.1A** | **5.1A, 7.3H** | |
| | 1 | Very unlikely | **4.1A** | **1.2H, 8.2H** | **1.2A, 2.2H, 2.2A, 8.2A, 8.3H, 8.3A** | **4.1H, 5.3H, 5.3A, 5.4H, 5.4A, 6.1A, 6.3A, 7.2H** | |

Comments on the risk assessment process is attached (Appendix E), here a short explanation of probability and consequence assessments are described. The three unwanted events in the yellow area are extracted from the PHA and presented in Table 10. Two of these unwanted events regards risk for humans (3.1H and 7.3H) and both of them are activities concerning snow removal activities with potentially major or catastrophic consequences. The last hazardous event in the ALARP area is concerning risk for assets, specifically the roof.

*Table 10: Identified ALARP risks from post-barriers assessment*

| **Nr. /Top event** | **Triggering event(s) (Cause)** | **Potential consequence(s)** |
|---|---|---|
| **3.1H**<br>Falling from roof while conducting snow removal activities | • Climbing towards the roof to clean away snow or ice. There are two main reasons why this could be necessary:<br>I. Risk of exceeding the maximum bearing capacity of the roof/construction<br>II. Risk associated with sudden and uncontrolled release of energy (e.g. snow avalanches or falling ice) | • Small wounds and bruises<br>• Larger bones fractured (ribs, femoral etc.)<br>• Concussion with loss of consciousness<br>• Internal bleeding and/or damaged vital organs resulting from fall injuries<br>• Critical head injuries or fatality |
| **5.1A**<br>Falling snow or ice from higher roofs | • Thaw and freeze cycle forming ice dams/icicles<br>• Various snow cleaning techniques involving heavy equipment at the roof<br>• Snow drifts<br>• Roof located in the trajectory of snow avalanche or cornices from higher roofs/buildings<br>• Interior heat loss/building heat: poorly insulated roofs | • Damage due to unbalanced snow loads<br>• Exceedance of maximum capacity of the lower lying roof (If the roof below already has snow accumulated) |
| **7.3H**<br>Injured people/personnel due to snow removal techniques conducted from underneath cornices | • Created by vortices induced at the edge of the roof, the phenomenon is usually observed at flat roofs and is a result of snow drifting mechanisms (see subchapter 2.3)<br>• Large cornices are often related to blizzards or strong winds | • Small wounds and bruises<br>• Concussion with loss of consciousness<br>• Critical head injuries with permanent damage and irreversible brain injury or fatality<br>• Other head injuries |

### 4.3.3 Risk evaluation

As we have seen from the last two risk matrices (pre-barrier and post-barrier) the total risk picture is significantly reduced after barriers are included. If we take a closer look at the matrices, we see that the general reduction in risks is due to both reduction in probabilities (prevention) and consequences (reduction). To reduce the last three events, which are still not an acceptable situation, the concept of airflows to prevent snow accumulations could be a preventive barrier. The discussion regarding the feasibility and effect of such a system, is discussed in chapter 4.4. If we assume that airflows are feasible for this purpose, this active barrier have not only the ability to get the last three events to the green zone, but also the potential to lower the risk for 13 of the remaining 37 events at the same time.

Although most of the hazardous events do not require any risk reduction, implementation of a system based on the same principles investigated in this thesis, could contribute additional redundancies in the risk reducing barriers. As mentioned earlier, the assessed risks presented in the matrices are dependent on all the listed barriers to work as intended. An airflow system could for instance contribute to keep the roof free from snow between snow guards and eaves or at limited areas of the roof directly over emergency exits/entrances – if not applied for the entire roof.

As seen from collapses in the later years, it is often elderly houses, barn or industry buildings that collapses from snow loads (Kesser, 2018). The reason is often that they are constructed according to old standards or absent snow removing leading to exceedance of critical loads. Hence, it is important to enlighten that the probability of collapses could be category 2 (unlikely) instead of 1 (very unlikely), for old houses and houses where maintenance procedures are not followed.

#### 4.3.3.1 Post-implementation risk matrix

The last risk matrix presented is the "post-implementation" which shows the risk picture after implementation of an ideal airflow system (Table 11). From this matrix we that all hazardous events are in the green zone, meaning that additional risk reduction is not necessary. However, several of the events that already was in the green area is reduced even further. As it appeared from Aven & Renn (2010, p. 121), chasing risk reduction in the acceptable area is not unnecessary if it is done with a voluntary approach. From the latter, one can interpret that it is not recommended to spend non-negligible resources to reduce the risk further. Nonetheless, if airflows are implemented as a preventive barrier for the three ALARP events in Table 9, potential reduction of the other 13 events could be seen as positive "side effects". Thus, potential reduction of the 13 acceptable events and three ALARP events, may contribute to make it justifiable and to pursue further research and development in this field of study. By justifiable in this case, we mean in terms of time, money and efficiency related to realization of such a system.

*Table 11: Post-implementation risk matrix*

| Risk Matrix | | | Consequence | | | | |
|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | E |
| | | | Negligible | Minor | Moderate | Major | Catastrophic |
| Probability | 5 | Frequent | | | | | |
| | 4 | Probable | | | | | |
| | 3 | Occasional | | | | | |
| | 2 | Unlikely | **5.5A** | **3.1H, 3.2H, 5.5H** | | | |
| | 1 | Very unlikely | **1.1H, 1.2H, 1.4H, 1.4A, 1.5A, 4.1A, 6.4A** | **2.1H, 2.1A, 2.2H, 6.4H, 8.2H** | **1.1A, 1.2A, 1.3H, 2.2A, 5.2A, 6.2H, 6.2A, 7.1H, 7.1A, 8.1H, 8.1A, 8.2A, 8.3H, 8.3A** | **4.1H, 5.1A, 5.3H, 5.3A, 5.4H, 5.4A, 6.1A, 6.3A, 7.2H, 7.3H** | |

### 4.3.4 Reliability analysis

The function analysis system technique (FAST) is a way of visualizing the functions of the system in question. We start at the left side of the diagram with a main function and simply ask *how* this function is intended to be accomplished (Figure 49). We ask the same question until we get the desired level of details. The diagram can be used the opposite way, then by asking *why* for each function (Rausand & Høyland, 2004, p. 73). A detailed analysis of the system is important in relation to assess the reliability of the system. If we do not know the required functions, we do not know the extent of what can go wrong. As declared earlier (2.6), system failure in this context is defined by functions no longer performing as required.

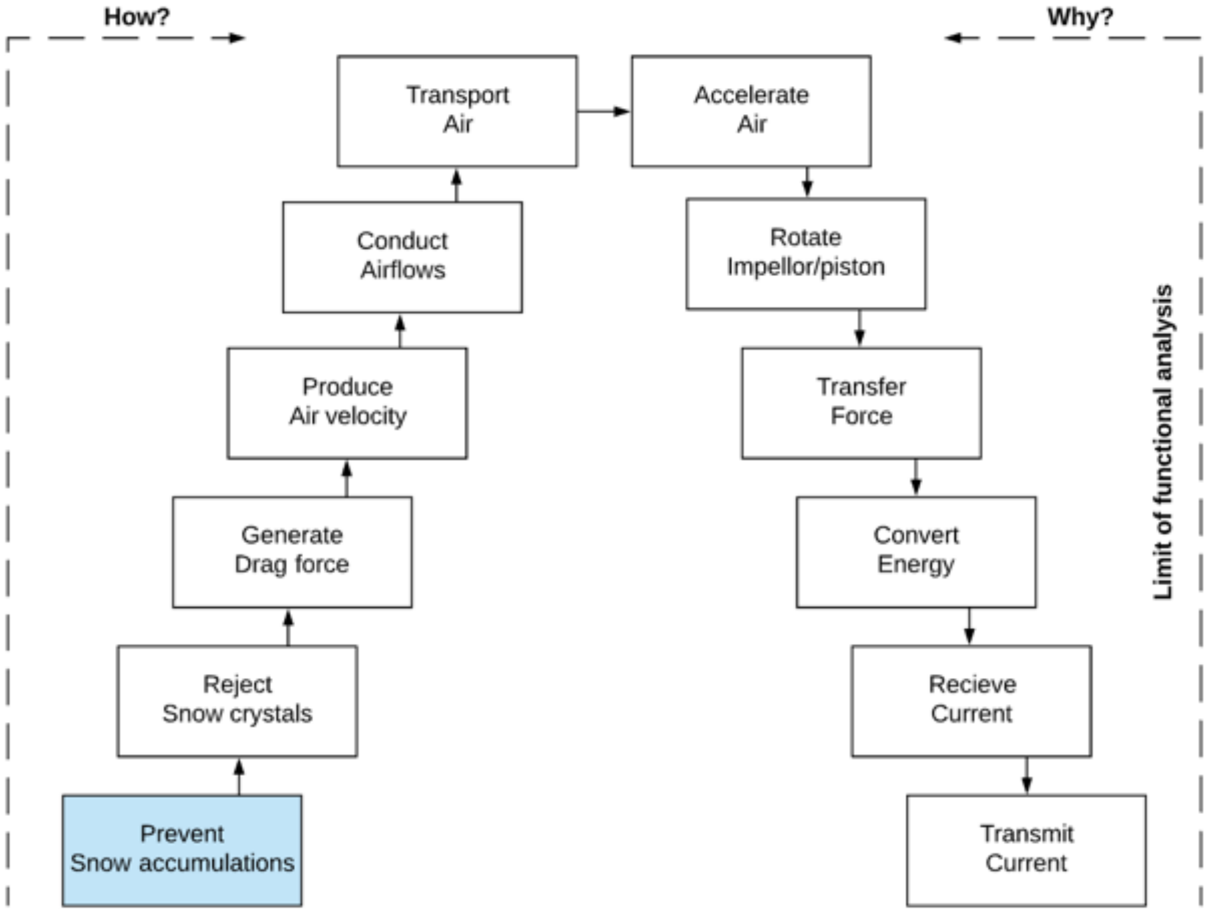



*Figure 49: FAST diagram*

Since a system like the one in question in this study requires high reliability, it should be *designed for maintenance*. The reason why it is recommended to not *design out maintenance* in this case is because of the high costs associated with the required reliability for all parts in the system, given that it has to operate at all time during snowfall. However, the system should be designed for relatively long maintenance intervals, perhaps same interval as the roofing, as it would possibly make the implementation more attractive in a pragmatic point of view. As we saw in chapter 2.6.1, there will always be a trade-off between R&M, which is why maintainability should be given the same attention as the desired reliability. The most likely scenario is, perhaps, that an airflow system would participate to reduce risks along with other barriers. If we consider all risk reducing barriers as one system, then the implementation of the airflow system would increase the system reliability and add redundancy to the system (Equation 17). This is because the airflow system would be added as a subsystem in parallel (Figure 50) to the other subsystems (barriers).

*Equation 17: Parallel system reliability (Yuan, 2018, p. 20):*

$$R_S = 1 - (1 - R_1)(1 - R_2)\dots(1 - R_n) \tag{17}$$

Where $R_S$ is the system reliability and $R_n$ is the subsystem reliability, which in this case are the barriers.

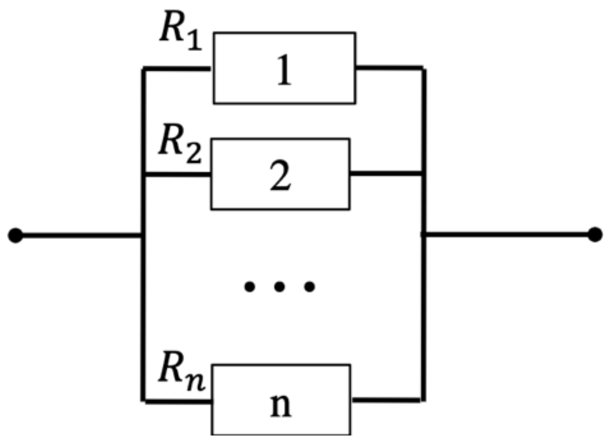



*Figure 50: Subsystems in parallel (Yuan, 2018, p. 20)*

## 4.4 Experiments

In this fourth and last aspect of chapter 4. Result and Discussion, a review of the results from the five experimental cases presented in Table 3 takes place and are discussed consecutively. Further, the aim and objective for the experiments (chapter 1.2) will be discussed in this chapter. As mentioned earlier, the analysis methodology for the experiments is visual analysis, which in this case means that the figures in the following are image sequences from the video in Appendix A. As the image sequences from the attached video occupies a whole page per sequence, it has been limited to maximum three image sequences per case. This does not, however, affect the possibility for a productive discussion. Nevertheless, it is recommended to view the attached video in addition to the selected images in this chapter. Applying airflows from only one side of the model as stated in chapter 3.4 was not done, the reason was simply that it was calm weather with no dominant wind direction during the experiments.

The head loss for the experiment setup is relatively low due to hydraulically smooth regime. The Reynold's number (Re) varies from 25 000 to 140 000 throughout the system, confirming that the fluid flow is turbulent. However, from the outlets, Re varies between 25 000 to 51000. The head loss determined from equations listed in chapter 2.4.3, gives us values between 9 000 and 10 000. Since head loss is pascal per meter, we see that this equals about 0.1 bar per meter hoses. This is an important consideration if the system is to be realized or for further studies.

### 4.4.1 Case A

Case A is the only scenario where it is four hoses operating at the same time. As we saw from the CFD model (Figure 28), the numerical part of the study relied on several outlets at each side of the model. As case A have two outlets at each side, it can be considered to be the scenario most comparable to the simulation part. However, this does not make the other cases useless, as they all have different properties and initial conditions. As we see from the first figure from case A (Figure 51), the red circle follows a single snowflake falling towards the ground. The snowflake's trajectory from image 1 to 4 is not a normal path as it falls towards the surface with approximately 60 degree relative to the ground (image 1) and is rejected before reaching the surface (image 2). The crystal is then accelerated in the opposite direction as it originated from (image 3). At the end of the sequence, we see the same crystal at its way beyond the possibility to land at the surface of the model. The snowflake is blown away in approximately the same angle as it approached when falling freely (image 4). However, this is one of the scenarios where the snowflake behaves perfectly according to the empiricism, which was not always the case.

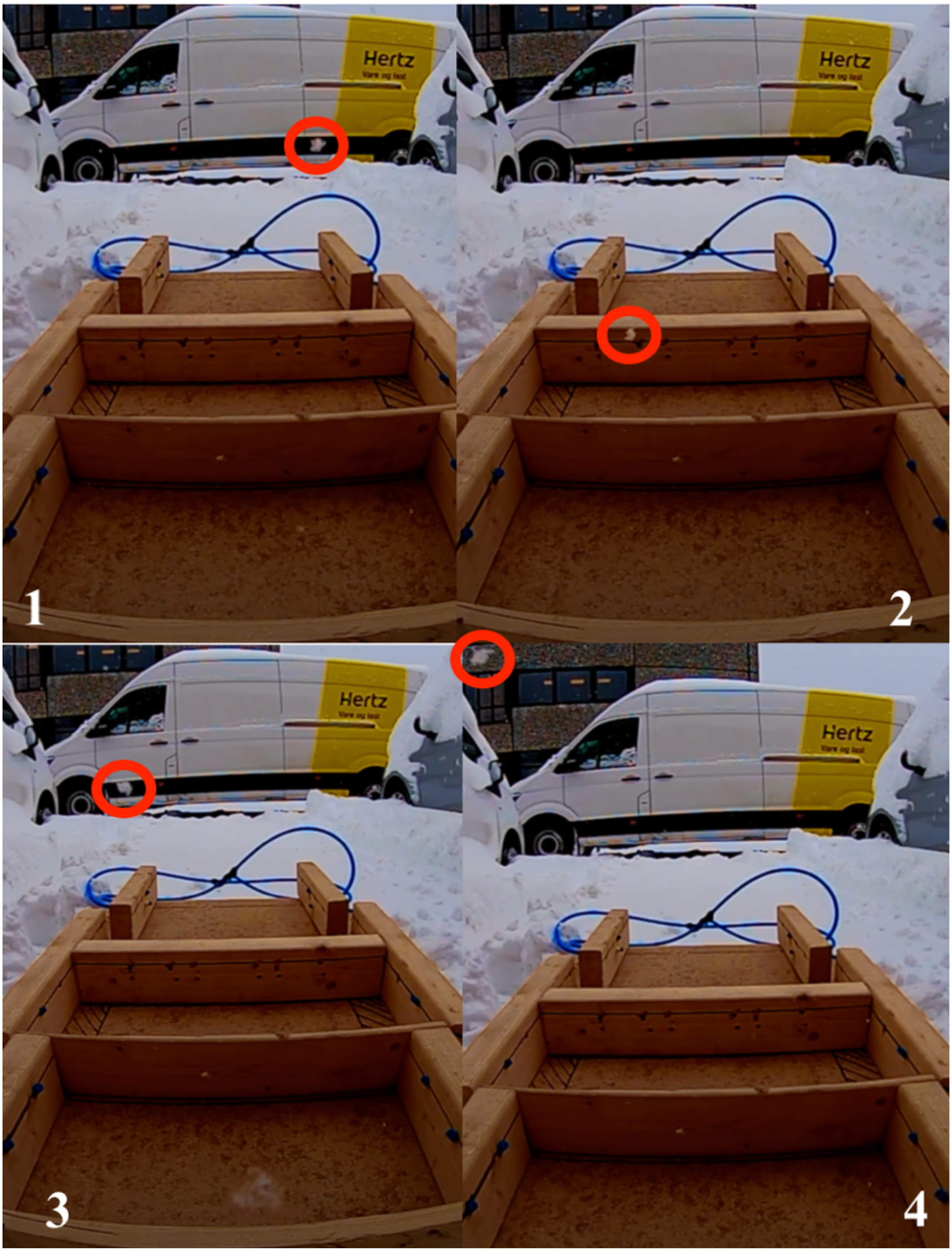



*Figure 51: Image sequence 1 - Between 0:24-0:28 in Appendix A (Tromsø, 2020, 31. March)*

The next figure shows another scenario, where the snowflake avoids the flow field from the perpendicular flow at first, and then hits the airflow closer to the surface where the velocity is greater (Figure 52). As we saw from chapter (2.4.1), the velocities closer to the outlets are significantly greater than the corresponding velocity for the middle point of the model. As a result of the sudden impact of high velocity air, the snowflake is blown into pieces and ends up at the surface anyway. The latter occurred a few times throughout the experiments, which can imply that too high air velocities will only crush the snowflakes into smaller pieces which ends up at the surface anyway.

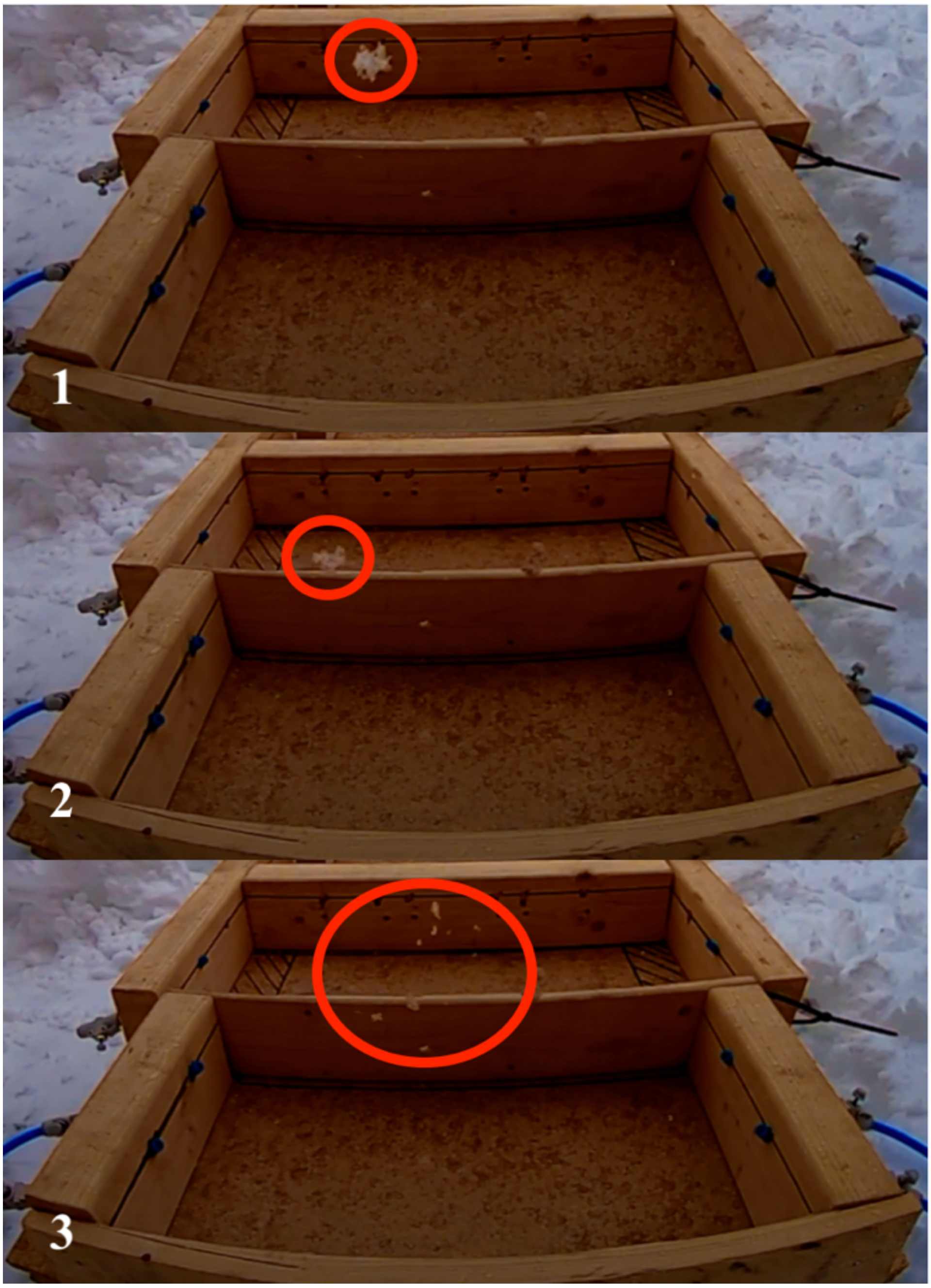



*Figure 52: Image sequence 2 - Appendix A between 0:35-0:39 (Tromsø, 2020, 31. March)*

In the last figure from case A, it was quite heavy snowfall and as in the two previous figures, there was mainly large dendrites present. The characteristic snow crystals are according to the Nakaya diagram, produced when there is high level of supersaturation and temperatures either close to zero or between 10 and 20 degrees below zero (Figure 2). At this day, the temperature was close to zero at sea-level and humidity ca. 100%, which very accurately lead to formation of dendrites.


*Figure 53: Image sequence 3 - Appendix A between 1:25-1:30 (Tromsø, 2020, 31. March)*

Throughout the experiments, the majority of the falling snow was larger snowflakes (Figure 53). We see that the snowflake in the figure above is split into smaller pieces as it is blown away. It seemed like the snowflakes had to fall straight towards the centerline of the airflows to be efficiently rejected from falling onto the surface. As mentioned in chapter 4.2 CFD Analysis, the velocities have to be higher than the minimum of 3 m/s in reality. Not only because of extern wind influence, but because of snow crystals forming larger snowflakes, which have a larger mass and thus require larger drag force in order to reject it from falling to the surface.

### 4.4.2 Case B1

This case has the same properties as case A, except that there are only two outlets. It was not groundbreaking differences from case A and B1, besides that there was fewer snowflakes interacting with the airflow. Since two outlets covers a narrower area than four outlets, more snowflakes made it to the surface of the model, even though the velocity is grater with only two outlets. The increased velocity seemed to only affect how far from the surface the snowflakes are influenced by the airflows (Figure 54). We do not need to alter the direction of falling snow at a greater distance from the surface, rather more accurate closer to the surface.

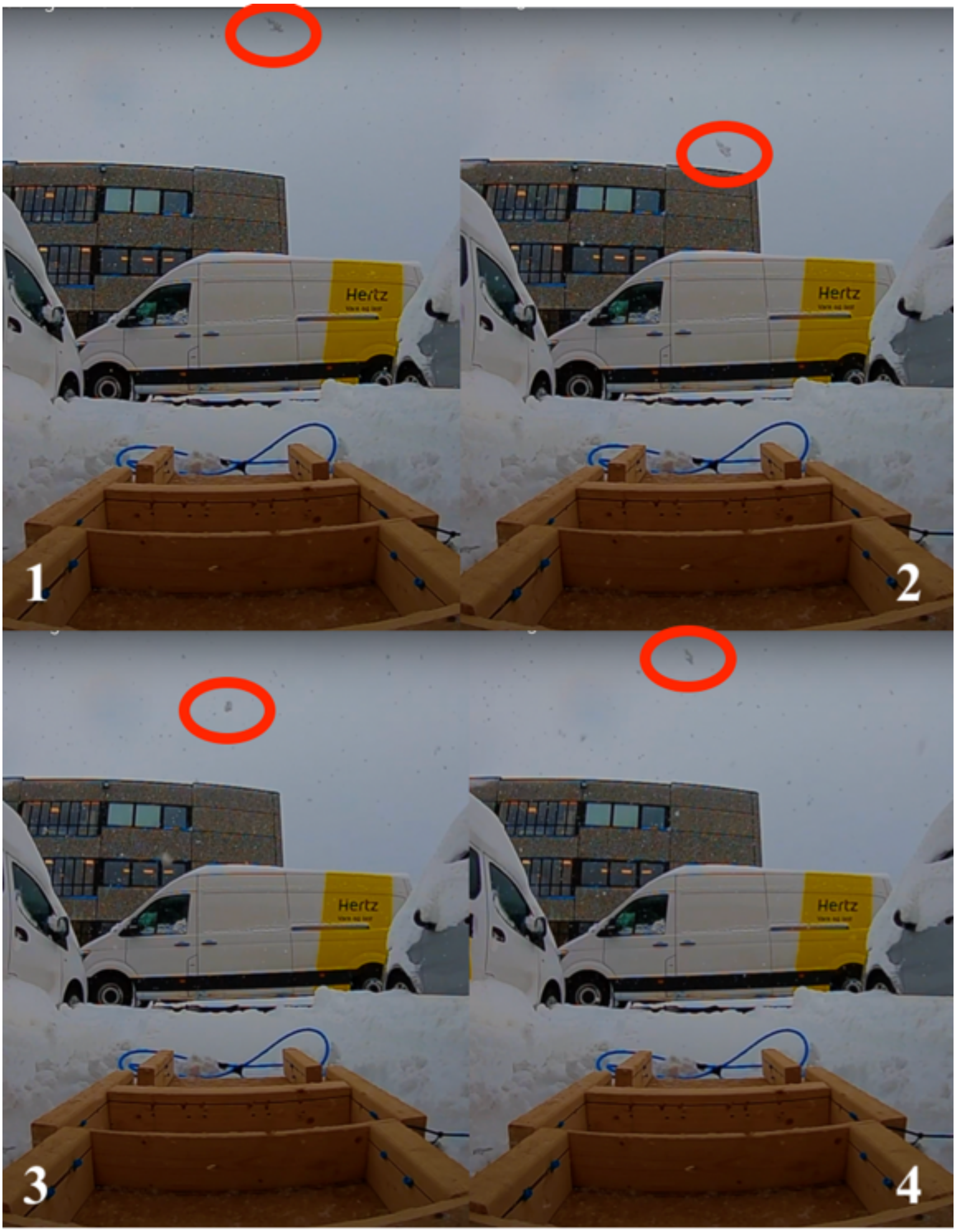



*Figure 54: Image sequence 4 - Appendix A between 1:57-2:01 (Tromsø, 2020, 31. March)*

### 4.4.3 Case B2

This case is the only one where we applied airflows in a pattern which were not simulated at any point. As it implicitly may have emerged at this point, case B2 was not planned from the beginning and was included in the study to compare it to the other perpendicular flows. It is safe to say that this was the case with fewest snowflake interactions (Figure 55 & Figure 56).

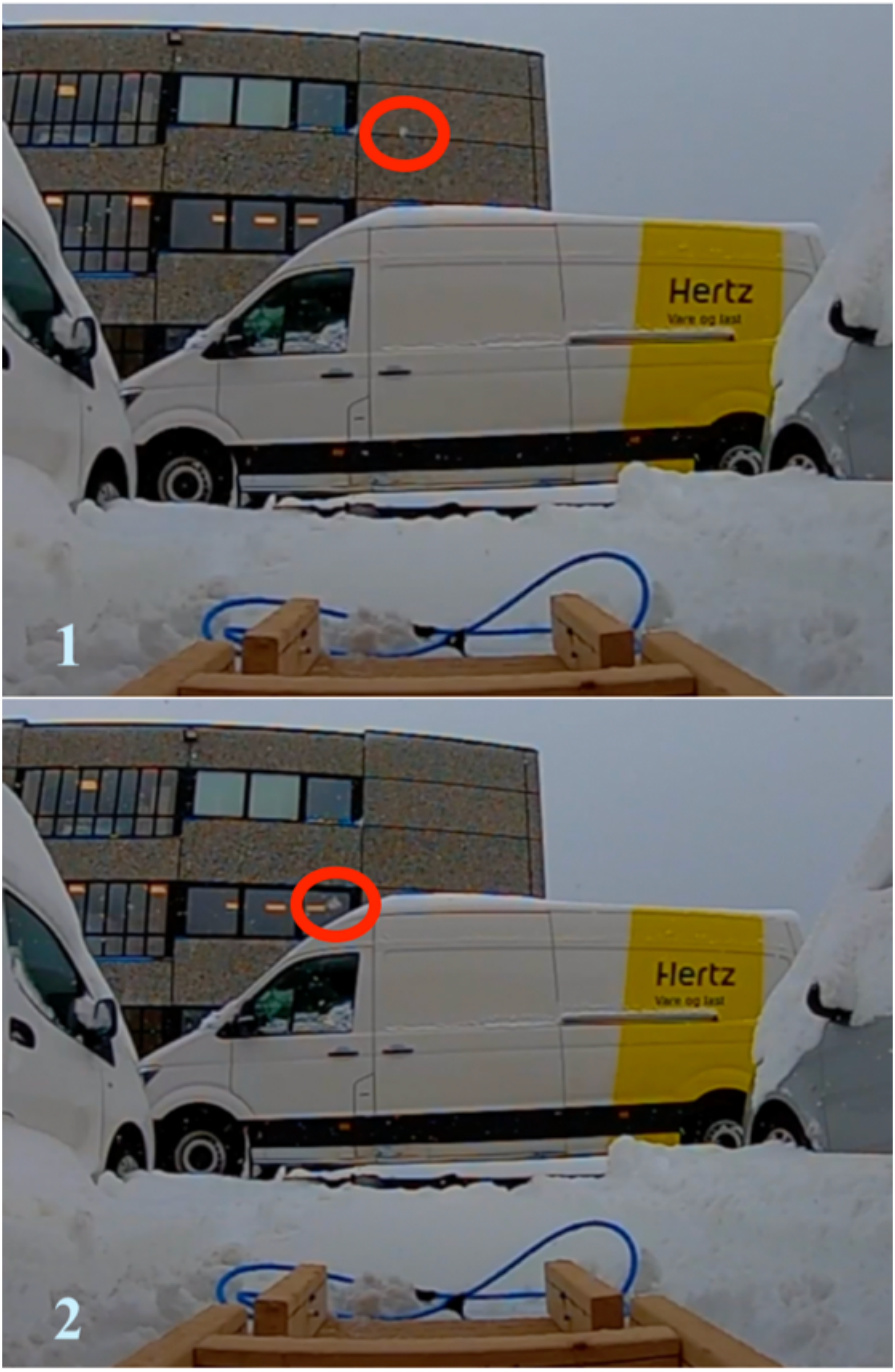



*Figure 55: Image sequence 5 [1/2] - Appendix A between 2:22-2:24 (Tromsø, 2020, 31. March)*

One reason for the latter could be that the area covered by airflows above 3 m/s – directly above the surface of the model - is greater with perpendicular airflows than parallel airflow. With perpendicular airflow, the flows from each side meets at the middle and the characteristic cone formed airflow (Figure 5) is spread over a larger area after impact with the opposite airflow (Figure 48).

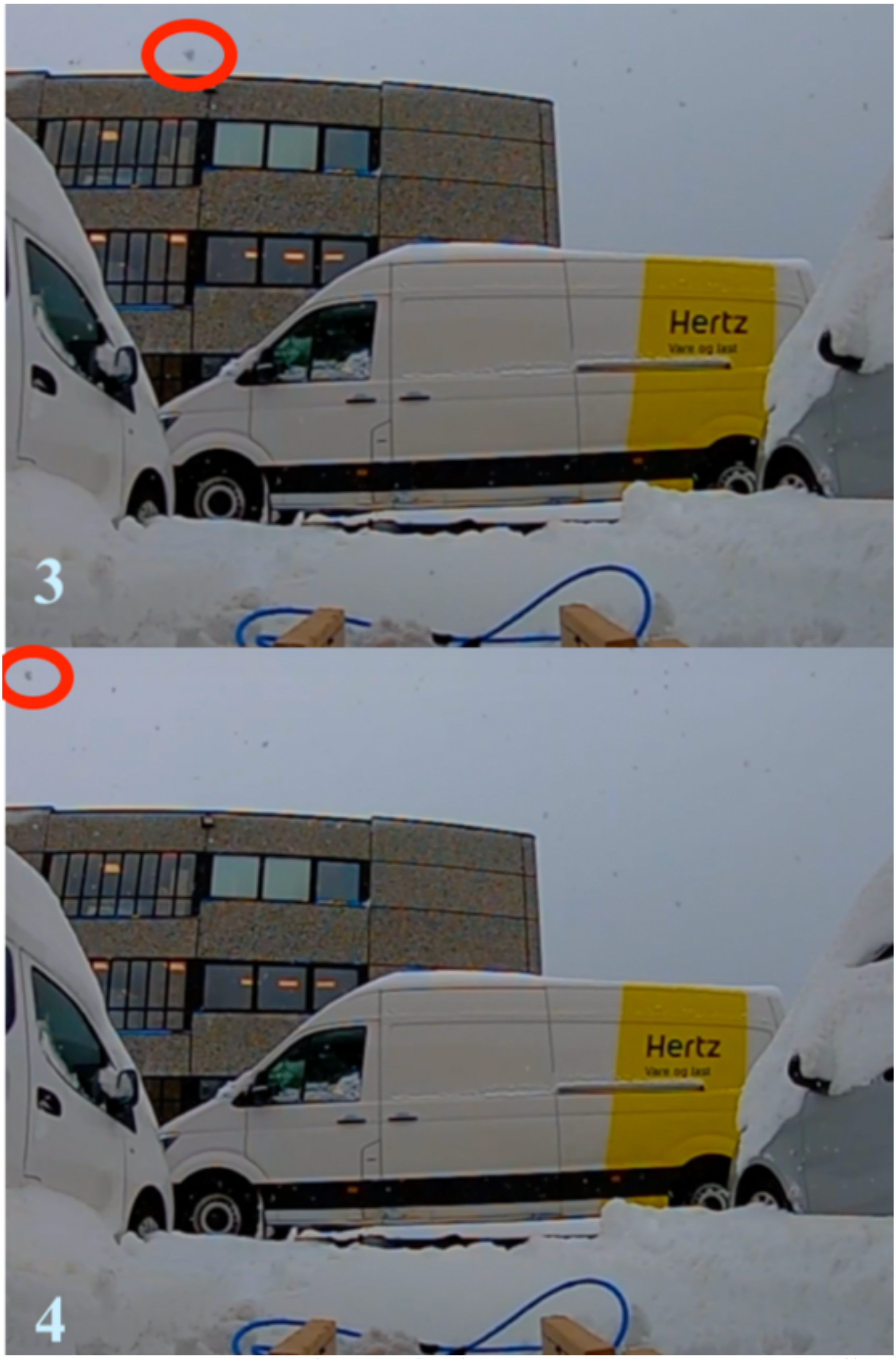



*Figure 56: Image sequence 5 [2/2] - Appendix A between 2:22-2:24 (Tromsø, 2020, 31. March)*

Case B2 is similar to B1 by how far from the surface the snowflakes are affected by the airflows. In case A, the snowflakes rejected fell closer to the surface before they were blown away.

### 4.4.4 Case C

Case C along with A had the most interactions with falling snow. Although the intensity of the snowfall varied throughout the experiments, case A and C was the most successful in order to reject incoming airborne snow.

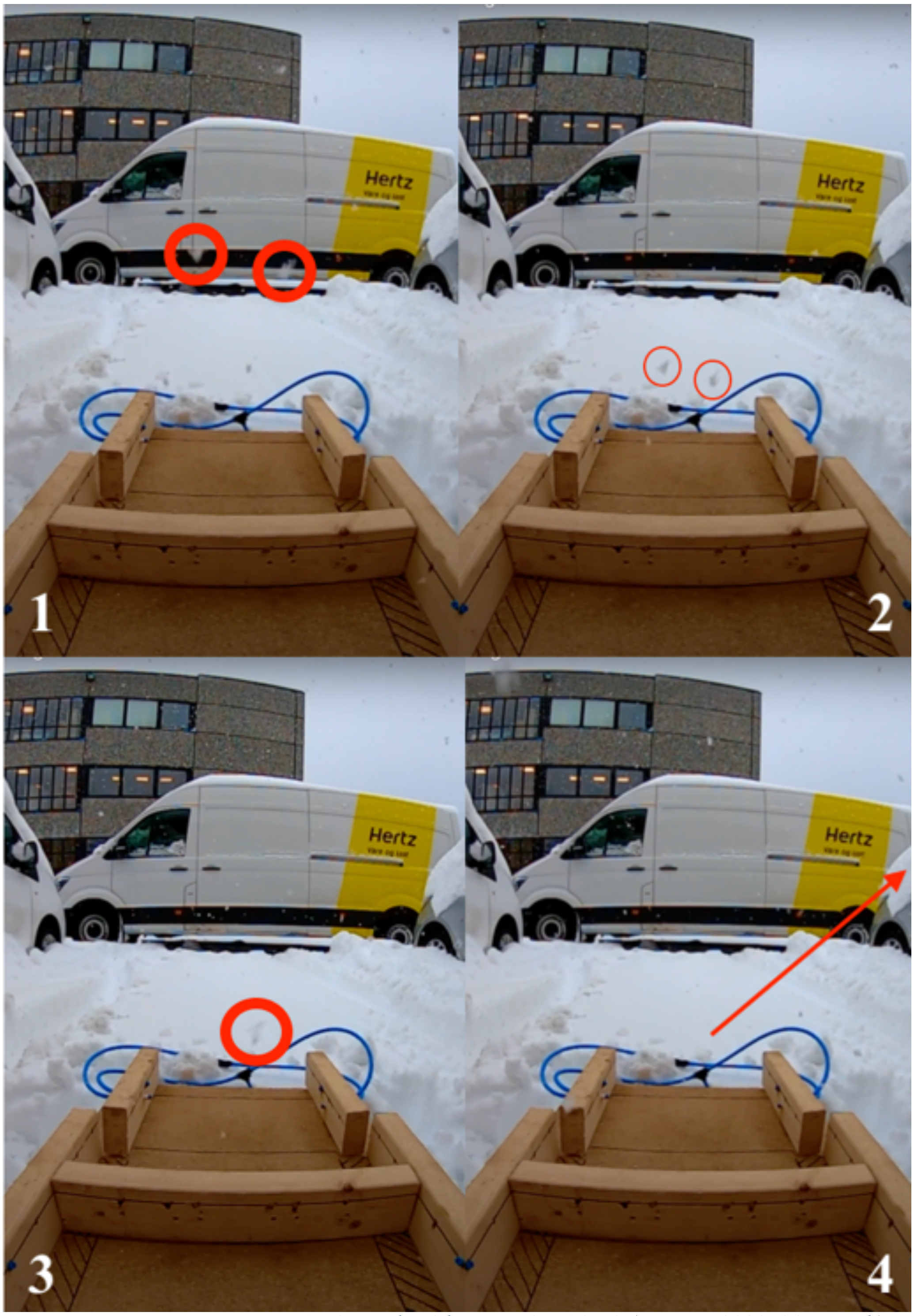



*Figure 57: Image sequence 6 - Appendix A between 2:56-2:58 (Tromsø, 2020, 31. March)*

In case C, the distance between the outlets are increased by 10 cm. The velocity from the two outlets are equal to B1 and B2. From Figure 57, we saw two separate snowflakes rejected at the same time and pulverized as they were blown away from the surface.

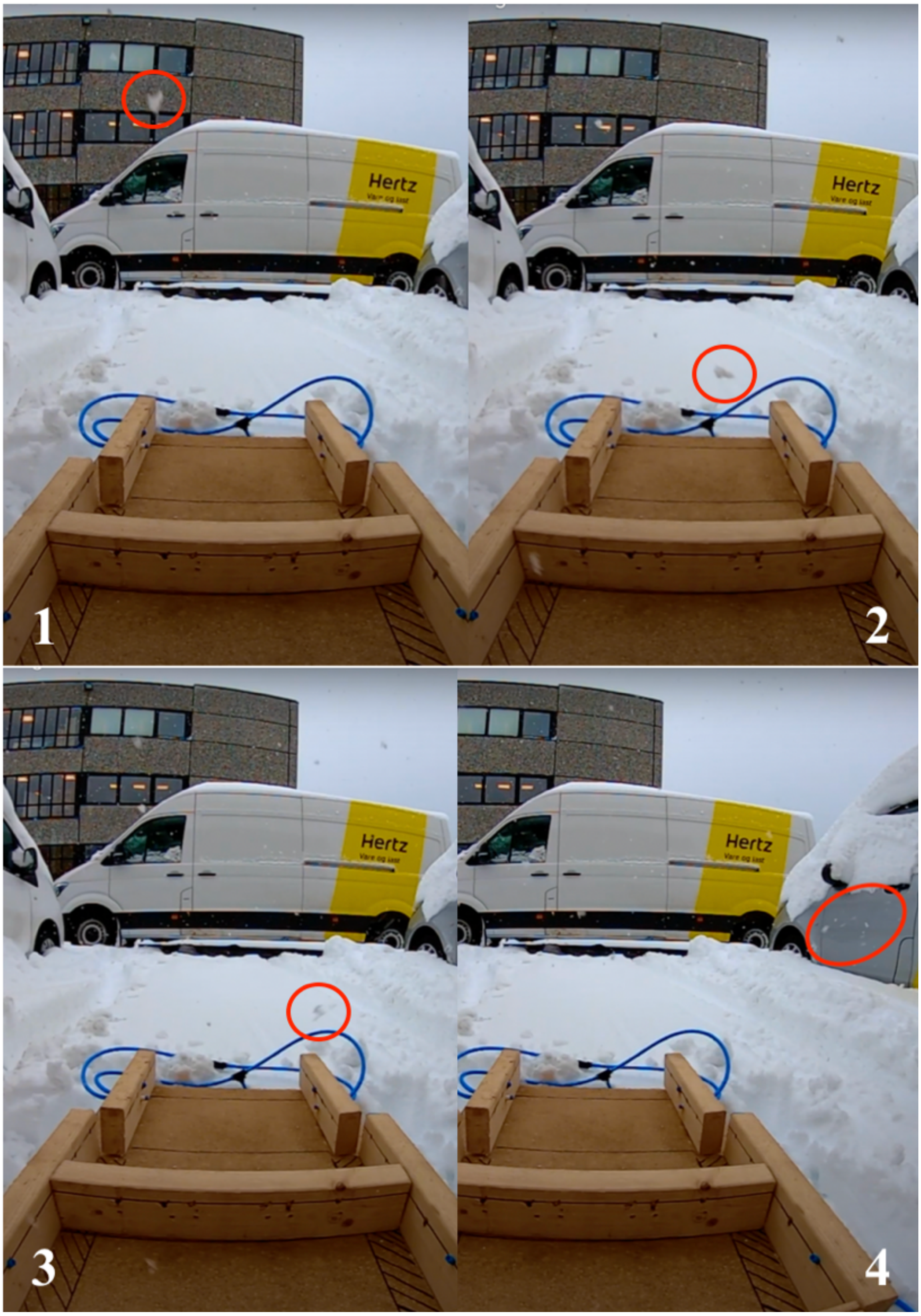


*Figure 58: Image sequence 7 - Appendix A between 3:02-3:04 (Tromsø, 2020, 31. March)*

Figure 58 is very similar to the previous figure, as the snowflake is crushed into pieces here too, before it is blown away. From these perfect interaction between airflow and snowflake, it seems realistic to achieve the objective of the experiments, which is to blow away the snow before it reaches the surface. However, there are also many snow crystals and snowflakes that is not rejected before they reach the surface. The latter is not easy to see from these images since the temperature was just above zero degree Celsius, making the snow melt short time after landing on the plywood plate.

The last image sequence from case C (Figure 59) shows that the velocity has the potential to blow away snowflakes quite far from the outlet. An interpretation we can make of this, is that the velocity is more than adequate to blow away snow crystals, even large snowflakes, at a relatively long distance. The distance from the snowflake to the outlet is about 1 meter, this implies that the falling snow can be prevented from reaching the surface if the airflow has a sufficient spread.

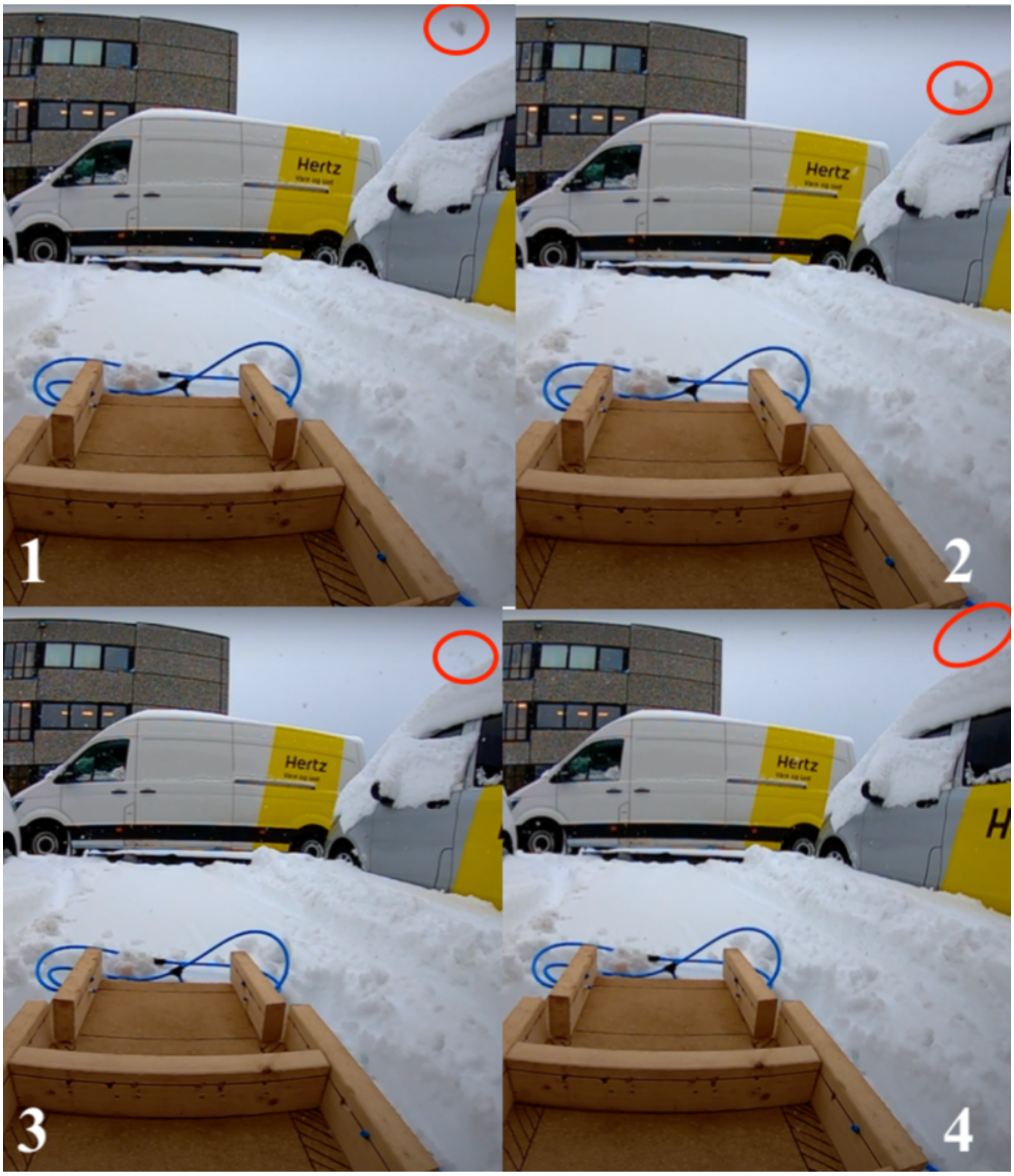



*Figure 59: Image sequence 8 - Appendix A between 3:13-3:15 (Tromsø, 2020, 31. March)*

With use of a nozzle or other ways to expand the area covered by airflows, achieving a higher level of rejected snowflakes is realistic. By expand the area covered by airflows, we mean modifying the characteristic cone formed airflow to a more elliptical or flatter airflow in the horizontal direction. The aim for the experiments is achieved, firstly, in the way that airborne snow is being rejected with the precalculated drag forces. Secondly the flow field seemed to behave in the same way as it was intended, according to the CFD simulations. The empirical velocity distribution, maximum velocity and radius of the airflow also seems to correspond to the visuals from the image analysis and initial velocity measurements. Before conducting any of the experimental cases, the velocity and spread of the airflow was measured using the same anemometer used for initial tests of hoses and manifold in subchapter 3.5.1.

### 4.4.5 Case D

Case D is the last of the five experimental cases and the only one where it was used 10 mm hoses (Figure 60). The distance between the two outlets in this case is the same as for case A, B1 and B2. From the figure next page, we follow the trajectory of two snowflakes, and it looks similar to several of the previous figures recently presented. Even though the $V_{xm}$ is grater for case B1 and C, the empirical velocity for case D is decreasing less from the outlet to the middle point of the surface than the other cases. The reason for this is found by viewing the airflow cone, which is well known by now. With a wider outlet, the airflow starts off in a wider distribution than the 8 mm hoses and ends up maintaining higher velocity along the centerline of the flow - relative to the $V_0$. In terms of efficiency, the 10 mm hose appears to reject incoming snowflakes in the same way as case B1 and C. Case B1, C and D have the highest $V_{xm}$, this can also be seen from the way the snowflakes interact with the airflows. Further, many of the snowflakes are crushed or pulverized immediately after encounter with the airflow, which only appears to be a negative effect if it happens close to the surface.

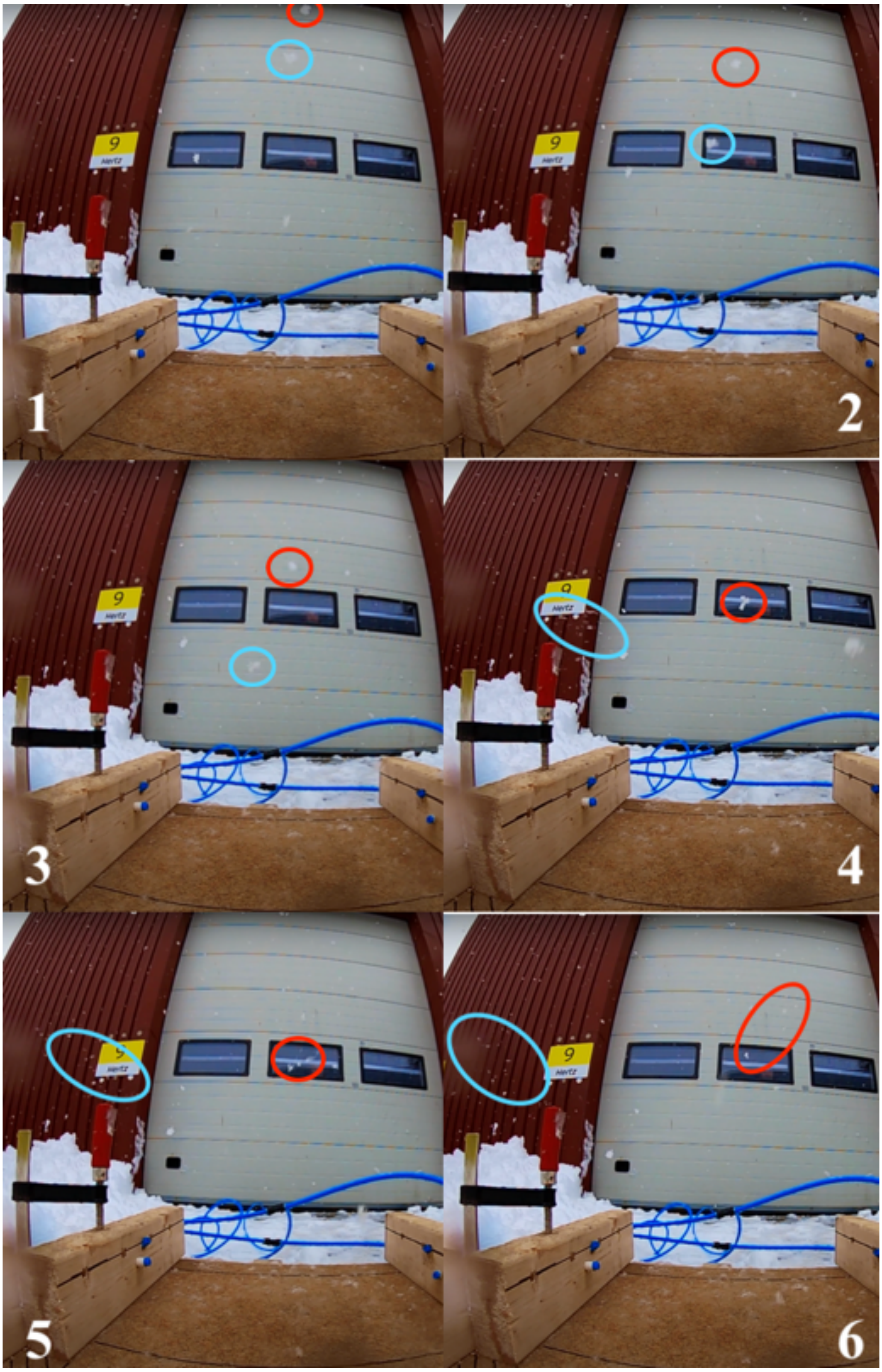



*Figure 60: Image sequence 9 - Appendix A between 3:42-3:44 (Tromsø, 2020, 31. March)*

### 4.4.6 Expanded polystyrene (EPS)

As mentioned in the methodology, the "bonus" experiment using EPS was conducted while waiting for snowfall. The EPS behaved very similar to the real snowflakes while influenced by airflows. One important finding from this extra experiment, was that the EPS - just like the snowflakes – was rejected with direct impact from the airflow, but somehow found its way around in other cases. It was not easy to see how this was possible with the snowflakes, but with EPS, it was a clearer pattern as it was not any external wind to disturb the trajectories (Figure 61).

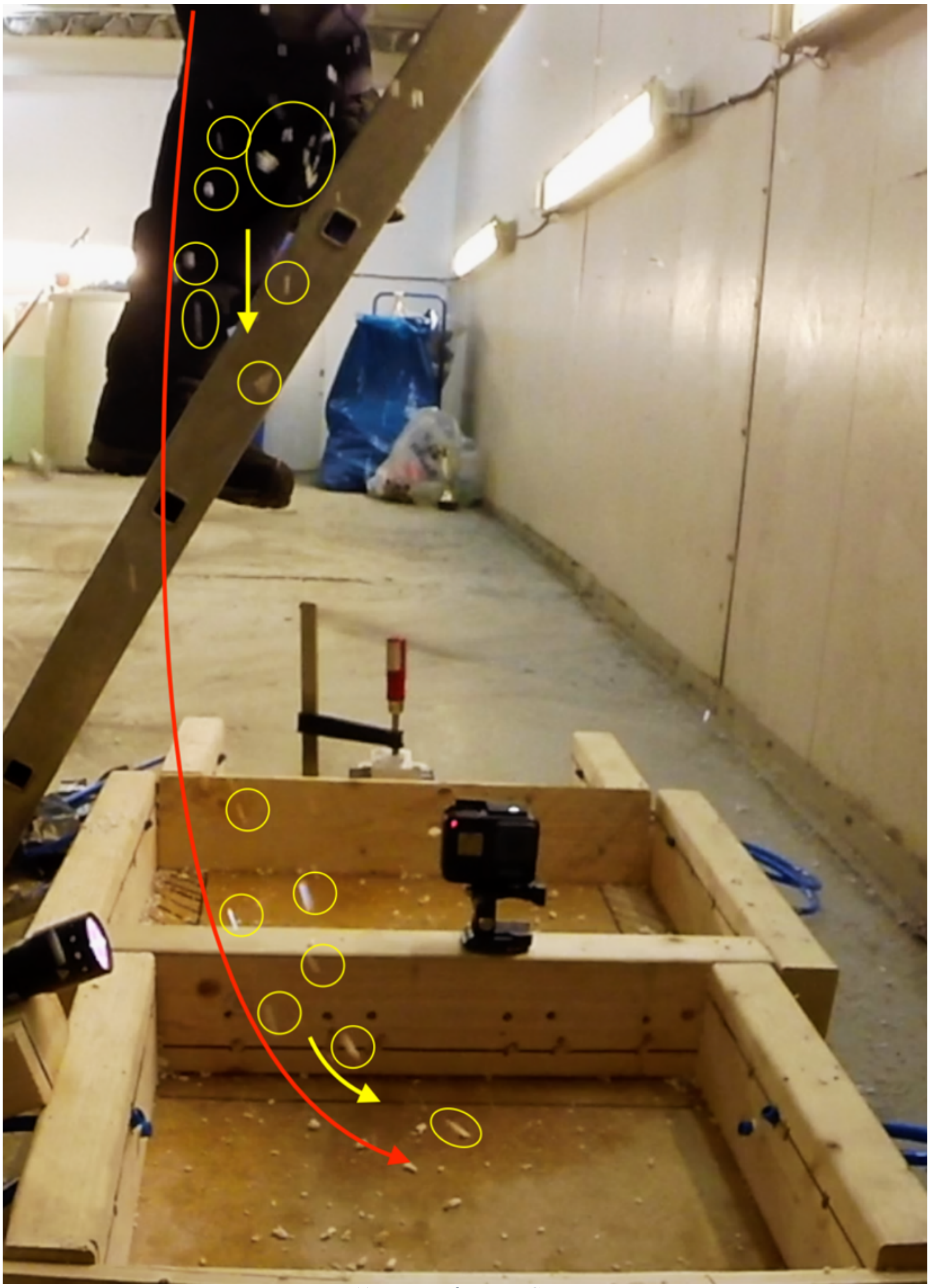


*Figure 61: Image from EPS experiment*

It seems like the EPS flakes are pulled underneath the airflow. An explanation to this phenomenon could be the fact that the air flows from higher pressure areas to lower pressure areas. The lower pressure area is created underneath the airflow due to driving potentials (Mulley, 2004, p. 65). A possible solution to this problem could be to spread the airflow in a more horizontal direction as proposed in chapter 4.4.4. However, if the latter problem would occur in a full-scale experiment – with 6 or 12 outlets at each side - we do not know for sure.

### 4.4.7 Evaluation of the experiments

The results from the last case (D), may seem to point towards benefits of using larger outlets, since the velocity decreases less with larger hoses, relative to its initial velocity. This means that we can lower the initial velocity significantly by using larger outlets and maintain sufficient airflow velocity at the same time. The latter also implies that pneumatics my not be the best fitted method to use for this study's purpose, as it would require an inconveniently large pressure tank to provide steady airflows. Hence, it is perhaps more realistic to use fans (impellers) in order to achieve a more efficient and justifiable airflow system.

The principle solution researched in this thesis is based on drag force and thus also by air velocity. As more thoroughly explained in chapter 3.5 Experiments, pneumatic equipment from Festo combined with a compressor as the source, made the setup less complicated. As to accomplish the objective of the experiments, this approach was considered to be suitable. It was not said to be the most efficient method for realizing a system that meets the overall aim and objective. However, the method appeared to be the most convenient for testing the fundamental concept of the thesis and accomplish the aim and objective for the experiments.

A few experiments were conducted during the night with temperatures just below zero. The amount of snow accumulated directly underneath the airflow was slightly less than the adjacent surface, at its best (Figure 62). However, the compressor was not able to sustain adequate velocities for more than a few minutes at the time. Therefore, it is hard to say if there would be any differences if the source was able to sustain a constant flow over a longer period of time. The phenomenon revealed in the last chapter (4.4.6), could be a contributing explanation for observation in the figure next page. Further, the results from the experiments would probably be different if it was possible to conduct the full-scale experiment shown in Figure 40.

*Figure 62: Accumulated snow at surface of test model (Tromsø, 2020, 28. March)*

## 4.5 Comparison of Empirical, Numerical and Experimental Results

Comparison of the three fundamental aspects of fluid dynamics are conducted in this chapter and discussed consecutively in relation to the aim and objective declared in chapter 1.2.

We see from the CFD simulations that the area covered by 2-4 m/s increases with distance from the outlet, which we have seen from the empiricism as well. The area covered by sufficient velocities is decreasing in relation to the airflow cone (Figure 45), however, it increases in relation to the contour areas seen in Figure 46-47. If we are to accomplish a larger area covered by sufficient airflows, the airflows have to be spread over a larger area. The results from the experiments also seem to support this interpretation. As it appeared from the experiments, the snowflakes were only rejected at a narrow space in front of the outlets. Further it was discussed in chapter 4.4.4 Case C, that a nozzle could be applied to make the airflow wider.

Determining drag forces from 3 m/s, rather than 27 (preliminary study) or maximum velocity ($V_{xm}$) determined from the outlets, was done mainly because of airflow diffusions. The cone formed airflow is theoretically covered by velocities greater than 3 m/s at 29 to 45 % of the cross-sections presented in Table 4 and illustrated in Figure 45.

Further, larger outlet resulted in less decreased velocity, relative to its initial velocity $V_0$, this also seemed to apply for the experiments. Case D was the only case where it was used larger outlets. From the analysis of the experimental data, case D seemed to obtain the same velocities as the other cases with two outlets. This interpretation comes from the fact that we know the velocity from the 10 mm outlet is lower from calculations (Table 4) and it is not any less efficient in terms of rejecting incoming snow.

Throughout the experiments, the test model was not able to prevent the snow from accumulating at the surface. Driving potential, down-scaled experiments, inadequate source of airflow could be some of the reasons to explain these results, as the numerical and empirical results looked more promising. Another explanation, that would probably lead to less snow rejected, is the results from wet snow conditions and drag force coefficient from 3 m/s. From these results (4.1.1) we saw that the average drag force from wet snow conditions and 3 m/s velocity was smaller than the average gravity force from all the snow crystals (Equation 15). The same was the case for Equation 16, minimal drag force coefficient ($C_D$) combined with 3 m/s velocity. These empirical results mean that we will need slightly higher velocity to accomplish the requirement of $F_G < F_D$, when determining the average from all snow crystals in wet and/or minimum $C_D$. Nevertheless, the snowflakes actually interacting with the airflows, seem to behave as determined. The objective for this thesis is to contribute with a principle solution to prevent snow from accumulating. It is safe to say that the solution is not ready, however, the potential for improvements advocate that further feasibility studies are not a waste of time.

## 4.6 Research questions

The research question established in chapter 1.3 are discussed in the following. Moments from literature review, empirical, numerical and experimental method and results is used where it is relevant in attempt to answer the questions.

- **What risks are associated with accumulation of snow on the roofs?**

This research question is not arbitrary discussed firstly, as the risks associated with snow accumulations on roofs are the motivation for this study. We have presented and discussed related risks throughout all main chapters and the complete list of identified hazardous events is presented in its entirety in Appendix D, with related comments in Appendix E.

We have identified two different aspect of risk in this the risk assessment, which accordingly are risk for human and risk for assets. From literature review (2.7.4) we saw that falling from heights during snow removal is a serious risk for people. Further we also identified risks for assets as a result of snow removal from roofs. All the risks identified during the risk assessment were categorized in Table 5 (p. 84) to give an overview. After the risk assessment, three hazardous events were still in the ALARP zone. Falling from roofs or get hit by snow or ice while located underneath the roof, appeared to be the highest risks remaining after conducting the risk assessment. By the implementation of an ideal airflow system, these remaining threats can be removed, as well as additional risk reduction of potentially 13 other events in the green zone.

- **How changes in weather conditions effect snow accumulation?**

Weather conditions is the reason we have to deal with all risks identified in this study and it controls how the snow is accumulating on the roof, along with the roof properties. As we remember from the Nakaya-diagram (p. 23), the weather conditions in the form of supersaturation, water saturation and temperature determine the formation of snow crystals. The different types of snow crystals have different properties and require different drag force (3.4.1 & 4.1.1) in order to prevent them from landing at the given surface. Changes in the Nakaya-diagram is closely related to changes in drag forces determined from Equation 15 and Equation 16. The different type of snow crystal does not only look different, but the size and amount of vapor affects the two equations respectively.

Snow accumulations by the influence of wind is also important in order to understand how changes in weather affect accretions of snow. We saw that snow generally accumulate in "aerodynamic shadow zones" when influenced by winds. Further, strong winds can redistribute snow that is already settled at the ground (2.3).

With slippery sloped roofs (shed, gabled, arched), changes in conditions can be critical if temperature rises suddenly, or a rapid thaw and refreeze cycle occurs (Figure 10 & Figure 12). Accretions on flat roofs are not exempt from changes in weather conditions, as we saw in chapter 2.5.2, huge cornices can form at these roofs if not properly designed and localization is not optimized.

- **Is it possible to prevent snow accumulations on roofs using airflows?**

The results from empirical method, showed that the drag forces generated was sufficient in terms of reject incoming airborne snow. The percentage of the airflow covered by adequate velocities was found to be between ca. 30-50 % of the cone formed airflow, depending on the setup (Table 4). From the CFD simulations, the area covered by over 3 m/s seems to be about the same percentage as the empirical determined (Figure 48). From the experiments (4.4 & Appendix A) we clearly saw snowflakes getting rejected or steered away from the surface of the model. However, majority of the snowflakes found its way to the surface (Figure 62).

Because of the necessity of downscaling the experiments and only having the ability to maintain precalculated velocities for a short period of time, it is hard to tell which results a full-scale experiment could give. With velocities obtained from the compressor used here and with use of two or four outlets, it is not possible to prevent snow accumulations. However, as the snowflakes are clearly rejected at certain places, it seems like there are potentials with the concept of preventing snow accumulations. Although improvements have to be done with the outlets, e.g. spread the airflow in a more horizontal direction to cover a larger area, or more likely, rely on another source (impeller etc.) with larger cross-sectional outlets.

- **Would the system be justifiable in terms of efficiency, energy supply and reliability requirements?**

The system built for the experiments have a relatively low head loss (4.4) much thanks to the hydraulically smooth pneumatic hoses used. Nevertheless, As discussed in 4.4.7, using pneumatics would probably require an inconveniently large pressure tank in order to maintain the required velocity for all outlets. The diffusion of airflows seen in both chapter 3.5.2 and 4.1.2, shows us that it diffuses faster from smaller outlets. The latter indicates that larger outlets can be beneficial in terms of efficiency. However, for the setup used in these experiments, it is not justifiable in terms of efficiency, since it cannot prevent the snow from accumulating. Again, a full-scale experiment as was the intention, would give us a stronger evaluation of the efficiency.

Energy supply for a similar system as the one used in the experiments, would doubtfully be justifiable in terms of energy supply. This is because the system uses a 2200 W compressor (p. 70), only to supply maximum four outlets with adequate velocity for a few minutes at a time. However, for a system using larger outlets combined with impellers or other techniques of accelerating the air, rationalizing the required energy supply is not inconceivable.

The required reliability for the system intended in this study must be relatively high, as it intends to work continuously during snowfall. It also has to be designed for maintenance, as designing out maintenance is likely to be very expensive because of the high reliability requirements for all parts. The most likely scenario in terms of reliability and maintenance, is that such a system would contribute as an additional barrier, adding redundancy to the existing risk reducing barriers.

- **Is the system implementable in a practical point of view, or is there other more efficient designs?**

This last research question is a somewhat extension of the previous one. The system built in this study, with the main purpose of testing the concept, would imaginable be implementable, as the hoses is discreet and could be mounted from under the roofing. Nevertheless, as discussed in RQ 4, this particular system would not be justifiable in terms of energy supply and efficiency. Therefore, a more efficient design has to be compiled.

Fans or impellers at the roof could also be a design worth pursuing, if justifiable in terms of RQ 4. Using larger fans or impeller would likely be less discrete than the pneumatic system, but perhaps practical to implement. If designing a system with significantly larger hoses, mounted in the same way as the ones in these experiments, the design is not unlikely to be practically implementable.

# 5 Conclusion, Challenges and Further Work

The conclusions presented from this feasibility study, shows potential in order to prevent snow accumulations. Challenges and suggestions for further work is given separately at the end. Conclusions regarding aim and objective, research questions, risk assessment and reliability analysis are formulated in this last chapter. Initially in chapter 1.3, we derived the following five research questions.

1. What risks are associated with accumulation of snow on the roofs?

2. How changes in weather conditions effect snow accumulation?

3. Is it possible to prevent snow accumulations on roofs using airflows?

4. Would the system be justifiable in terms of efficiency, energy supply and reliability requirements?

5. Is the system implementable in a practical point of view, or is there other more efficient designs?

From the identified risks, falling from roof while removing snow, damaged roof due to snow removal and getting hit by falling snow or ice, are the hazardous events with highest risks. Changes in weather conditions affect where the snow deposit and erodes by the influence of wind. Further the generated drag force has to be monitored as changes in temperature and humidity causes different characteristics for the snow crystals (wet/dry conditions and drag coefficient).

It seems realistic to prevent snow accumulations using airflows, although it was not achieved in this study. The reason it seems possible is the behavior of the snowflakes that interacted with the airflow. However, findings in the result and discussion indicates that pneumatics are not the preferred choice, mainly because of the energy supply. It seems more efficient to change the design to larger hoses and use impeller/fans as source of the airflows. Further, the EPS experiment indicated that snowflakes potentially can be dragged underneath the airflow, as a result of driving potentials. The experimental system was not justifiable in terms of efficiency, as it did not prevent enough snow from landing at the surface. However, if attempting to conduct the full-scale experiment intended in this study, the airflows should be spread in a wider area (horizontally) in order to cover a larger part of the surface.

According to the aim of preventing snow accumulations using airflows, we were not able to achieve this. However, valuable results and discussion of possible reasons why the aim was not achieved emerges from this thesis. The objective of contributing with a principle solution were not completely accomplished, as it was difficult to tell if the system will solve the problem of accumulating snow. Complications related to the experiment setup was among the reasons it was challenging to reach the objective.

In terms of managing the risk associated with snow accumulations on roofs, a risk assessment was conducted. The results showed that the concept of preventing snow accumulations using airflows turned out to be a potential risk reduction barrier. Implementation of a system operating as intended, could lower the three ALARP events remaining after the risk assessment and pursuing risk reduction for 13 acceptable risks.

Reliability is an important aspect when designing a technical system, especially when safety for human and asset depends on its ability to perform as intended. Because of high reliability requirements for the intended system, it was proposed to choose the *design for maintenanc*e approach. The latter is mainly reasoned by the high costs associated with *designing out maintenance*, which is not always possible, due to the high reliability required for all parts. An airflow system would most likely contribute – along with existing barriers – as additional redundancies in the system of risk reducing barriers.

The behavior of falling snow by the influence of airflows, seemed to comply with the empiricism. Further, the airflows were apparently flowing in the same pattern as for the preliminary CFD simulations. However, inadequate airflows delivered from the source made a few obstacles, resulting in a need for down scaling the experiments. As a sequel from the down scaled experiments, it was not possible to test the full-scale experiment from the simulations. Further feasibility research is recommended, either by conducting the full-scale experiment or changing the design, as the experiments showed potentials.

**Challenges**

Challenges related to the experiments affected the results, nevertheless, the outcome was sufficient for comparison with empirical and numerical findings. The pandemic situation during this period made a huge impact for millions of people and still does. This was also the root cause of the related challenges in the experiments. The University had to lock down, meaning that the laboratory was unavailable for seven weeks and so was the compressor which the experiments relied on. Since the experiments depended on actual snow fall, they could not be postponed, even though the deadline for the submission was. With a limited budget, a mobile compressor was bought. It turned out that it could not supply enough airflow to conduct the full-scale experiments. Hence, the experiments had to be scaled down to the point where it was barely acceptable in terms of the initial calculations and simulation parts.

There was also challenging to see what was going on from time to time in the experiments due to poor contrasts and light conditions. Improvements could be having a black background and a second camera behind the outlets to have several angles.

**Further work**

- Conduct the full-scale experiments which was the intention in this study, making sure that the source for the airflows are sufficient.
- Further research of the feasibility of using airflows to prevent snow from accumulating at surfaces. Using another design or approach, i.e. Impellers or fans with or without hoses, instead of pneumatics.
- Research of the feasibility of applying airflows to prevent snow accumulations on smaller areas like solar panels.

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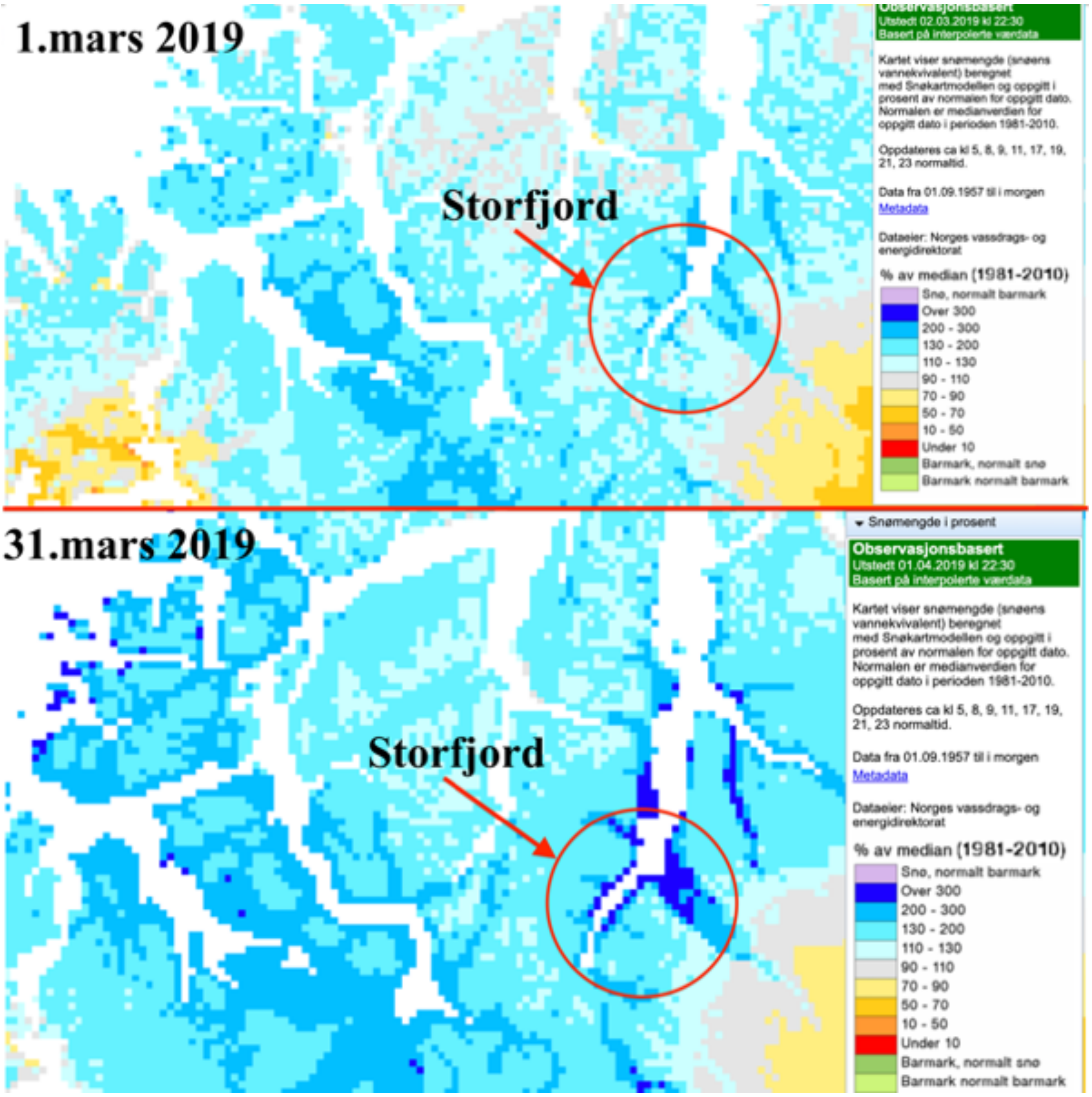
# Appendix A

## Video from experiments

Appendix A is attached here and as a link to the video uploaded at YouTube:
[https://www.youtube.com/watch?v=xLQ28p4qU34&feature=youtu.be]

# Appendix B

## Amount of snow in percentage of the normal (1981-2010)




(Source: senorge.no)

# Appendix C

## Table of snow properties and results from Eq. (15) and (16)

**Equation(15)**

mN=milli Newton

$$F_D = \frac{(Uwind - Usnowflake)^2 \cdot Msnow \cdot g}{Umax^2} \text{ [N]}$$

**Example:**

| | |
|---|---|
| Uwind [m/s] | 3 |
| Usnowflake [m/s] | 0,5 |
| Umax [m/s] | 1,5 |
| Msnow [kg] | 6,00E-08 |
| g [m/s^2] | 9,81 |
| Fd [N] = | 1,64E-06 |

| | | | *dry snow* | *wet snow* | *dry snow* | *wet snow* | *dry snow* | *wet snow* | |
|---|---|---|---|---|---|---|---|---|---|
| **Snow type** | **Mass [kg]** | **Fall velocity [m/s]** | **Fd(3 m/s) [mN]** | **Fd(3 m/s) [mN]** | **Fd(27 m/s) [mN]** | **Fd(27 m/s) [mN]** | **Uwind ≥ [m/s]** | **Uwind ≥ [m/s]** | **Fg [mN]** |
| Powder snow | 6,00E-08 | 0,5 | 1,64E-03 | 9,20E-04 | 1,84E-01 | 1,03E-01 | 1,58 | 2,06 | 5,89E-04 |
| Needles | 4,00E-09 | 0,5 | 1,09E-04 | 6,13E-05 | 1,22E-02 | 6,89E-03 | 1,58 | 2,06 | 3,92E-05 |
| Spatial dendrites | 1,50E-07 | 0,6 | 3,77E-03 | 2,12E-03 | 4,56E-01 | 2,56E-01 | 1,62 | 2,09 | 1,47E-03 |
| Rimed crystals | 1,80E-07 | 1 | 3,14E-03 | 1,77E-03 | 5,31E-01 | 2,98E-01 | 1,80 | 2,24 | 1,77E-03 |
| Graupels | 8,00E-07 | 1,8 | 5,02E-03 | 2,83E-03 | 2,22E+00 | 1,25E+00 | 2,34 | 2,69 | 7,85E-03 |

**Equation (16)**

$$F_D = -\frac{\pi}{8} \cdot d^2 \cdot \rho_f \cdot C_D \cdot V^2 \text{ [N]}$$

**Example:**

| | |
|---|---|
| Diameter [m] | 0,002 |
| ρf [kg/m^3] | 1,342 |
| Cd [dimensionless] | 0,07 |
| V [m/s] | 3 |
| Fd [N] = | 1,32805E-06 |

| | | **Cd = 0,07** | **Cd = 0,5** | **Cd = 0,07** | **Cd = 0,5** | **Cd = 0,07** | **Cd = 0,5** |
|---|---|---|---|---|---|---|---|
| **Snow type** | **Diameter [m]** | **Fd(27 m/s) [mN]** | **Fd(27 m/s) [mN]** | **Fd(3 m/s) [mN]** | **Fd(3 m/s) [mN]** | **Uwind ≥ [m/s]** | **Uwind ≥ [m/s]** |
| Powder snow | 2,00E-03 | 1,08E-01 | 7,68E-01 | 1,33E-03 | 9,49E-03 | 2,00 | 0,75 |
| Needles | 1,50E-03 | 6,05E-02 | 4,32E-01 | 7,47E-04 | 5,34E-03 | 0,69 | 0,26 |
| Spatial dendrites | 4,00E-03 | 4,30E-01 | 3,07E+00 | 5,31E-03 | 3,79E-02 | 1,58 | 0,59 |
| Rimed crystals | 2,50E-03 | 1,68E-01 | 1,20E+00 | 2,08E-03 | 1,48E-02 | 2,77 | 1,04 |
| Graupels | 2,00E-03 | 1,08E-01 | 7,68E-01 | 1,33E-03 | 9,49E-03 | 7,29 | 2,73 |

# Appendix D

## Preliminary Hazard Analysis

| Hazard/ Threat | Triggering event(s) (Cause) | Nr | Hazardous event (top event) | Potential Consequence(s) | Risk | | | | Existing barriers (Preventive/Reductive) | Risk updated | | | | Risk updated after airflow system implemen-tation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | F | Cate-gory | S | RPN | | F | Cate-gory | S | RPN | F | Cate-gory | S | RPN |
| 1. Snow avalanche | • Friction between the snow and the roof surface becomes less than its corresponding gravity force:<br>- Increased snow load due to temperature increase<br>- Increased load due to accumulation of snow (falling or drifting)<br>- Wind load pushing the snow in the same direction as the gravity force<br>• Loss of cohesion/bond between snow molecules:<br>- Increased air temperature<br>- Solar radiation<br>- Rain<br>- Lack of night frost<br>• Changing weather conditions:<br>I. Changes in temperature/wind/atmospheric moisture creating different layers within the accumulated snow, resulting in weak spots. Eventually the snow cover can spontaneously | 1.1 | Gutter ripped off eaves | • Formation of icicles due to dripping from roof<br>• Icing on adjacent walls<br>• Formation of ice on lower lying roofs/ emergency exits<br>• Wreckage hitting people walking/standing underneath roof | 3 | Human | B | 5 | • Internal drainage<br>• Rows of snow guards<br>• High friction roofing materials (e.g. granular faced asphalt composition)<br>• Smooth roofing with low friction factor in order to restrict the buildup of potential energy, through sliding off smaller snow avalanches<br>• Shoveling off snow from the roof | 2 | Human | B | 4 | 1 | Human | A | 2 |
| | | | | | | Assets | C | 6 | | | Assets | C | 5 | | Assets | C | 4 |
| | | 1.2 | Broken/displaced vents | • Causing ventilation problems in the building<br>• Tear of the ceiling<br>• Internal leakages<br>• Wreckage hitting people walking/standing underneath roof | 2 | Human | A | 3 | • Single snow guards<br>• Vents placed further from eaves<br>• Shoveling off snow from the roof | 1 | Human | B | 3 | 1 | Human | A | 2 |
| | | | | | | Assets | C | 5 | | | Assets | C | 4 | | Assets | C | 4 |
| | | 1.3 | Unaware people underneath the roof hit by avalanche | • Concussion with loss of consciousness | 4 | Human | D | 8 | • Rows of snow guards | 2 | Human | C | 5 | 1 | Human | C | 4 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | fracture at the weak spot and slide off the roof | | | • Critical head injuries with permanent damage and irreversible brain injury or even fatality<br>• Small wounds and bruises<br>• Other head injuries | | Assets | **-** | **N/A** | • Heating wires located at eaves to prevent accumulation behind snow guards<br>• Snow avalanche warning signs<br>• Separated/closed off area directly underneath roof<br>• In the design phase of the roof: particular attention given to anticipating snow avalanche trajectories<br>• Shoveling off snow from the roof | | Assets | **-** | **N/A** | | Assets | **-** | **N/A** |
| | | **1.4** | Injured people/personnel due to snow removal techniques conducted from underneath roof | • Concussion with loss of consciousness<br>• Critical head injuries with permanent damage and irreversible brain injury or even fatality<br>• Internal injuries if hit by several hundred kg compact snow<br>• Small wounds and bruises<br>• Other head injuries<br>• Material damaged | **4** | Human | **D** | **8** | • Personal protective equipment (PPE) (helmet, robust shoes and clothing)<br>• Job safety analysis (JSA)<br>• Use of lift or other machines to separate the trajectory of an avalanche from working position<br>• Proper training in snow removal techniques<br>• Shoveling off snow from the top of the roof | **2** | Human | **B** | **4** | **1** | Human | **A** | **2** |
| | | | | | | Assets | **C** | **7** | | | Assets | **B** | **4** | | Assets | **A** | **2** |
| | | **1.5** | Avalanche hits material or equipment underneath the roof | • Loss of personal belongings<br>• Major material losses (vehicles, machines, constructions etc.) | | Human | **-** | **N/A** | • Snow guards<br>• Robust physical shielding between assets and the avalanche trajectories | | Human | **-** | **N/A** | | Human | **-** | **N/A** |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **5** | Assets | **D** | **9** | • Separated/closed off area directly underneath roof<br>• In the design phase of the roof: particular attention given to prediction of snow avalanche trajectories<br>• Shoveling off snow from the roof | **2** | Assets | **B** | **3** | **1** | Assets | **A** | **2** |
| **2. Falling icicles/ice blocks** | • Refreeze of meltwater from melted snow or ice can form blocks of ice or icicles<br>• Typical weather conditions for icicles to grow is temperatures above 0 during the day followed by freezing temperature at night<br>• Rain or solar radiation followed by freezing temperature is also common growing conditions for ice on roofs<br>• A poorly ventilated inner roof (ceiling) can cause melting of snow under the snow covering the surface of the roof. Refreezing of this water then occur when it gets exposed to the cold air again<br>• Interior heat loss/building heat: poorly insulated roofs (often warm sloping roofs) resulting in water vapor finding its way through the roof to the cold air outside. Designed without a proper vapor | **2.1** | Falling ice from roof | • Concussion with loss of consciousness<br>• Critical head injuries with permanent damage and irreversible brain injury or even fatality<br>• Small wounds and bruises<br>• Other head injuries<br>• Can be destructive to the roof when tear away (tearing away shingles)<br>• Loss of personal belongings<br>• Major material losses (vehicles, machines, constructions etc.) | **4** | Human | **E** | **9** | • Heating wires to prevent meltwater to refreeze at the eaves<br>• Heating mats to prevent meltwater from refreezing<br>• Robust physical shielding from ice falling trajectory<br>• Warning signs<br>• Area underneath physically closed off for people<br>• Cold sloping roofs. Ventilates heat and moist from the building away from the surface of the outer roof<br>• Physically remove ice from eaves | **2** | Human | **B** | **4** | **1** | Human | **B** | **3** |
| | | | | | | Assets | **D** | **8** | | | Assets | **B** | **4** | | Assets | **B** | **3** |
| | | **2.2** | Gutter ripped off eaves | • Icing on adjacent walls<br>• Formation of ice on lower lying roofs/ emergency exits | | Human | **B** | **2** | • Internal drainage<br>• Heating wires to prevent meltwater to refreeze at the eaves | | Human | **C** | **4** | | Human | **B** | **3** |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | retarder on the warm side of the roof. "The higher the internal moisture and the colder the outside temperature, the better the vapor retarder must be" (Hjorth-Hansen et al., 2000, p. 215) | | | • Increased formation of icicles | **2** | Assets | **C** | **5** | • Cold sloping roofs. Ventilates heat and moist from the building away from the surface of the outer roof<br>• Physically remove ice from eaves<br>• Shoveling off snow from the roof | **1** | Assets | **C** | **4** | **1** | Assets | **C** | **4** |
| **3. People falling from heights** | • Climbing towards the roof to clean away snow or ice. There are two main reasons why this could be necessary:<br>I. Risk of exceeding the maximum bearing capacity of the roof/construction<br>II. Risk associated with sudden and uncontrolled release of energy (e.g. snow avalanches or falling ice) | **3.1** | Falling from roof while conducting snow removal activities | • Small wounds and bruises<br>• Critical head injuries or fatality<br>• Concussion with loss of consciousness<br>• Larger bones fractured (ribs, femoral etc.)<br>• Internal bleeding and/or damaged vital organs resulting from fall injuries | **4** | Human | **D** | **8** | • Fall protection belt/strap<br>• Job safety analysis (JSA)<br>• Proper training in snow removal techniques<br>• Design phase: particular attention given to ultimate limit state (ULS), to reduce the need for clearing the roof from snow. Meaning that the maximum load the construction can withstand should be based on return periods corrected for updated climate predictions<br>• Heating wires to reduce icicles at eaves and thus the need for removing ice | **3** | Human | **C** | **6** | **2** | Human | **B** | **4** |
| | | | | | | Assets | **-** | **N/A** | | | Assets | **-** | **N/A** | | Assets | **-** | **N/A** |
| | | **3.2** | Slip and fall from ladder | • Small wounds and bruises<br>• Smaller bones fractured (e.g. fingers) | **4** | Human | **C** | **7** | • Fall protection belt/strap<br>• Job safety analysis (JSA) | **2** | Human | **B** | **4** | **2** | Human | **B** | **4** |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | • Larger bones fractured (ribs, femoral etc.)<br>• Serious head injury<br>• Concussion | | Assets | - | N/A | • Use of lift<br>• Design phase: Refined ULS for bearing capacity of the roof and the construction (as explained in existing barriers for 3.1) | | Assets | - | N/A | | Assets | - | N/A |
| **4. Emergency exit blocked** | • Heavy drifting snow from higher roof<br>• Snow avalanche in front of the exit<br>• Emergency exit from a higher floor onto a lower lying roof is covered with accumulated snow | **4.1** | Window or door used as emergency exit blocked by snow | • Door is stuck or window blocked in an emergency situation<br>• As a direct consequence of unavailable emergency exit in case of fire:<br>I. Skin burns<br>II. Carbon monoxide poisoning<br>III. Death as an ultimate consequence<br>• Damaged door or window due to snow avalanche | **5** | Human | **D** | **9** | • Design: Emergency exit not placed at leeward side of the building/roof. This is because the drifting snow typically accumulates all the way up to the wall at the opposite side of average direction of wind<br>• Design: Emergency exit not placed under higher roofs with potential of snow avalanches<br>• Heating wires in front of exit | **1** | Human | **D** | **5** | **1** | Human | **D** | **5** |
| | | | | | | Assets | **B** | **7** | | | Assets | **A** | **2** | | Assets | **A** | **2** |
| **5. Roof damages** | • Thaw and freeze cycle forming ice dams/icicles<br>• Various snow cleaning techniques involving heavy equipment at the roof<br>• Snow drifts<br>• Roof located in the trajectory of snow avalanche or cornices from higher roofs/buildings | **5.1** | Falling snow or ice from higher roofs | • Damages due to unbalanced snow loads<br>• Exceedance of maximum load capacity of the lower lying roof (If the roof below already has snow accumulated) | **4** | Human | **-** | **N/A** | • Rows of snow guards<br>• Heating wires to reduce icicles at eaves or formation of cornices. | **2** | Human | **-** | **N/A** | **1** | Human | **-** | **N/A** |
| | | | | | | Assets | **D** | **8** | • Heated drainage system<br>• Heating mats to prevent meltwater from refreezing | | Assets | **D** | **6** | | Assets | **D** | **5** |
| | | **5.2** | Non-uniform distribution of snow or ice loads | • Overload at the eaves<br>• Damaged windows or doors as the construction may | | Human | **-** | **N/A** | • Heating mats to prevent meltwater from refreezing | | Human | **-** | **N/A** | | Human | **-** | **N/A** |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | • Interior heat loss/building heat: poorly insulated roofs | | | experience an overload of stress and strain | 5 | Assets | C | 8 | • Design: roof designed with particular attention to dominant wind direction for storms and average wind direction during winter months. This in order to reduce leeward sides of the roof | 2 | Assets | C | 5 | 1 | Asset | C | 4 |
| | • Substantial unbalanced snow and ice loads<br>• Slippery sloped roofs fail to slide off snow<br>• Exceedance of dimensioning snow and ice loads for the roof<br>• Heavy drifting snow<br>• Mitigation measures not conducted | 5.3 | Roof collapse | • Progressive collapse<br>• Injured people inside building<br>• Fatal accident<br>• Loss of livestock | 2 | Human | D | 6 | • Design: ULS corrected for climate predictions and sufficient safety factor for maximum load<br>• Shoveling off snow from the roof | 1 | Human | D | 5 | 1 | Human | D | 5 |
| | | | | | | Assets | D | 6 | | | Assets | D | 5 | | Assets | D | 5 |
| | | 5.4 | Progressive collapse | • Injured people inside building<br>• Fatal accident<br>• Loss of livestock<br>• Huge economical losses<br>• Loss of assets | 1 | Human | E | 6 | • Design: Redundancies in the construction, in this case meaning that the integrity of the building has to be maintained even if the collapsing roof tear apart supporting beams | 1 | Human | D | 5 | 1 | Human | D | 5 |
| | | | | | | Assets | E | 6 | | | Assets | D | 5 | | Assets | D | 5 |
| | • High maximum daily snow depth (MDSD)<br>• Frequent thaw and freezing cycle, resulting in snow freezing onto roof or destructive ice dams/icicle formation | 5.5 | People conducting snow and ice removals at the roof to prevent related damages | • Fall accidents<br>• Leakages<br>• Wear and tear on the roof | 4 | Human | D | 8 | • Fall protection belt/strap<br>• Job safety analysis (JSA)<br>• Use of lift to save the roof from damages | 2 | Human | B | 4 | 2 | Human | B | 4 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Assets | C | 7 | • Using snow removal techniques that does not require heavy equipment on the roof<br>• Using avalanche snow cleaner (subchapter 2.8) if the roof has the required availability | | Assets | B | 4 | | Assets | A | 3 |

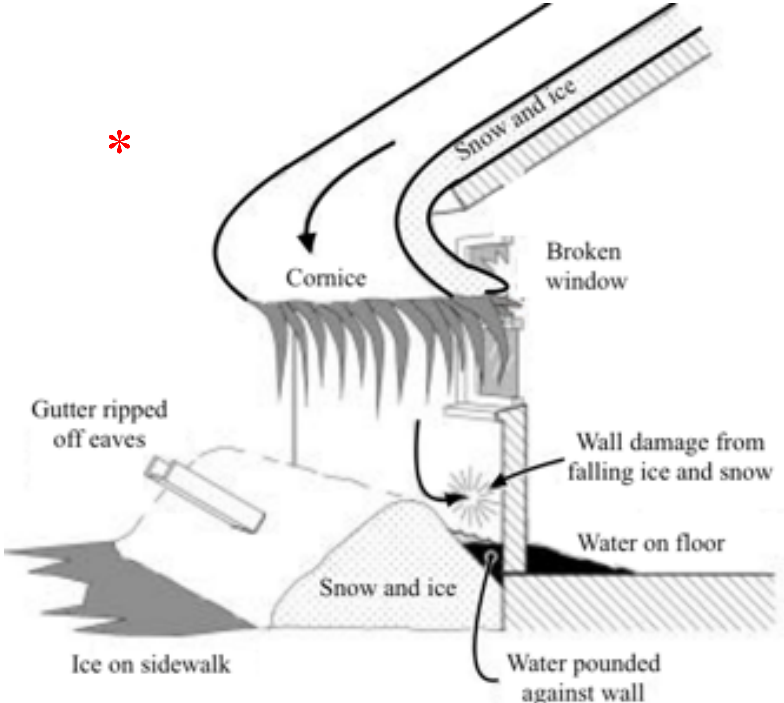
| Hazard/ Threat | Triggering event(s) (Cause) | Nr | Hazardous event (top event) | Potential Consequence(s) | Risk | | | | Existing barriers (Preventive/Reductive) | Risk updated | | | | Risk updated after airflow system implementation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | F | Category | S | RPN | | F | Category | S | RPN | F | Category | S | RPN |
| **6. Roof leakages** | • Trapped water due to complex roof geometry<br>• Trapped water under snow cover<br>• Frequent thaw and freezing cycle<br>• Various snow cleaning techniques involving heavy equipment at the roof<br>• High internal vapor pressure inside the building combined with poor vapor retarder and large temperature differences from inside to outside. | **6.1** | Trapped meltwater | • Infiltrating the roof causing leakages<br>• Unequal load distribution at the roof due to refreezing of trapped meltwater<br>• Increased loads as a result of formation of ice dams<br>• Increased snow load on roof. E.g. slippery sloped roofs designed for the snow to shed off, is not shedding it off because refreeze water holds it on the roof. | **3** | Human | **-** | **N/A** | • Design: Less complex geometry of the roof and as few valleys as possible<br>• Heating wires at scuppers and leaders<br>• Internal drainage system | **1** | Human | **-** | **N/A** | **1** | Human | **-** | **N/A** |
| | | | | | | Assets | **D** | **7** | | | Assets | **D** | **5** | | Assets | **D** | **5** |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6.2 | Ice-blocked scuppers and leaders | • Increased loads as a result of formation of ice dams<br>• Formation of icicles<br>• Leakages | 3 | Human | C | 6 | • Heating wires at scuppers and leaders<br>• Internal drainage system | 2 | Human | C | 5 | 1 | Human | C | 4 |
| | | | | | | Assets | C | 6 | | | Assets | C | 5 | | Assets | C | 4 |
| | • Seams/ribs not designed to follow the trajectories of potential snow avalanches | 6.3 | Bended metal seams/ribs | • Tear on the roof<br>• Huge leakages<br>• Internal heat loss<br>• Creating holes in the roof | 2 | Human | - | N/A | • Design: Seams/ribs always heads in the same direction as potential snow avalanche trajectory<br>• Extensive use of snow guards | 1 | Human | - | N/A | 1 | Human | - | N/A |
| | | | | | | Assets | D | 6 | | | Assets | D | 5 | | Assets | D | 4 |
| | • Frequent thaw and freezing cycle creating ice dams/icicles<br>• Complex roof geometry leading to large amount of snow deposited on the roof or in valleys. | 6.4 | People conducting snow and ice removals at the roof to prevent leakages | • Climbing on roofs with shovels or other equipment as a preventive measure to prevent leakages, can easily become the reason for the leakage, as walking on roofs often leads to tear and wear.<br>• Fall accidents | 4 | Human | D | 8 | • Heating wires at scuppers and leaders<br>• Internal drainage system<br>• Slippery sloped roof<br>• Fall protection belt/strap<br>• Job safety analysis (JSA)<br>• Use of lift to save the roof from damages<br>• Using snow removal techniques that does not require heavy equipment on the roof | 2 | Human | B | 4 | 1 | Human | B | 3 |
| | | | | | | Assets | C | 7 | | | Assets | B | 4 | | Assets | A | 2 |
| **7. Snow cornices** | • Created by air vortices induced at the edge of the roof, the phenomenon is usually | 7.1 | Information signs and lights mounted on the wall of the building gets ripped off or crushed | • Material loss<br>• Short circuit leading to sparking or fire | 3 | Human | C | 6 | • Clearing off snow cornices before they grow massive | 2 | Human | C | 5 | 1 | Human | C | 4 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | observed at flat roofs and is a result of snow drifting mechanisms (see subchapter 2.3)<br>• Large cornices are often related to blizzards or strong winds | | | • People stroked by falling objects | | Assets | C | 6 | • Design: Avoid signs and lights mounted at vulnerable positions where cornices are likely to form<br>• Design: Inwards inclined roof edge. This could reduce the formation of cornices | | Assets | C | 5 | | Assets | C | 4 |
| | | 7.2 | Unaware people underneath the roof hit by cornices | • Concussion with loss of consciousness<br>• Critical head injuries with permanent damage and irreversible brain injury or even fatality<br>• Small wounds and bruises<br>• Other head injuries | 2 | Human | D | 6 | • Clearing off snow cornices before they grow massive<br>• Design: Inwards inclined roof edge. This could reduce the formation of cornices | 1 | Human | D | 5 | 1 | Human | D | 5 |
| | | | | | | Assets | - | N/A | | | Assets | - | N/A | | Assets | - | N/A |
| | | 7.3 | Injured people/personnel due to snow removal techniques conducted from underneath cornices | • Concussion with loss of consciousness<br>• Critical head injuries with permanent damage and irreversible brain injury or even fatality<br>• Small wounds and bruises<br>• Other head injuries | 4 | Human | D | 8 | • Design: Inwards inclined roof edge. This could reduce the formation of cornices<br>• SJA<br>• Use of lift to avoid roof damage or standing underneath cornices while removing them | 2 | Human | D | 6 | 1 | Human | D | 5 |
| | | | | | | Assets | - | N/A | | | Assets | - | N/A | | Assets | - | N/A |
| **8. Extensive snowfalls** | • Polar lows<br>• Climate projections of Increased annual rainfall by 18% (Hanssen-Bauer et al., 2015, p. 67) | 8.1 | Blocked air intake due to extensive snowfalls | • Mold as a result of reduced ventilation in the building | 3 | Human | C | 6 | • Design: Air intake placed on a wall<br>• Shoveling off snow from the roof | 2 | Human | C | 5 | 1 | Human | C | 4 |
| | | | | | | Assets | C | 6 | | | Assets | C | 5 | | Assets | C | 4 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | • A global temperature rise could lead to more extreme weather as warmer air potentially can hold onto more water particles (subchapter 2.2.1) | 8.2 | Buried plumbing vent | • Problems related to sanitary/plumbing systems<br>• Gas and odors not ventilated out from the building | 2 | Human | B | 4 | • Design: Longer ventilation pipes<br>• Shoveling off snow from the roof | 1 | Human | B | 3 | 1 | Human | B | 3 |
| | | | | | | Assets | C | 5 | | | Assets | C | 4 | | Assets | C | 4 |
| | • Combination of icicles at the end of a snow avalanche* | 8.3 | Broken windows | • Glass shards on the ground<br>• Smaller wounds, scratches<br>• Further material damage or losses if not handled or discovered immediately | 2 | Human | C | 5 | • Shoveling off snow and ice from the roof<br>• Rows of snow guards<br>• Cold sloping roofs to reduce thaw and freeze cycle | 1 | Human | C | 4 | 1 | Human | C | 4 |
| | | | | | | Assets | C | 5 | | | Assets | C | 4 | | Assets | C | 4 |

*




(Figure illustrating how icicles combined with snow avalanche can break windows (Buska & Tobiasson, 2001, p. 340))

# Appendix E

## Risk assessment

| Hazard Nr | Comments on the risk assessment |
|---|---|
| 1.1 | Frequency decreases as measures is taken. None of the listed consequences is reduced by barriers. On the other hand, severity for human increases as one of the barriers is to clear the roof from snow. In the end it will potentially decreases again, as there is no need for snow clearing if an airflow system were to work as intended. |
| 1.2 | Preventive barriers lower the frequency. Without any measures, the severity for humans are negligible. Increasing severity as snow removal is one of the preventive measures before it goes back to negligible, as the snow clearing is not relevant. Unchanged severity for assets. |
| 1.3 | Assets not relevant. Without any measures, it is probable to be hit by snow avalanches and the severity for human could be major. Likelihood decreases as preventive measures is implemented. Severity for human also drops, because of reductive barrier. At the case in the end it is very unlikely to imagine a snow avalanche if the managing to keep snow crystals airborne. |
| 1.4 | Being hit by snow in a greater or lesser extent is almost certain when clearing snow from underneath a roof and without any measures or precautions, the consequences could be fatal. After both preventive and reductive barriers, the risk is significantly reduced. The need for human interference for clearing the snow is significantly reduced at the last risk column and the frequency of occurrence is minimum. For the asset aspect, there could be cars or other materials damaged at the same time. |
| 1.5 | Human aspect not relevant. A large snow avalanche could easily do major damage to assets, however, if measures are taken, both severity and likelihood is in the green field of the matrix. |
| 2.1 | If all necessary measures taken, the probability is quite low of being hit by ice, but the consequences could be fatal. Falling ice can make serious impact on cars for instance and are not unlikely to happen in the high north if there are no barriers to prevent it. At the end the severity is not negligible because of the need for ice clearing will not be completely absent and ice clearing activities involves a risk. |
| 2.2 | Less likely for gutters to be ripped off by ice than a solid snow avalanche, but yet not very unlikely to occur. Could do moderate damage to assets. The increased severity for humans after measures is due to two measures involving climbing on the roof or standing underneath to clear off snow or ice. "Only if the entire roof slope from eaves to ridge is cleared of snow will the ice dam/icicles formation |

| | |
|---|---|
| | cease" (Hjorth-Hansen et al., 2000, p. 219), which explains why snow clearing on the roof could be a realistic measure. |
| 3.1 | Frequency of falling from roof while doing snow clearing is decreasing as the need for clearing snow decreases. SJA and training also lower the frequency of falling. As a reductive barrier, a fall protection belt/strap could be used, which will lower the severity of falling. At the last risk update, frequency decreases further as the need for climbing on roofs is unlikely. |
| 3.2 | Slipping and falling from a ladder could be almost as severe as falling from roofs and is equally probable. Use of lift and/or fall protection lowers the risk. |
| 4.1 | If locations of emergency exits are not thoroughly considered and no measures added to keep the exits clear from snow and ice, it will frequently be blocked. A blocked emergency exit in case of a crisis have potentially major consequences. Only if all measures are taken, the likelihood of blocked exits is very low. Still the consequences are the same. |
| 5.1 | Major damage could frequently happen to roofs adjacent to higher buildings/roofs. The severity is the same, but the frequency is reduced through mitigations. |
| 5.2 | Non-uniform distributed loads on roofs from snow and ice are very frequent sight in cold climates. The severity can be major, i.e. leading to collapsing roof. However, by mitigation measures, the frequency could be drastically decreased. |
| 5.3 | Roof collapsing is certainly associated with major losses. People located inside a building when the roof collapses, is exposed to major risks of getting injured by falling objects. Mitigations brings the likelihood to an acceptable level. |
| 5.4 | Progressive collapse is an extreme hazardous event and fortunately it is seldom. However, from time to time, a collapsed building as a result of snow load occurs. The consequences are often catastrophic when it happens. Most of the buildings collapsing are barns and industry buildings, which is known to house animals, and not unlikely people (Kesser, 2018; Svala, 2020). |
| 5.5 | People conducting snow removal at roofs is not an unusual sight (Pellicer, 2010; Hagen, 2012; VGTV, 2018), which can be dangerous if one is to fall from heights (Bylund et al., 2016). Even though the severity of falling is less when using fall protection or lift, the frequency of snow removal activities is not changed. The need for snow removal could be reduced to none by using an ideal airflow system. In an asset aspect, the damaged to the roof is moderate and can be reduced by using lift or other techniques that does not require climbing the roof. An ideal airflow system could take away all potential damages to the roof caused by snow clearing. |

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| 6.1 | Trapped meltwater is likely to do damage, but is easily prevented if the right measures are conducted. |
| 6.2 | Ice-blocked scuppers and leaders can lead to an increased load or non-uniform distribution of loads. It can also lead to leakages or formation of icicles, which have a potential to harm people standing under the roof. |
| 6.3 | Huge leakages can occur if metal seams on the roof bends and create wholes or rifts through the ceiling. It is not a likely scenario even without any specific barriers. |
| 6.4 | This hazardous event is more or less the same as nr. 5.5, but causes (triggers) are different. |
| 7.1 | Short circuit as a result of rupture or tear of power wires can cause harm to both people and assets. Preventive and reductive measures combined will lower the risk to acceptable. |
| 7.2 | Removing the cornices before they grow or prevent formation, will reduce the frequency of occurrence. |
| 7.3 | As the need for removing cornices decreases, the frequency of injured people conducting these operations will decay as well. In addition, if one cold prevents formation of the cornices in the first place, the need for removal operations will be absent. |
| 8.1 | Mold inside the building could at worst case scenario cause health hazardous environment over time and it can be damaging to integrity of wood for instance. |
| 8.2 | Buried plumbing vents are not very likely, since it they are designed to fit in the climate where they are installed. Nevertheless, towards the next century, an increased amount of snow could make it more frequent. |
| 8.3 | Broken windows as a result of icicles mounted on a snow avalanche is a realistic scenario, fortunately it belongs to the rarity. |