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Hanna Melsnes Svenneby

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NTNU
Norwegian University of
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Faculty of Engineering
Department of Energy and Process Engineering

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Characterisation of indoor environmental quality in storage areas of the NTNU Gunnerus Library

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Hanna Melsnes Svenneby

Energy Use and Energy Planning
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Supervisor: Guangyu Cao
Co-supervisor: Stein Johansen, Victoria Juhlin, Zhirong Yang

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Preface

This master thesis, regarding characterization of the indoor environment quality in the storage areas at the NTNU Gunnerus Library, is carried out at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim. The work has been conducted at the spring semester of 2019 as final part of the master of technology degree; Energy Use and Energy Planning.

In association with the thesis, I would like to thank my supervisor Guangyo Cao for guidance and helpful support throughout period. I would also give a thank to the working staff at the NTNU lab for offering help in the practical aspects of constructing the mobile car.

Further, a special gesture goes to Victoria Juhlin, paper- and book conservator MA, and Stein Olle Johansen, head of department at NTNU Gunnerus Library, for support and helpful in-house support and advice.

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Hanna Melsnes Svenneby

Hanna Melsnes Svenneby
Department of Energy- and Process Engineering, NTNU

Abstract

The primary objective of this master thesis was to characterize the indoor environment quality in the storage area at floor 10 of the NTNU Gunnerus Library through monitoring of temperature and relative humidity. The NTNU Gunnerus Library houses collections that consist of combinations of materials with different levels of instabilities. In view of this fact, the target condition needs to be a compromise in order to maintain the required environmental quality.

There are a number of consequences as a result of inadequate conditions of relative humidity, air temperature and air distribution. The main categories of degradation are biological, mechanical and chemical degradation. Literature states, that to minimize degradation of the cultural material stored at the library, it is of great importance to maintain stable thermo-hygrometric values.

The relationship between the outdoor and indoor temperature is surveyed through scatter plots and by linear regression analysis. The result indicates significant correlations, with positive r-values > 0,7, between the outdoor temperature and the temperature measured by the meters located in the area. The temperature of the supply air, however, shows a moderate negative correlation. As the supply air controls the temperature in the storage area, the temperature of the supply air will increase as the outside temperature decreases.

Analysis of the fluctuations of the long-term measurements is made, and displayed a wide range of thermo-hygrometric values to which the storage area is exposed. The result indicates that 36-81 % of the time, dependent on the location of the measurement meter, the state of the air is outside the comfort zone of 50 $\pm$ 10 % relative humidity and 19 $\pm$ 5 °C air temperature.

Field measurements of potential temperature gradients are performed with a mobile car. Color-contour figures of passage A, B and C show a maximum ΔT of 2, 1 and 0,5 °C/m height, respectively. Further analysis of the color-contour figures emerges higher temperature in the area close to the supply air inlet. This suggests that the supply air has a rather local influence, and do not provide an even temperature distribution to the entire storage area.

In the end, the thesis suggests improvements for the indoor environmental quality of the storage areas at the NTNU Gunnerus Library. Improvements regarding separate climate regulation systems for the different floors are suggested as well as a recommendation to consider an all-air system with a centralized air-handling unit. In addition, more passive solutions are suggested, such as changing the division of the shelves and to install more sensors to get a better overview of the indoor environment.

Sammendrag

Hovedformålet med denne masteroppgaven var å undersøke og kartlegge inneklimaet til de historiske lagringsmagasinene til NTNU Gunnerus Biblioteket. Dette ble gjort gjennom overvåkning av de termo-hygrometriske parameterne; lufttemperatur og relativ fuktighet.

NTNU Gunnerus Bibliotek er en av de viktigste kulturarvsbibliotekene i Norden, og huser store samlinger av norsk, nordisk og europeisk skjønn- og faglitteratur. Samlingene består av en samling av materialer med ulike nivå av stabilitet og med bakgrunn i dette, må det ideelle klimaet for lagringsmagasinene være en kompromiss.

Forholdet mellom ute- og innetemperatur er undersøkt ved hjelp av regresjonsanalyse. Resultatet av undersøkelsen viser en signifikant korrelasjon mellom utetemperaturen og temperaturen målt av dataloggerne i rommet, med positive r-verdier > 0,7. Temperaturen i innløpsluften derimot, viser en moderat negativ korrelasjon. Dette kan ses i sammenheng med at innløpsluften styrer temperaturen i lagringsmagasinet, og temperaturen vil derfor øke dersom utetemperaturen synker.

Videre presenterer oppgaven langtidsmålinger av lufttemperatur og relativ fuktighet fra lagringsmagasinet i 10. etasje. Analysen av måleresultatet viser til store variasjoner i både lufttemperatur og relativ fuktighet. Komfortsonen som benyttes i analysen er 50 $\pm$ 10 % relativ fuktighet og 19 $\pm$ 5 °C lufttemperatur, og representerer betingelsene for forsvarlig bevaring. Resultat indikerer at målingene for henholdsvis målemeter 1-4 ligger utenfor komfortsonen i 81, 36, 42 og 30 % av tiden.

Det er utført feltmålinger av mulige vertikale temperaturgradienter med hjelp av en fjernstyrt bil som gjorde det mulig å ta målinger på ulike høyder gjennom rommet. Målingene er fremstilt som fargekonturfigurer og viser maksimal ΔT for de tre passasjene på 2, 1 og 0,5 °C/m romhøyde. Fargekonturfigurene viser en økning i temperaturen i området nær innløpsluft inntaket. Dette tyder på at innløpsluften bare har en lokal påvirkning, og at den ikke sørger for en jevn temperaturfordeling

Til slutt presenterer oppgaven forslag til forbedring av inneklimaet i lagringsmagasinene på NTNU Gunnerus Bibliotek. Det er foreslått å dele opp klimaanlegget i separate system for hver etasje. Et luft-luft system med en sentralisert luftbehandlingsenhet blir omtalt som et mulig passende system for lagringsmagasinene. I tillegg er det foreslått flere passive forslag som innebærer å endre inndeling og plassering av bokhyllene, samt installasjon av flere sensorer for å få bedre oversikt over innemiljøet.

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1. Introduction

This chapter gives an understanding of the background for the given problem and the motivation behind it. In addition, the approach of the work is presented as well as the research questions for this master thesis. In the end, assumptions and practical limitations are listed.

1.1 Background

The NTNU Gunnerus Library, established in 1760, is the oldest scientific library in Norway. The library's special collections-books, manuscripts and archives, some dating back to the early 1300's, are held in four storage areas on four separate floors.

The storage areas share one climate regulation system, which is outdated and insufficient in its capacity. Thus, fluctuations and extremes in temperatures and relative humidity as well as the forming of microclimates are a constant threat to the historic collections. In 2019, the NTNU Gunnerus Library plans to install a new climate regulation system in the storage areas.

1.2 Objective

This master thesis will characterize the effect of outdoor climate and ventilation methods on indoor environment by carrying out field measurements in the book collection storage area at the NTNU Gunnerus Library.

The following tasks are to be considered:

1) Literature review regarding indoor environment quality and ventilation solutions in libraries.
2) Analyze existing monitoring data of the indoor environment and outdoor climate data by machine learning.
3) Perform detailed field measurements on the thermal environment fluctuations. In addition, perform field measurements of temperature gradients at NTNU Gunnerus Library with a mobile measurement system.
4) Make suggestions for the library improving the indoor environment based on the research results.
5) Prepare a research article.

1.3 Approach

At the beginning of the period, the main focus was on collecting relevant literature regarding indoor environment for storage areas, humid air and effects on the historical content as a consequence of inadequate environment.

Relevant literature has been searched for in several databases, most commonly used were Science Direct and Oria. The books "Achieving the desired indoor climate", "ENØK i bygninger" and "HVAC applications, ASHRAE handbook 2015" were diligently used to collect information regarding the topic.

To get an overview of the situation, visual investigation of the storage areas were conducted from early on, by guidance and supervision from Victoria Juhlin and Stein Olle Johansen, respectively the conservator and head of department at the NTNU Gunnerus Library.

Furthermore, fieldwork was conducted in order to measure the fluctuations in temperature and relative humidity at the storage areas as well as investigation of potential thermal gradients. The measurements have been processed and prepared using the Tiny Tag software and Microsoft Office Excel. Additionally, Excel has been used to analyze the correlation between the indoor and outdoor environment. Matlab has also been used to process the data obtained from the fieldwork.

1.4 Assumptions and practical limitations

The NTNU Technical Management section operating the climate regulation system at the NTNU Gunnerus Library was not able to give the precise percentage of fresh air supplied the recirculated air.

Another limitation is that the outdoor environment presented in this master thesis is collected at Voll, which is approximately 5 km distance from Gunnerus Library, and may not represent the local climate of Gunnerus Library precisely.

Due to a change in the localization of two of the measurement meters, the annual measurements for the two are not complete. Consequently, the measurements of meter 3 and 4 do not give a full annual overview as they were moved in early January.

Relevant case studies with similar conditions as the NTNU Gunnerus Library has been searched for, but not found. Consequently, accurate comparisons were not possible to preform although the obtained knowledge and their recommendations and suggestions are taken into consideration.

2. NTNU Gunnerus library

This chapter presents background knowledge concerning the NTNU Gunnerus Library storage areas. The following sections provide an overview of the location of the library, design of the storage areas, as well as the content in them. Further, the current climate regulation system associated with the storage areas will be elucidated.

2.1 NTNU Gunnerus Library storage areas

The NTNU Gunnerus library is situated in the middle of Norway in the city center of Trondheim. The library is considered to be the oldest scientific library in Norway. Figure 2.1 shows the location of the library. [5]

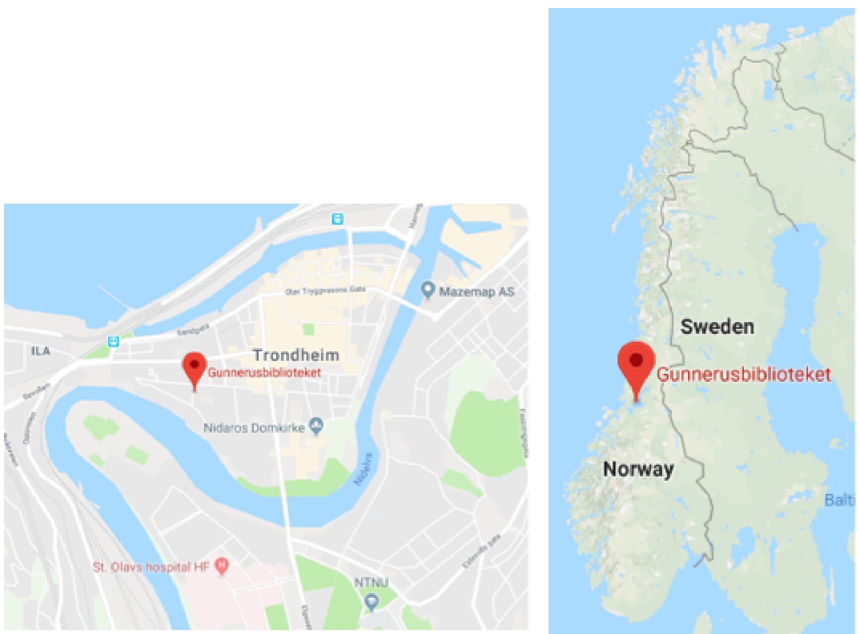

Figure 2.1: Location of the NTNU Gunnerus library

The library is a public NTNU library that is used by employers, students and other visitors. In addition, it also houses a study hall, offices, bindery and storage areas. In this thesis, the climate conditions in the storage area at floor 10 will be accounted for.

Further, the Gunnerus library is one of the most important cultural heritage libraries in the Nordic countries, and has since the late 18th century regularly received gifts and bought collections of literature. The storage areas house a large collection of Norwegian, Nordic and

European works of fiction and non-fiction dating back to the 16th and 17th centuries. To name a few, original manuscripts written by historic Norwegian figures such as Henrik Wergeland and Bjørnstjerne Bjørnson are stored at the storage areas at Gunnerus library. [6]

The collections consist of combinations of materials with different levels of instability. The content in the storage areas comprises of a vast amount of different materials. Overall there are mostly paper-based materials, but also some elements of different types of leather and parchment, textiles, a large range of media (ink, pigments, dyes etc.), various glues and metal components. There are also other materials such as glass, wood and plastics. Some of these materials are more sensitive than others to fluctuations or high/low values of air temperature and relative humidity. Most of the artifacts are composites, meaning that they consist of many different materials. Due to this, the target condition needs to be a compromise, or even special localized environments may be required for some parts of the special collections. [7]

It is essential to point out, that the investigated storage area is not open for visitors and is accessed by authorized personnel only. Meaning that the frequency of visits is limited, but still not accounted for. The visits are normally short and the artifacts are taken out of the storage room when used.

2.2 Description of the storage area

The special collections at NTNU Gunnerus Library are held in four storage areas, on four separate floors, floor 7 to floor 10. Each area measures approx. 200 m^2, with a ceiling height of 2,15 m, and thereby an approx. room volume of 430 m^3. The division of shelving is more or less the same for the four areas, with small adjustments. The exception is floor 7, where a smaller area of the storage is built as a semi-passive storage room, with the intent to prevent sharp fluctuations in the indoor environment. Floor 7 is not included further in this project work.

In general, the shelves run from floor to ceiling and primarily consist of two types; an older structure, which also has a load-bearing function, and a newer shelving structure. It appears after close observation of the shelves that the older structure over time has been affected by humidity and is slowly degrading. The new structure shows no signs of degradation.

Repetitive in all of the storage areas, are shelves packed to its full capacity. At some locations in the storage areas, the artifacts are in very close or in direct contact with the internal walls or ceiling. The limitation in space and structure of the shelves prevents proper airflow through the area. Pictures from one of the storage areas are shown in figure 2.2

Figure 2.2: Shelving in the storage area

In each storage area, the shelving and therefore the artifacts, are located close to the ventilation and cooling canals. This means that the artifacts close to the canals are in direct contact with airflow of varying temperature and strength. The localized and varying airflow combined with the placement of the shelving and artifacts can lead to microclimates with stagnant air holding a different temperature and relative humidity than other areas of the storage. Microclimates such as these can cause damage to artifacts.

Figure 2.3 shows an illustration of the division of shelves in the storage area. In addition, a sketch of the climate system is added to the illustration, showing the supply inlet, exhaust outlets and the cooling system.

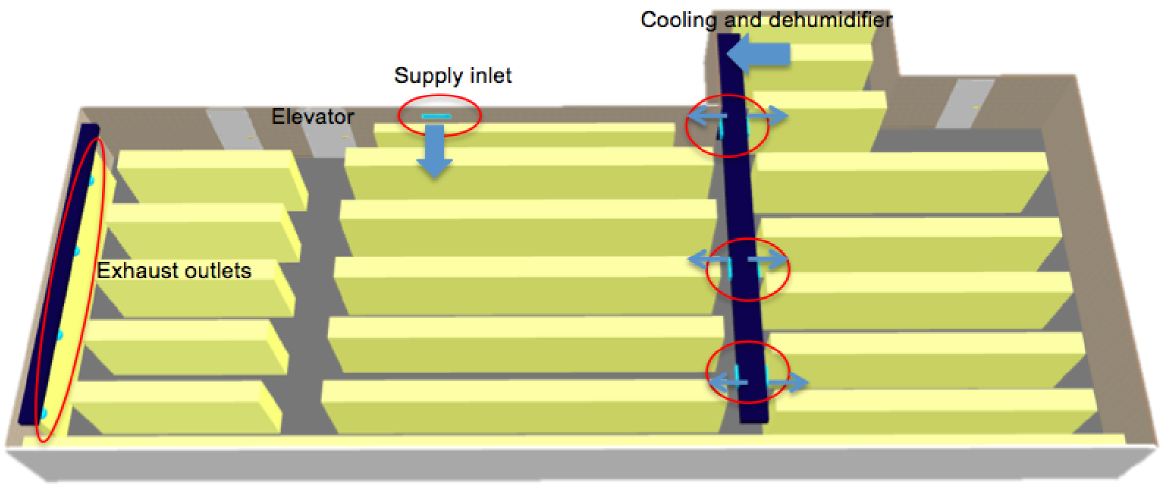

Figure 2.3: Floor plan of the storage area including an illustration of the climate system

2.3 HVAC system

All of the four storage areas share one climate regulation system, which was installed in the 1980s. The system uses re-circulated air and allows for heating/cooling of the storage areas. To achieve a slight over-pressure in the areas, the re-circulated air is mixed with a small amount of fresh air supplied from the main system. The system has a set point temperature of 19 °C, and if the temperature is too low, the temperature of the supply air will be heated by the heating coil. Conditions where the temperature is too high, individual cooling systems will start.

The climate regulation system does not allow for mechanical increase/decrease in relative humidity, despite the effect by a change in temperature. The system is operated externally by "NTNU Technical Management section" and the climate condition is managed from their own loggers located in the exhaust of each area.

Each of the storage areas has only one supply air inlet, which is located on the wall in the middle of the room. There are four exhaust air outlets on the right side of the room. In addition to this, there is an individual cooling and dehumidifier system, placed in each storage area. This is illustrated in figure 2.3 in the previous section.

Fire- and water leakage represents a big risk of damaging the content of the storage areas. Therefore, there are no water- or steam pipes in the storage areas. Previously there were radiators to provide heat, but they are now disconnected as a result of the mentioned risk factor.

Figure 2.4 shows the system sketch of the ventilation system for the storage areas in floor 7-10 at Gunnerus Library.

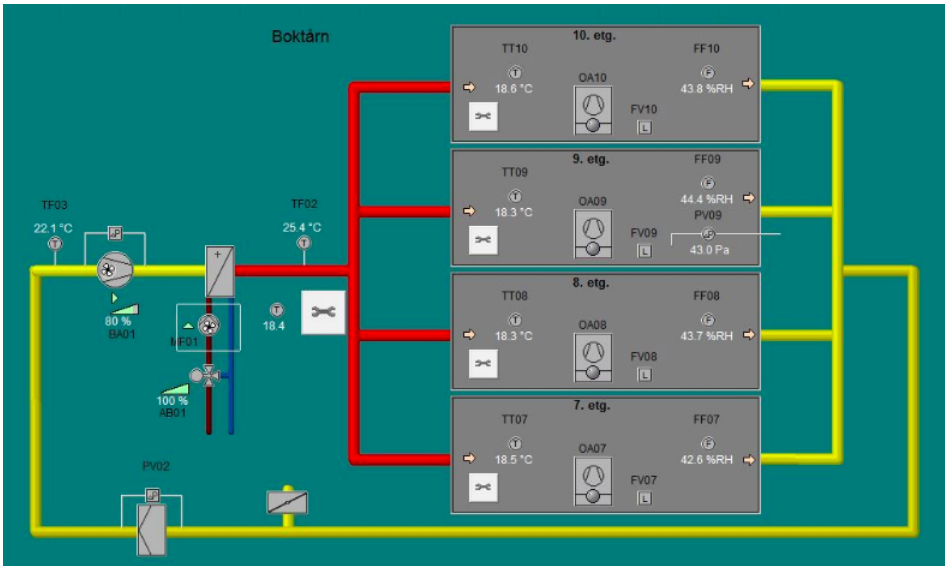

Figure 2.4: System sketch of the ventilation system for floor 7-10

3. Literature review

This chapter will first address some theoretical background knowledge concerning physical environmental variables, followed by factors influencing the indoor environmental quality. Further on, the chapter presents ways to monitor physical environmental variables and gives an understanding of data analysis with machine learning. Consequences related to inadequate storage conditions are presented, as well as an insight into standards and guidelines regarding indoor environmental conditions for library and archival materials. Theory regarding climate regulation systems is accounted for in addition to factors influencing the indoor air quality.

Further on, the chapter addresses the results obtained by the project work prior to the master thesis and gives an understanding of the growing interest for the conservation of cultural artifacts stored in archives, libraries and museums. In the end, some relevant case studies are presented.

3.1 Selection of physical environmental variables

3.1.1 Air temperature

The air temperature, more precisely the dry bulb temperature, is an indicator of the heat content in the air, which is not affected by the moisture content. The dry bulb temperature values are shown along the vertical axis to the left on the Mollier diagram, which is later illustrated in figure 3.1. Air temperature is a variable that is considered to be homogeneous within a space, meaning equal in each point of the space. In reality, however, the air temperature values tend to stratify, increasing in the upper part of the space. The difference is called the thermal gradient and can influence the preservation of the stored artifacts. [8]

At low air temperatures, some materials are in danger of becoming brittle and more easily fractured. However, exposure to too high temperatures represents a great risk for acceleration of the degradation. The anticipated longevity of stored materials decreases as the temperature rises. Due to this enlightenment, it is recommended that storage temperatures are held as low as possible. [9] [7]

However, one of the most significant consequences of inadequate fluctuation in temperature is the relative humidity that follows. A change in temperature will also affect the relative humidity level, meaning that a rise in temperature leads to a decrease in relative humidity, and vice versa. Therefore, they both require control in the same magnitude of importance. [7]

3.1.2 Air humidity

Humidity is the amount of water present in the air and is often referred to as absolute humidity, relative humidity or specific humidity. Relative humidity is the percentage amount of water vapor actually held in a specific amount of air compared to the amount of water vapor that the same amount of air can potentially hold at the same temperature and pressure. The water content in the air can be specified in several ways but the term "relative humidity" is frequently used. [9]

For every material, there is a level of environmental moisture content consistent with maximum chemical, physical or biological stability. When this level either becomes too high or too low, it presents a great risk of damaging the object. [7]

Organic materials such as paper, leather, wood and parchment respond directly to the level of relative humidity. Too high levels will encourage mold activity, while too low levels lead to desiccation, shrinking and cracking of the material. Literature states, when the level of relative humidity exceeds 65 %, the threat for mold growth becomes more and more significant. Graduate change in relative humidity and temperature, often as a result of seasonal changes, can be considered acceptable if it occurs over a period of one month or more. [10][11]

The specific humidity is defined as the proportion of the mass of water vapor to the total mass of moist air. Furthermore, the specific humidity does not vary as the air temperature or pressure of the air changes. As long as moisture is not added or subtracted, the specific humidity remains constant. [9]

3.1.3 Mollier diagram

The Mollier diagram is a variant of the psychometric chart and gives a graphic representation of the relation between air temperature, moisture content and enthalpy at a constant air pressure of 1 bar. The chart is often used in building physics and is a way to approximate changes in state for the air. [1]

Figure 3.1 illustrates a t-x diagram and is a simplification of a Mollier diagram to show the relation between the different variables. This representation of values can be useful to evaluate if the comfort zone is guaranteed within a space.

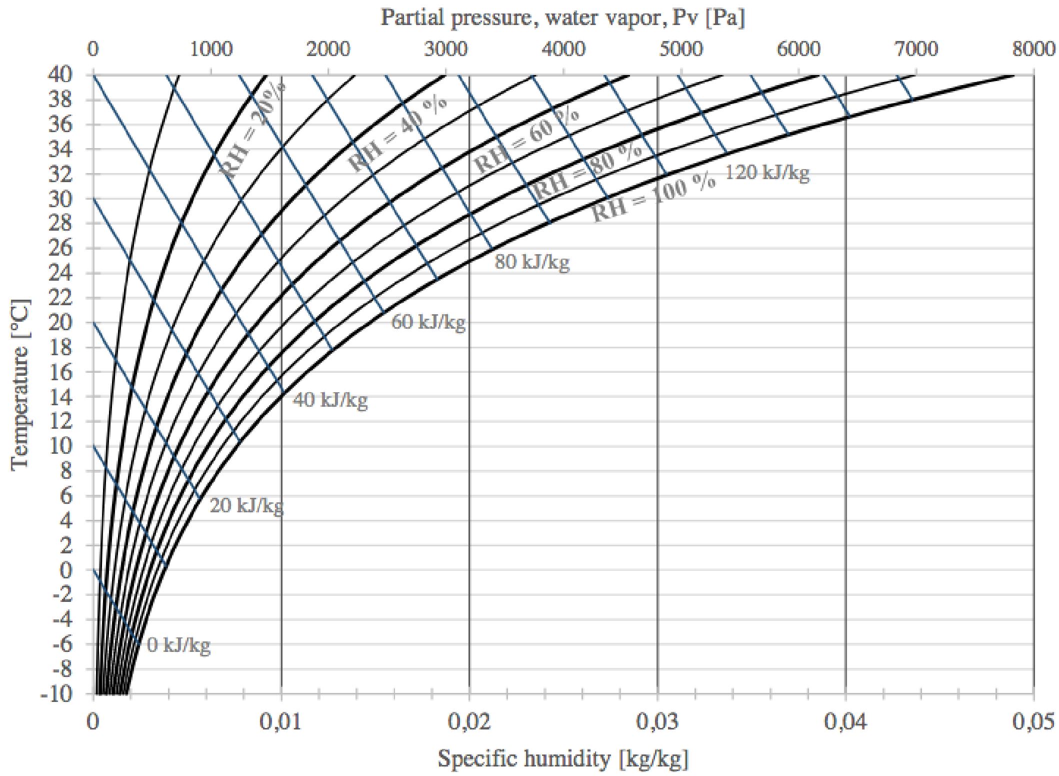

Figure 3.1: Simplification of the Mollier diagram [1]

The horizontal x-axis gives the specific humidity and the vertical y-axis gives the air temperature. The lines curving from the origin of the diagram and increasing upwards to the right are the relative humidity lines. The saturation line is shown by the rightmost of those lines and is the state where the air is saturated with water vapor.

When managing environmental conditions, it is essential to understand that air is capable to hold more water vapor at higher temperatures. In the Mollier diagram in Figure 3.2 there is illustrated two scenarios which are equally saturated, but differ in specific humidity and therefore also differ in temperature. This represents the fact that higher temperatures have the ability to store more humidity than lower temperatures. The results for the two different scenarios are presented in table 3.1.

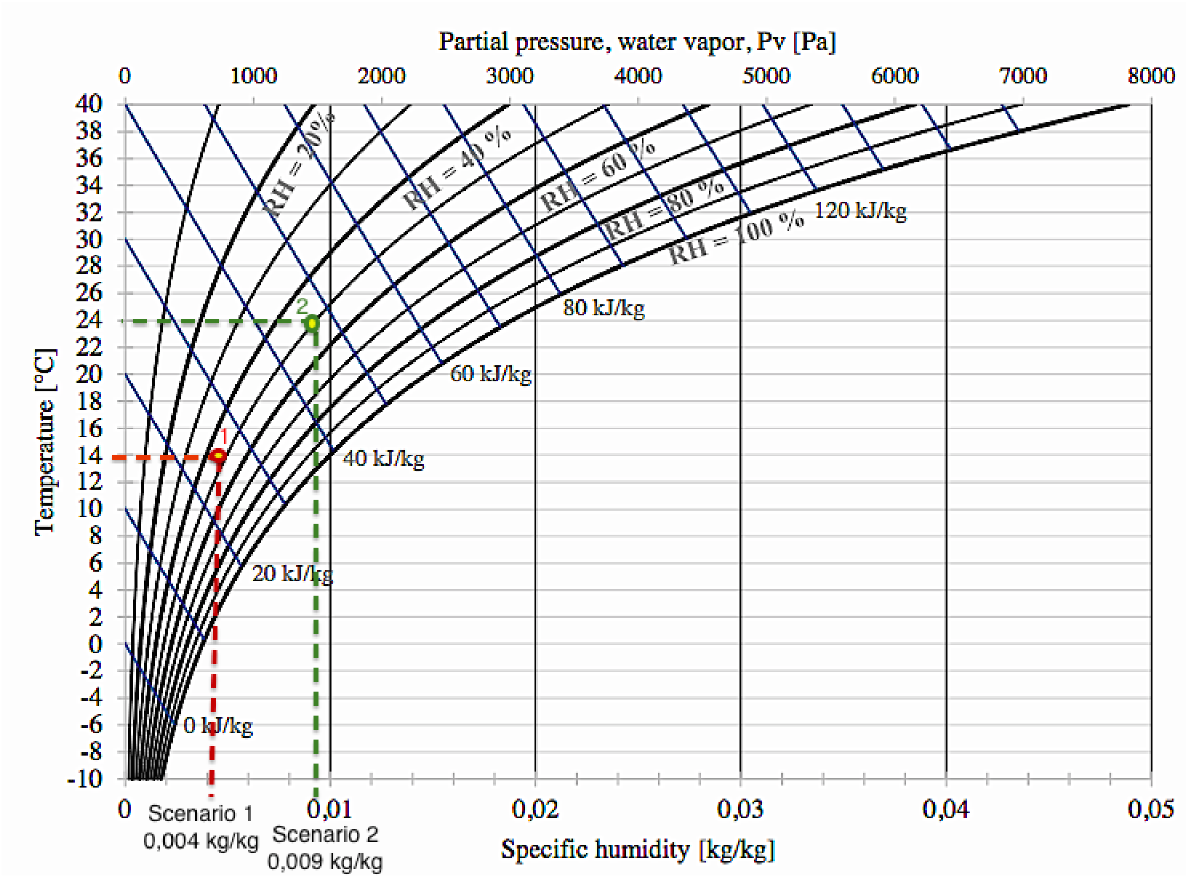

Figure 3.2: Simplification of the Mollier diagram with sketch of scenarios [1]

Table 3.1: Results for the two different scenarios

	Air Temperature	Relative humidity	Specific humidity
Scenario 1	14 °C	50 %	0,004 kg/kg
Scenario 2	24 °C	50 %	0,009 kg/kg

3.2 Factors influencing indoor environment quality

The state of the air is at constant change, and will always strive to reach the equilibrium with the surroundings. The following subsections present outdoor and indoor impacts regarding the indoor environment.

3.2.1 Outdoor

The state of the outdoor air varies depending on seasonal variations and global climate. Both temperature and pressure differences between the outdoor and indoor air leads to heat and air transport through the building envelope. The temperature and humidity level varies throughout the day and season. Weather data should be measured as close as possible to the real conditions experiences by the building, and hence recorded from the closest meteorological station. In figure 3.3, there are presented the outdoor conditions of relative humidity and temperature at Voll, Trondheim, for 2018. [12]

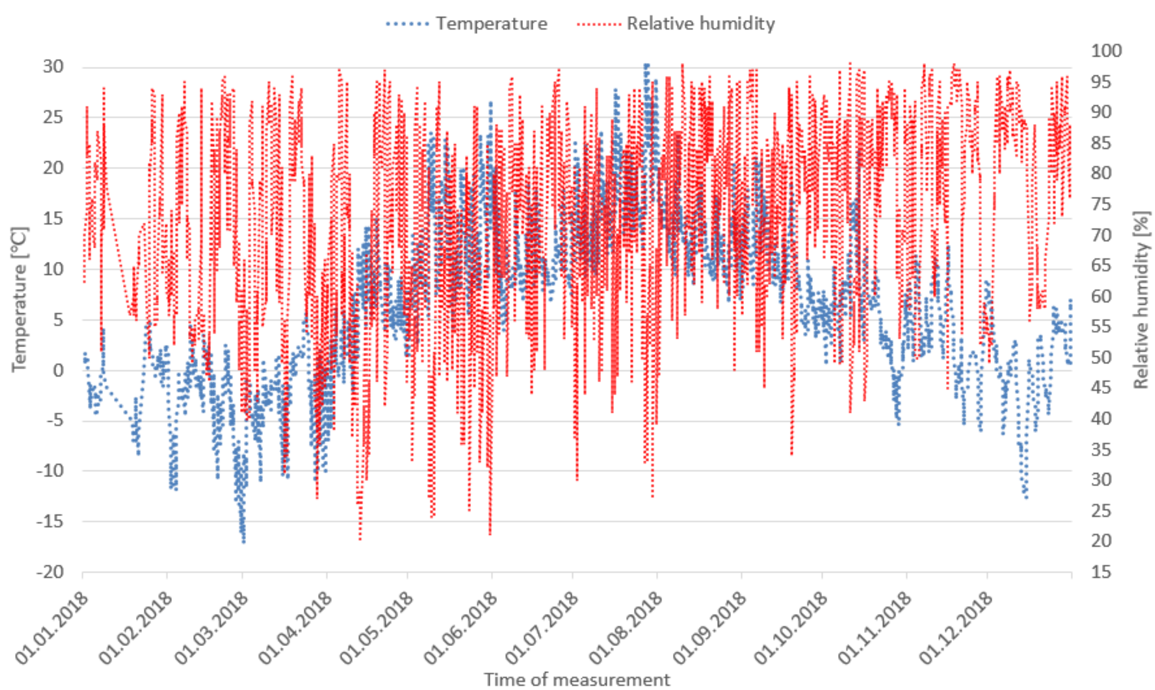

Figure 3.3: Outdoor temperature and relative humidity in Trondheim, Voll, 2018 [2]

Values for outdoor temperature and relative humidity from Voll weather station are collected from the Norwegian Meteorological Institute, MET Norway. As Trondheim have four distinctive seasons, the graph presents evident variations in thermal conditions throughout the year with outdoor temperature ranging from -17 to 30 °C.

Exterior insulation provides good opportunities to eliminate air leaks, and to decrease the impact of the outdoor climate conditions concerning the indoor environment in the storage areas. Insulation of the outer constructions could contribute to a more stable indoor climate, with less external influence. In other words, this means that the relationship between the outdoor and indoor is dependent on factors including type of ventilation, weather season, insulation and behavior of the occupants. [12]

3.2.2 Indoor environment

There are a wide variety of environmental sources found in the indoor environment, such as building materials, furniture, human activity, stored artifacts and also the building envelope. The indoor concentration of pollutants, and in this case humidity, is determined by the strength of indoor pollution sources and the air supplied by both ventilation and infiltration. [9]

The humidity content in an indoor environment can be determined by several factors. The main parameters for the determination are the ventilation rate through the building envelope, the condition of the air supplied the environment and the moisture production from indoor sources. [9]

3.3 Monitoring physical environmental variables

Monitoring of the indoor environment is an on-going process that takes considerable time and it is important to collect long-term data, in order to obtain an adequate overview of the annual climatic changes. The positioning of instruments to record the indoor environment can be a complex decision and is often determined by the number of data loggers available. [13]

Both air temperature and relative humidity must be measured in spots, which reflect the climate experienced by the artifacts. In order to achieve this, it is advisable to perform measurements at several points in an area; close to walls, close to the floor, close to the ceiling, in the center of the room and close to the artifacts that must be preserved. [8]

While analyzing data of air temperature and relative humidity, it is interesting to evaluate [8]:

- Daily trends of minimal/maximal thermal excursion.
- Weakly/monthly trends, showing the variations in the width of minimal/maximal thermal excursion and the relations between internal and external condition.
- Annual trends, from which it is possible to evaluate the seasonal cycle.

While analyzing the trends, attention must be paid to [8]:

- Peak, minimum and maximum values, which represents the extreme conditions.
- Abnormal values, punctual or lasting a certain time, that might be due to heating systems, presence of humans, or particular episodes of ventilation of the environments.
- The relation between indoor and external conditions of hygro-thermal parameters.

3.4 Data analysis

Machine learning is a way to analyze data, make assumptions, learn and provide predictions at a scale of detail that is impossible for humans to manage. Machine learning is a part of artificial intelligence and program machines to optimize performance criterion by using example data or past experiences. The models can be both predictive to make predictions for the future, or descriptive to gain knowledge from the data. The algorithms build mathematical models based on sample data in order to make predictions or decisions without being explicitly programmed to perform the task. There are several machine learning algorithms that differ in approach, type of input and output data and the type and difficulty of the problem that they are intended to solve. [14]

Machine learning provides systems the opportunity to recognize patterns and make predictions from huge data sets. Further on in this thesis, there is used a simplified version of machine learning by using Excel, to find the correlation between the indoor and outdoor environment. Computer tools such as Python, R and Matlab have the advantage over Excel that they more easily and faster handles big data sets and a large number of nodes, including overlapping nodes. On the other hand, Excel has the advantage of being interactive. [14]

3.4.1 Correlation between indoor and outdoor environment

To analyze data is a process that inspects and transforms data in order to extract useful information that is required by using analytic and logical reasoning. The correlation coefficient is a statistical measure that calculates the strength of the relationship between the relative movements of two variables. There are several data tools that calculate correlation, and Microsoft Excel can be used to find a simple correlation between two variables. [15]

There are different types of correlation coefficients, but the most commonly used is the Pearson Correlation (r). The Pearson correlation measures the strength and direction of the linear relationship between two variables. This method is not able to neither capture nonlinear relationships nor differentiate between dependent and independent variables.

In order to calculate the correlation between two data sets, it is possible to use built-in correlation formulas in Excel, for example: Correl or Pearson. In cases where there are more than two data sets, one must use Excel‘s Data Analysis Plugin. The Pearson and Correl function both compute the Pearson linear correlation coefficient, the only difference is that in earlier versions of Excel the Pearson function may exhibit some rounding errors. In more recent versions, however, both the functions should provide the same results.

Table 3.2 shows a rule of thumb for interpreting the strength of a relationship based on the absolute value of the correlation coefficient (r).

Table 3.2: Rule of thumb for interpreting strength of correlation [4]

Correlation coefficient, r (absolute value)	Strength of relationship
r < 0,3	None or very weak
0,3 < r < 0,5	Weak
0,5 < r < 0,7	Moderate
r > 0,7	Strong

Coefficient of determination, r^2, is the square of the coefficient of correlation. R squared is a measure that assesses the ability of the model to predict how many data points that fall within the line formed by the regression equation. The coefficient of determination is a value between 0 and 1, and respectively indicates the regression line to represent none or all of the rate. In general, high values of coefficient of determination indicate that the model is a good fit for the data, although interpretations of fit depend on the context of the analysis. [4]

When investigating correlation coefficients in Excel, the best way to get a visual representation of the correlation between the data is to create a scatter plot with a trend line. Another way to illustrate the correlation is by creating an XY plot that draws each variable separately.

Potential problems associated with calculating the correlation coefficient in Microsoft Excel is that the Pearson Product Moment Correlation only reveals a linear relationship between variables. Furthermore, the Pearson correlation cannot distinguish dependent and independent variables. Meaning, that one should be aware of the data for the parameters supplied.

3.5 Consequences of inadequate environment

Inadequate indoor conditions of relative humidity, temperature and air distribution may cause damage of different kind and scale on historical artifacts. Traditionally these concerns have led to narrow specifications for guidelines for museums, archives and libraries. The main categories of degradation are biological, mechanical and chemical degradation. For optimal preservation of paper-based material, it is beneficial to minimize the biological, mechanical and chemical stress on the content of the archive, by maintaining relatively low and stable values of air temperature and relative humidity.

3.5.1 Biological degradation

Biological degradation is the decomposition of organic matter by microorganisms such as bacteria and fungi. Due to the organic nature and its hygroscopic properties, paper can be referred to as a good source of nourishment for mold growth and other microorganisms. Biological degradation corresponds to mold growth on organic matter and is a consequence of inadequate temperature and relative humidity. Generally, mold begins to reproduce around 65 % relative humidity. [7] [16] [11]

3.5.2 Mechanical degradation

Very low or fluctuating relative humidity or temperature can lead to mechanical damage of artifacts. The fundamental cause is expansions and contractions of materials, combined with some form of internal or external restraint. One of the main sources of mechanical degradation is that paper tends to absorb moisture faster than it desorbs. Thus, fluctuations of thermodynamic parameters over short periods may result in swelling, tearing and other structural degeneration. A rather low humidity or temperature also increases the stiffness of organic materials, making them more vulnerable to fracture. The effects of expansion and contraction of the materials are considered to be cumulative in a long-term perspective. [7] [16]

3.5.3 Chemical degradation

Chemical deterioration is defined as increased aging due to chemical reactions within the books or with the surroundings. The deterioration accelerates when the temperature is too high. Higher temperature and a moderate amount of moisture can lead to a rapid decay in chemically unstable artifacts, especially some paper-based and other archival materials. [7] [16]

3.6 Current standards and guidelines

Authorities and different standards disagree on the ideal environmental condition for library and archival materials. In literature, there are a number of different recommendations, where some are more precise than others. Recurring for all is the crucial requirement to maintain stable conditions regarding relative humidity and temperature. There are specifications for both seasonal changes, which refers to changes in condition over a period of one month or more, and short-time fluctuations, which refers to a time period of 12-24 hours. A prerequisite for the standards and guidelines is that every archive environment is different, and needs to be evaluated and decided as a collaboration between an experienced conservator, a climate control engineer combined with in-house expertise. [10]

3.6.1 Standards and guidelines for thermo-hygrometric parameters

ISO 11799:2015 by the The International Organization for Standardization (ISO) was adopted as Norwegian Standard NS-ISO 11799:2015 in 2016 as the standard for "Document storage requirements for archive and library materials". The standard applies to archive and library materials held in repositories, where mixed media may be stored together with paper-based material. This standard can be used for general guidance concerning storage of archive and library materials, and specify four different temperature ranges for the storage of mixed collection; Room, Cool, Cold and Subzero, shown in table 3.3. The standard stresses the importance of doing research on the local climate conditions and adapting the indoor air quality control based on information about the geographical area that the storage area is intended for. [17]

Table 3.3: Temperature ranges for storage of mixed collections

Condition	Air Temperature [°C]	Relative humidity	Suitability
Room	16-23		Fair
Cool	8-16	Assuming 30-40 %	Good
Cold	0-8	for each condition	Very good
Subzero	-20-0		Necessary for some materials

PD 5454:2012 Guide for the storage and exhibition of archival materials by BSI Standards Publications gives guidance and recommendations with the purpose to help create and maintain appropriate conditions for archive storage. The guidelines recommended environmental conditions for mixed storage are shown in table 3.4. PD 5454:2012 also states that the environment chosen for a mixed collection of materials should be based on protecting the most sensitive document within it. Gradual changes in relative humidity and air temperature from upper- to lower limit, often as a result of seasonal changes, can be acceptable if it occurs over a period of one month or more. However, this standard does not specify any values for acceptable seasonal fluctuations. [11]

Table 3.4: Environmental conditions for mixed storage

	Air Temperature [°C]	Relative humidity [%]
Mixed storage	13-20	35-60 %

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), has been developing indoor climate guidelines for different climate classes for museums, galleries, archives and libraries. The classes are divided from AA-D, where AA is the most strict and D the least strict fluctuation and set-point regulations. The temperature and relative humidity specifications for collections for the two uppermost classes; AA and A, are given in table 3.5.

Table 3.5: Temperature and relative humidity specifications for collections

Set point	Class of control	Short fluctuations plus space gradients	Seasonal adjustments in system set points
50 % RH.	AA	± 5 % RH, ± 2 °C	No change in RH, ± 5 °C
15-25°C Temperature	A	± 5 % RH, ± 2 °C	± 10 % RH, ± 5 °C

Class A is often considered as the optimal choice for most museums and galleries, as the AA has a higher potential for energy consumption in addition to being problematic to achieve for buildings located in cold climates.

The specifications given by ASHRAE were not intended to be prescriptive but had the intention to provide a framework of knowledge to help develop custom climate specifications for any particular museum. However, without profound knowledge of factors affecting the risk profile for the content, a translation from a risk profile agreed upon into climate specification is very difficult. These factors may include the composition and the sensitivity of the collection, construction of the building, outdoor climate conditions and impact by visits etc. [18]

3.6.2 Ventilation requirements

Adequate airflow and air distribution are necessary to prevent stagnant air and the formation of microclimates around books and shelves. There are several factors applicable to achieve and secure properly distribution of the room air. The most important ones are an appropriate selection of air-terminal units, the supply air temperature in relation to the air temperature in the room and air velocity of the supply air. [11] [19]

The rate of air circulation should be determined from the cooling load to maintain the recommended conditions of temperature and relative humidity. The optimal air change rate will vary depending on the size and the content of a storage area. The recommended value of air changes is often between six and eight air changes per hour. [19]

In order to provide a proper air distribution in the storage area and to avoid areas with stagnant air, a minimum amount of re-circulated air is preferable. Positive pressure inside the storage should be maintained by including up to 5 % fresh air to the air flow. A small positive pressure inside the building is desirable, as it reduces the air infiltration through the building envelope. Infiltration occurs through the envelope and depends upon the difference of air pressure between the inside and outside. [11]

Separate ventilation systems are recommended to control the indoor air quality for each of the storage areas individually. Furthermore, it is recommended that the shelving is ventilated and that the artifacts are stored at least 50 mm from the floor, wall and ceiling. This is to ensure that air circulation behind and around the artifacts is possible and to avoid forming of microclimates. PD 5454:2012 recommends an air gap of at least 150 mm between collections and the building fabric, and 50 mm between collections and the shelf above. It is also stated that supply air should not blow directly towards collections. [11] [19]

3.7 HVAC-systems for storage areas

To achieve the environmental goals for the storage areas it is important to determine the suitable HVAC-system, which is a system of heating, ventilation and air conditioning. The purpose of the HVAC-system is to simultaneously control parameters of the supply air, and thereby the air in the conditioned space; temperature, humidity, cleanliness and air distribution in the room. HVAC-systems for preservation environment must maintain stable conditions for temperature and relative humidity, as well as secure an even air movement within the space. Special HVAC system usually is divided into two categories; Museum and galleries, and other spaces where sensitive objects are displayed, and libraries and archives, which primarily store paper-based collections and objects. The main requirement for the system is high performance with low or limited annual operating budgets. [9] [20]

Depending on how large the fluctuations in the heat surplus and heat deficit are, certain types of HVAC-systems are more suitable than others. Despite the fact that air-water systems dominate in the northern European climate, an all-air system is the preferred choice for storage areas to avoid the presence of water pipes in the storage areas, and the risk they represent. In addition, an all-air system allows a stricter control of temperature, relative humidity and pollutant concentration. [9] [21]

In order to control airflow rates provided to a room, there are two main methods, constant air volume (CAV) and variable air volume (VAV). In a constant air volume system, the airflow rate is held constant, whereas the temperature of the supply air is varied in the response to the heat surplus/deficit in the zone. In comparison, the supply air temperature in a variable air volume system is constant, whereas the airflow is varied in response to the heat load measured. [9]

A proper airflow filters the room air and controls the relative humidity and temperature and will avoid the growth of mold. The mentioned factors are usually best met with a CAV-system. A VAV-system tends to be inappropriate for storage areas such as at NTNU Gunnerus Library. This grounds in inadequate humidity control and airflow, maintenance disruption and inflexibility to meet the environmental demand. The cost and space required for a proper designed VAV-system usually gives no advantages over a CAV-system. Although a VAV-system may lead to lower energy consumption, it will out of most times be at the expense of the content in the storage areas. [9] [20]

3.8 Project work prior to the master thesis

This section summarizes the results and conclusions made in the project work carried out in the autumn 2018, with the title "Investigation of indoor environment quality in the storage areas of the NTNU Gunnerus Library". The project work focused on investigating the indoor environment of the historic storage areas at the NTNU Gunnerus Library through monitoring the thermo-hygrometric parameters; temperature and relative humidity.

The indoor environment of the storage areas of floor 8 and 10 was monitored for six weeks. The measurements were compared with results from the long-term measurements carried out by Victoria Juhlin, paper- and book curator at the library. In view of the fact that the storage areas share one climate regulation system, a comparison of the environment of the different floors and the different locations inside the storage area was made. The project work detected variations in the environment for both different floors and locations inside the areas.

Figure 3.4 compares the data gathered from the six-weeks measurements and the long-term measurements. From the figure, one can see that they correlate. Moreover, with the accuracy of the measurement devices in mind, no conclusions can be drawn from the difference in fluctuations shown in the graph. Due to this result, the measurements made by the long-term meters are assumed to correspond to the environment and will be used further in the analysis.

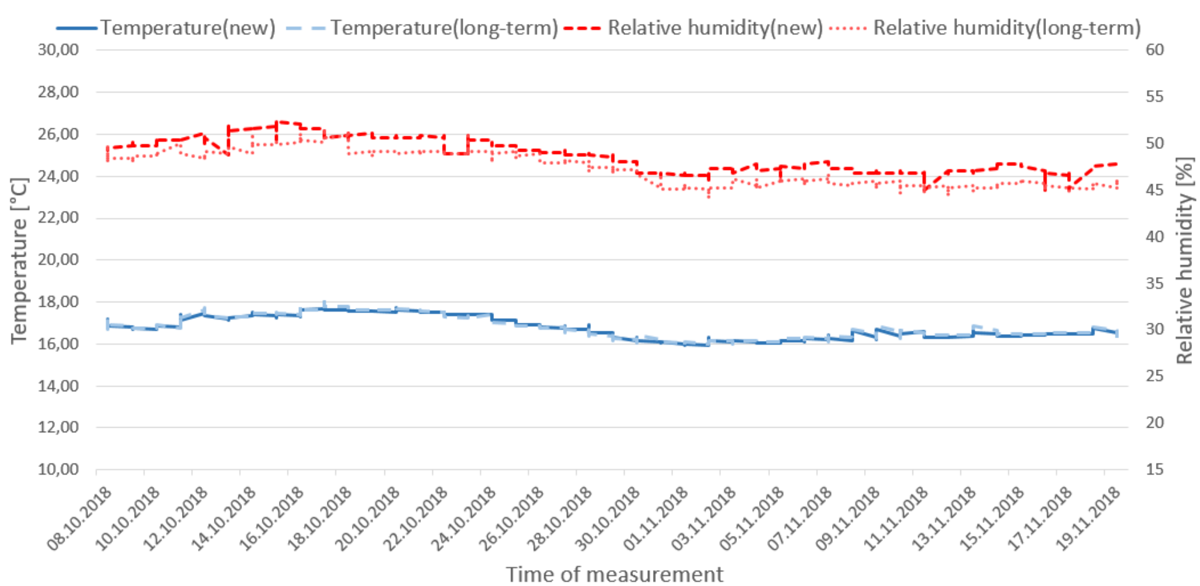

Figure 3.4: Comparison of six-weeks measurements and long-term measurements, project work

Analyses of the measurements in relation to standards and guidelines were made and the temperature and relative humidity fluctuations were evaluated. The analyses of the measurements indicated a wide range of temperature and relative humidity to which the storage areas are exposed. Figure 3.5 displays the temperature fluctuations for storage area 10 measured from April to December 2018.

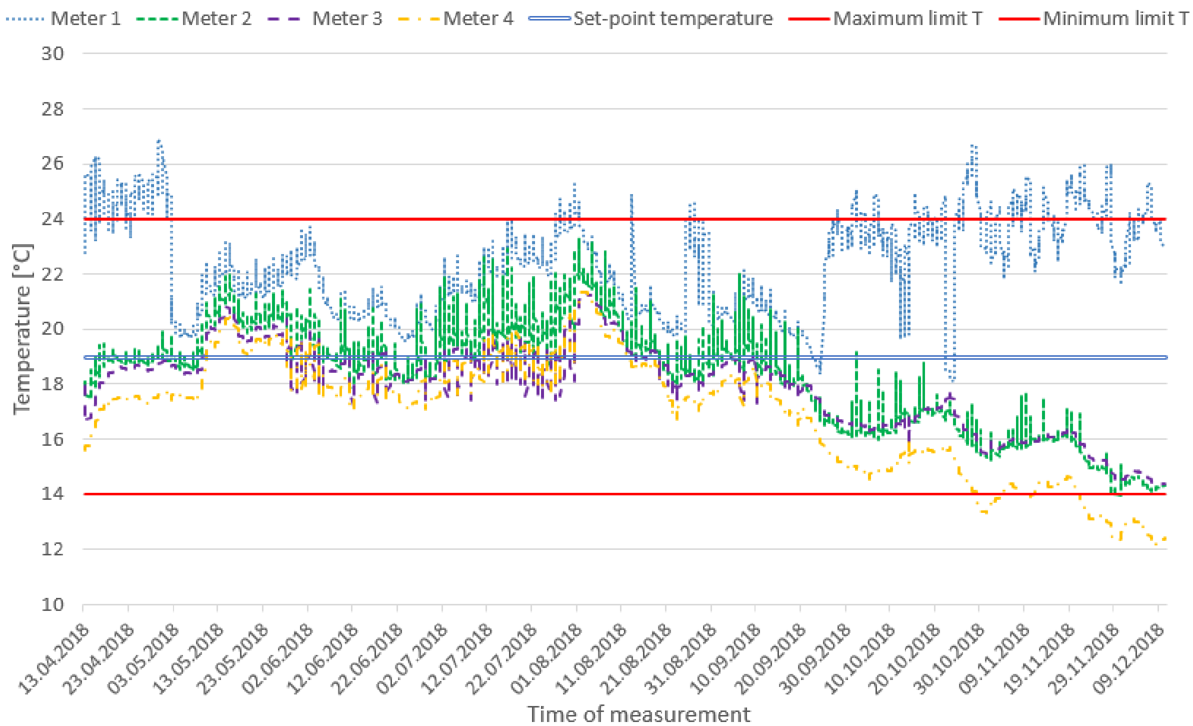

Figure 3.5: Long-term temperature measurements, project work

Further on, the project work concludes that monitoring of indoor environment is a time-consuming task. In order to achieve a reliable and useful overview of the indoor environment at the storage areas, it is necessary to consider a longer measuring period, including all the seasons. Therefore, this master thesis presents analyses of the environment of a whole year.

The results suggest that the assumption of a varying environment in the storage area is correct, and that measurements conducted by the "NTNU Technical Management section" of the exhaust air in each floor, will either underestimate or overestimate the climate condition of the area. Recurring for the measurements were substantial variations in the state of the air throughout the storage area. Due to this, vertical thermal gradients are evaluated further in this master thesis.

3.9 Earlier indoor climate measurements

The study of indoor environment and microclimate is widely discussed in literature, with the studies of Camuffo and Thomson as main documents in the area. [22] [23]

Preservation of historical artifacts is profoundly influenced by fluctuations in temperature and, especially, relative humidity. Thus, it is crucial to maintain stable hygrothermal conditions in museums, libraries and archives who store those artifacts. Studies also show that other parameters, such as the vertical thermal distribution of the air masses, the concentration of pollutants, lighting and ventilation strategies can affect the degradation of artifacts. The recurring focus of the monitoring and the analysis are mainly the thermo-hygrometric parameters; temperature and relative humidity. In addition, researchers also try to evaluate the impact of air pollutants, such as CO2, SO2 and NO2, on collected exhibits. [21]

There has been a growing interest for the tutelage, the restoration of historical cultural resources and the necessity of better conservation of works of art and cultural heritage housed in museums, galleries, libraries and archives. Literature enlightens the need for appropriate HVAC systems in order to maintain the optimal conditions for preservation.

There are several studies evaluating and monitoring the indoor environment of historic buildings with respect to the risk management of cultural properties. Financial and construction restrictions often complicate the use of advanced HVAC systems, especially for historic buildings. In such cases, the only way to improve the quality of the microclimate in the rooms is to amend the control of the existing system. [24]

Further, some relevant case studies are accounted for in the following subsections.

3.9.1 HVAC systems to control microclimate in the museums

Italian researches at the University of Naples(DETEC), have written a paper concerning HVAC systems to control microclimate in museums. The paper presents a case study regarding the HVAC systems of a simulated museum, built according to a modern conception. The focus of the paper is particularly on the HVAC system of the exhibition room and stock space, which require an appropriate system in order to prevent, control and limit the degradation process of the artworks. [21]

The paper recommends all-air systems, with a centralized air-handling unit that keeps filtration, dehumidification, humidification, maintenance and monitoring away from the collections. An all-air system is the preferred choice, not only because it allows strict control of temperature and relative humidity and pollutant concentration, but also because it avoids the presence of water pipes and removes the risk of water leaks. [21]

Further, the chosen HVAC system for the study-case is represented by a single duct multi-zone constant volume air system (Multi-zone fan system, MZS), with or without desiccant dehumidifier, which is one of the most cited systems in literature for this kind of system applications. The study presents separate MZS systems, where one is dedicated to the exhibition space and the stock zone and the other system to the remaining zones of the museum. [21]

Based on the results, the study concludes that strict control of temperature and relative humidity is costly, but also necessary for long-time conservation of the artworks. However, as a way to reduce the operating cost, they suggest separate HVAC systems for space that require strict control and space that do not has as stringent requirements for indoor environment control. [21]

3.9.2 Necip Paşa Library

The Necip Paşa Library in Turkey was built in 1827 and holds historically valuable and prominent manuscripts and books. The aim of the research was to assess the degradation potential of indoor climate on valuable manuscripts dating back to the 12th century. [16] [25]

Five data loggers, four inside the museum and one outside, were used for the measurements of temperature and relative humidity. Temperature and relative humidity were continuously monitored for one year and analyzed by the requirements indicated by ASHRAE. The analysis was made to evaluate the mechanical, chemical and biological degradation risks correlated to the monitored variables. [16] [25]

A split-type air-conditioner is placed into the Entrance for cooling and heating purposes, whereas there is no HVAC system where the manuscripts are held. Therefore, the manuscripts are preserved in free-floating microclimate. The manuscripts are separately preserved in a structure made of wood-framed glass shutters and fences, and the air circulation is assumed to be maintained by opening of the shutters and fences. [16] [25]

Two cases, one introducing mechanical ventilation to the main hall and one introducing natural ventilation, were integrated into the library and tested via a Building Energy Performance (BEP) model to use the cooling potential of both systems on the indoor environment. Both of the ventilation strategies were bound to the external weather conditions of the Library, where the outdoor temperature in the summer out of most times are above 20 °C. Out of this reason, both of the ventilation strategies did not qualify as good enough to keep the temperature requirement in the manuscript zone. [16] [25]

The study concludes that in order to reduce the degradation risk, an HVAC system to control the temperature and relative humidity is required. However, the planning of the HVAC system on historical buildings requires attention, a more multidisciplinary viewpoint, and more qualitative research. The result of the study suggests that wrong HVAC system designs may cause considerable damages and degradation on manuscripts. Therefore, the indoor environment and hygrothermal behavior of the library needs to be well-analyzed before any decisions nor installations is done. [16] [25]

3.9.3 Classense library

The paper concerning the Classense library in Italy investigates the interaction between the outdoor environment and the indoor microclimate. Classense library houses about 800 0000 bibliographic units of different categories, including prints, manuscripts and maps. The aims of the research were threefold: the first one was to correlate the indoor microclimate of the Classense Library with the outdoor climate conditions. The second was to compare the monitored data with the specific values recommended by different norms and standards. The final aim, was to apply a mathematical model to confirm that the correlations between the outdoor and indoor pollutants level can be explained in terms of the building walls characteristics, e.g. their ventilation and air exchange rates. [26]

The measurements were carried out in two periods of the year, one in the summer period and one in the winter period. The periods were chosen as they are considered to be the "extremes" from the meteo-climatic point of view. No HVAC system is installed in the library. The opening of windows is planned and made in collaboration by the libraries curator and director of the library. This method is, according to "UNI 10586", the suggested solution for situations where no HVAC system is installed and an air exchange needs to be ensured. Furthermore, the paper points out that the investigated rooms are only accessed by authorized personnel only. [26]

The result of the study shows that the Classense Library had, due to the heat-sink in the building materials and the packed shelves with the thermal and hygric inertia of the books, high thermal inertia. However, because of extreme outdoor weather conditions, the values of temperature and relative humidity is observed at values outside the range of standards for conservation of librarian arts of works. [26]

3.9.4 Malatestiana Library

Malatestiana Library in Italy, a UNESCO Heritage, is one of Historic Indoor Microclimates study cases. The library does not possess any kind of technical systems, and the regulations of the indoor microclimate characteristics are done exclusively by managing the openings of windows. [27]

Evident consequences on microclimatic indoor conditions are happening due to the climatic variations, which include both daily and seasonal meteorological variations. The monitoring activity of the indoor microclimate conditions at the Malatestiana Library consisted of monitoring temperature and relative humidity. Given the absence of technical systems, the indoor air temperature follows the trends of the external conditions. [27]

The study evaluates the distribution of temperature and relative humidity in the environment. The result shows that the distribution was not homogeneous, as there was some degree of variations. In order to elaborate "cartography" of indoor microclimatic conditions, the study suggests the planning and positioning of a continuous monitoring system of the library environment. [27]

3.9.5 Hermitage Museum Amsterdam

Full-scale measurements were conducted in the Hermitage museum located in Amsterdam. The Hermitage museum works predominantly with loans from the State Hermitage Museum (St. Petersburg, Russia), but other exhibitions in collaboration with other museums are also being exhibited. The exhibitions are open to visitors, which make an impact on the internal heat and moisture production of the indoor environment. The employed indoor environment specifications are 21 °C and 50 % relative humidity without permissible fluctuations, aiming for a stable museum environment. [18]

The aim of the study assessed the energy impact of the three levels of museum climate presented by the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE). The comparison of the energy consumption is based on full-scale dynamic measurements of the air-handling unit (AHU) system. Measurements of temperature and relative humidity were conducted in order to monitor the fluctuations compared to standards. [18]

Hermitage Museum is originally from the 17th-century, but the construction has over time been changed frequently. The most recent renovation dates back to a period from 2007-2009. During this renovation, the building envelope was upgraded to a high insulation level, floor heating was applied in the non-exhibition areas, all-air systems were installed to condition the exhibition areas, and also an Aquifer Thermal Energy Storage (ATES) system was installed for heat and cold storage in the ground. [18]

An AHU conditions the main exhibitions. The AHU consists of a mixing section (outdoor air mixed with recirculation air), dust filter, cooling coil, steam humidifier, humidification coil with bypass, fan, heating coil and a filter section. Most of the time the air is being recirculated. The amount of fresh outdoor air is managed after the CO_2 level and increases when the level exceeds the threshold value of 1000 ppm. [18]

The paper concludes that there is a significant energy saving potential for relaxing the temperature and relative humidity specifications of the museum. The result shows that by relaxing the specifications, the hourly fluctuations have decreased and the daily fluctuations have increased; The museum's hygrothermal mass limited fluctuations. Lastly, they recommend that the most sensitive object should be placed and stored in display cases. [18]

4. Methodology

This chapter gives an insight on how the visual inspections were conducted, followed by a walk-through of the planning, set up and execution of the field measurements conducted at the NTNU Gunnerus Library. First, the execution of the measurements of potential vertical thermal gradients is explained including the process of constructing the mobile car. Additionally, the measurement points throughout the storage area are illustrated. In the end, the continuous temperature and relative humidity measurements are accounted for, followed by information concerning the measurement instrument used.

4.1 Visual inspection

Visual inspections were conducted in the four storage areas at the NTNU Gunnerus library. All the inspections were supervised by either Victoria Juhlin or Stein Olle Johansen, due to the strict security regulations of the library. In the inspections of the storage areas, the focus was on localize the supply inlet, exhaust inlets and the cooling system. Additionally, it was paid attention to the placement of the shelves, in particular, the placement in relation to the walls, floors, ceiling and climate regulation canals.

Out of the four storage areas, floor 10 was considered to be the most appropriate space to perform the measurements. This decision was made in collaboration with the curator at the Library. The storage area at floor 10 was chosen, as it is more spacious between the shelves than the other floors. Consequently, reducing the risk for the mobile car to crash into the shelves and do damage to artifacts.

4.2 Execution of measurements of thermal gradients

The project work prior to this master thesis indicated a varying environment through the storage areas of the NTNU Gunnerus Library, which led to an interest in identifying potential vertical thermal gradients in the area.

The storage areas have very strict security regulations regarding accessing the areas. Hence, the execution of the measurements needed to be done during working hours. To cover the whole area in the limited time frame, the experiment was executed during three separate days, each day covering 9 measuring points. Consequently, the logging took place March 25th, 26th and

27th, each day from 8 am to 16 pm. The eight loggers were programmed to start simultaneously, with a sampling interval of one minute.

Due to the response time of the Tinytag data loggers, the measuring period of every point was set to be 40 min, which included 25 minutes for the loggers to stabilize and 15 minutes of real measurements. After finishing the measurements of each day, the measured data were collected and the loggers were restarted in order to perform new measurements the next day.

4.2.1 Construction of the mobile car

In order to perform detailed field measurements of potential thermal gradients at NTNU Gunnerus Library, a mobile measurement system needed to be built. The working staff at the NTNU lab contributed to build and mount a rack on the mobile car.

The criteria of the construction were that the rack needed to be able to do measurements at different heights of the area. In addition, the construction needed to be portable so it could be transported from the NTNU LAB at Gløshaugen to the Gunnerus Library. The storage areas also have space limitations, which had to be taken into account during the construction of the rack. For that reason, accurate measurements needed to be executed in advance at the Gunnerus Library.

Further, to map the indoor environment at different heights through the storage area, eight data loggers were mounted on the rack from floor to ceiling. Figure 4.1 shows the mobile car with the mounted data loggers inside the storage area.

Figure 4.1: Illustration of the mobile car with the data loggers mounted on the rack

Table 4.1 shows the specific height of the different loggers used in the experiment.

Table 4.1: Height of the data loggers mounted on the rack

Data logger	Height from the floor
A	6 cm
B	42 cm
C	70 cm
D	87 cm
E	122 cm
F	148 cm
G	176 cm
H	205 cm

4.2.2 Measurement points through the storage area

To make the measurement points as accurate as possible for the three passages, a blue tape was attached to the floor. The distance was then measured and noted on the tape. The measurement points through the area are illustrated in figure 4.2. The specific position is further explained in table 4.2.

The measurement experiment of passage A was conducted March 25th, while the measurements of passage B and C were conducted respectively March 26th and 27h.

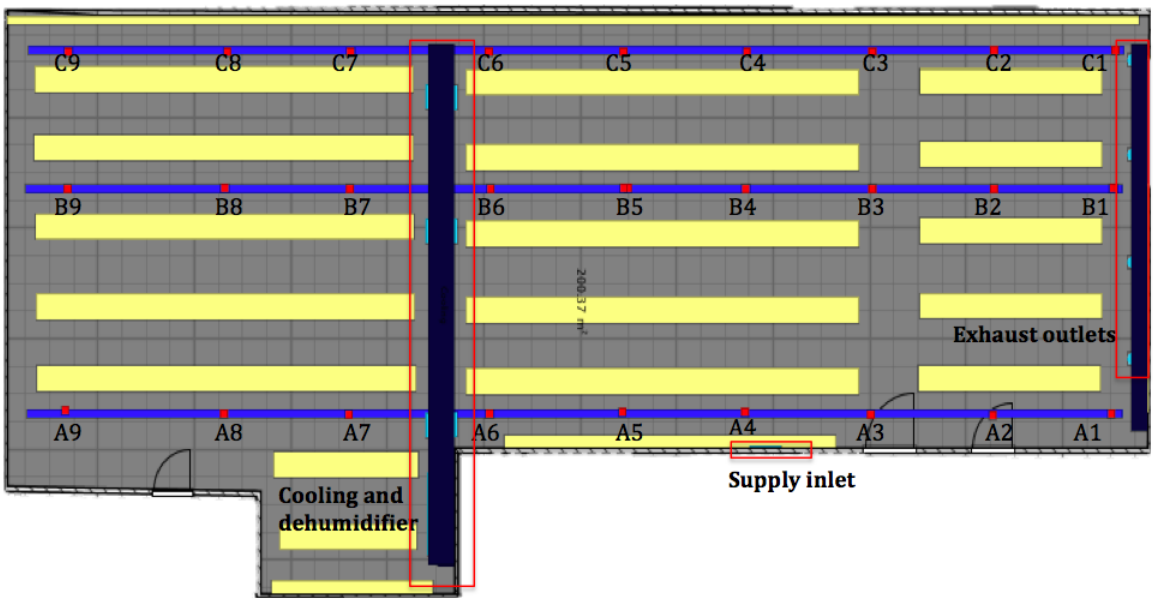

Figure 4.2: Measuring points through the storage area at floor 10

Table 4.2: Position of the measuring points

	Distance from wall (exhaust outlet)	Comment
A1, B1, C1	0,5 m	Close to exhaust outlet
A2, B2, C2	3 m	
A3, B3, C3	5,5 m	
A4, B4, C4	8 m	A- Close to supply inlet
A5, B5, C5	10,5 m	
A6, B6, C6	13 m	Close to cooling
A7, B7, C7	15,5 m	Close to cooling
A8, B8, C8	18 m	
A9, B9, C9	20,5 m	

4.3 Continuous temperature and relative humidity measurements

The conservator of the Gunnerus Library has placed four data loggers in each of the four storage areas. Since the 4th of April 2018, the data loggers have continuously logged the temperature and relative humidity every third hour.

The placement of the loggers located in floor 10 is shown in figure 4.3. The localization of two of the data loggers, logger 3 and 4, has recently been changed. The new localization is added to the illustration and marked as 3* and 4*.

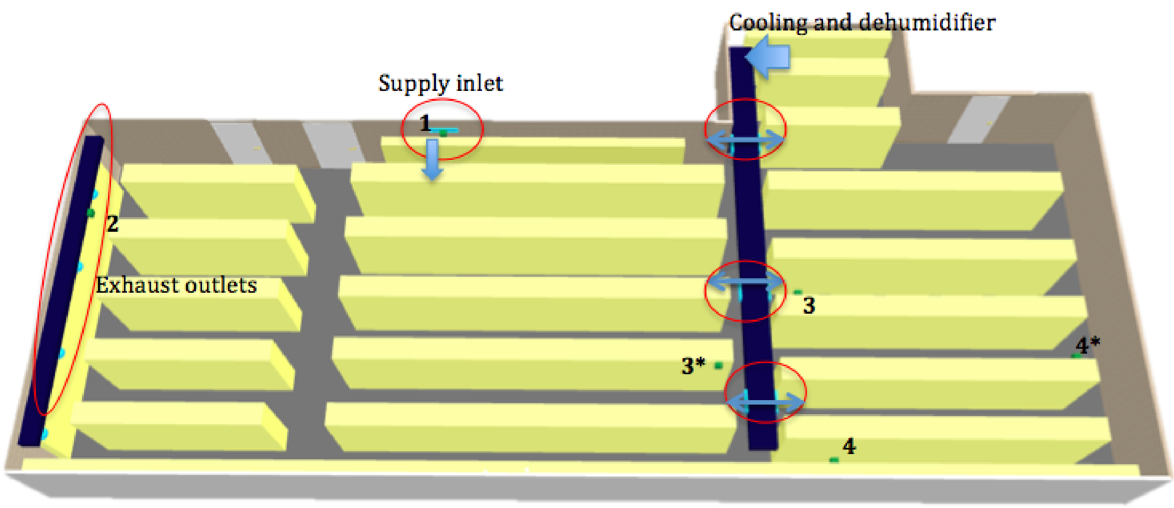

Figure 4.3: Placement of data loggers in floor 10

All of the loggers are placed on the same height, except the logger placed in the supply inlet, which lies at a higher height. Table 4.3 gives a further description of the placement of the four Tinytag loggers.

Table 4.3: Placement of Tinytag meters

Meter	Height from floor [m]	Additional comment
1	2.0	Located close to the supply air inlet
2	1.8	Located close to the exhaust outlet
3	1.8	Located close to the cooling inlet
3*	1.8	Located close to the cooling inlet opposite side of meter 3
4	1.8	Located on the inside of the outer wall
4*	1.8	Located to the right in the storage

4.3.1 Instrument for thermo-hygrometric parameter measurements

Tiny Tag plus 2 is used for the measurements of the thermo -hygrometric parameters, relative humidity and temperature. The product type of the meters is called Tinytag Plus 2, TGP-4500, temperature and relative humidity, and illustrated in figure 4.4. The Tinytag meters are designed for measuring climatic changes in temperature and relative humidity in a variety of environments. [3] [7]

Figure 4.4: Tinytag Plus 2, TGP-4500 [3]

The device measures temperature and relative humidity with a working area of -25°C to 85°C. and 0-100% in relative humidity. The meters have an uncertainty of $\pm$ 0,45°C in temperature and $\pm$ 3 % in relative humidity at 25°C. Further, the device has a capacity of 32 000 readings, that can be transferred to a computer via the USB port. The Tinytag software produces customized charts and graphs that illustrate the conditions over time. Tinytag Plus 2, TGP-4500 has a response time for relative humidity and temperature of respectively 90 seconds and 25 minutes to 90 % FSD in moving air. [3]

5. Results and discussion

The following subsections enlighten and deliberate the results obtained in this master thesis. First, the outcome of the visual observations of the storage areas is presented, followed by an evaluation of the correlation between the indoor and outdoor temperature. Further on, the chapter presents analyses of the long-term measurements of the environment at floor 10, in relations to standards and guidelines. Finally, the results of the experiment performed with the mobile car including evaluation of potential thermal gradients are presented.

5.1 Observations after visual inspection

Experiences from the visits to the storage areas refer to a noticeable change in climate condition for the different parts of the storage area. The division of shelves and the content of the storage area are often placed too close to external walls, floor, wall and ceiling. In addition, the distance between the books and ventilation inlets and outlets is in many cases too small, which lead to the artifacts being directly exposed to airflow of varying strengths. Moreover, the division of the fully packed shelf racks also indicates the occurrence of microclimates throughout the area.

The overall impression of the existing situation may not comply with the recommendations given to secure sufficient air distribution throughout the storage area. Figure 5.1 shows the packed shelves placed close to the wall and ceiling, and content located close to the exhaust outlet. In addition, more pictures from the storage area are added to appendix A.

Figure 5.1: Visual inspection showing packed shelves and books located near the exhaust

5.2 Correlation between indoor and outdoor temperature

This section analyses the relationship between the outdoor and indoor temperature at floor 10 at the NTNU Gunnerus Library. Figure 5.2 shows the correlation between the outdoor and indoor temperature visually. The figure displays the temperature measurements from the four meters placed in floor 10 and the outdoor temperature measurements.

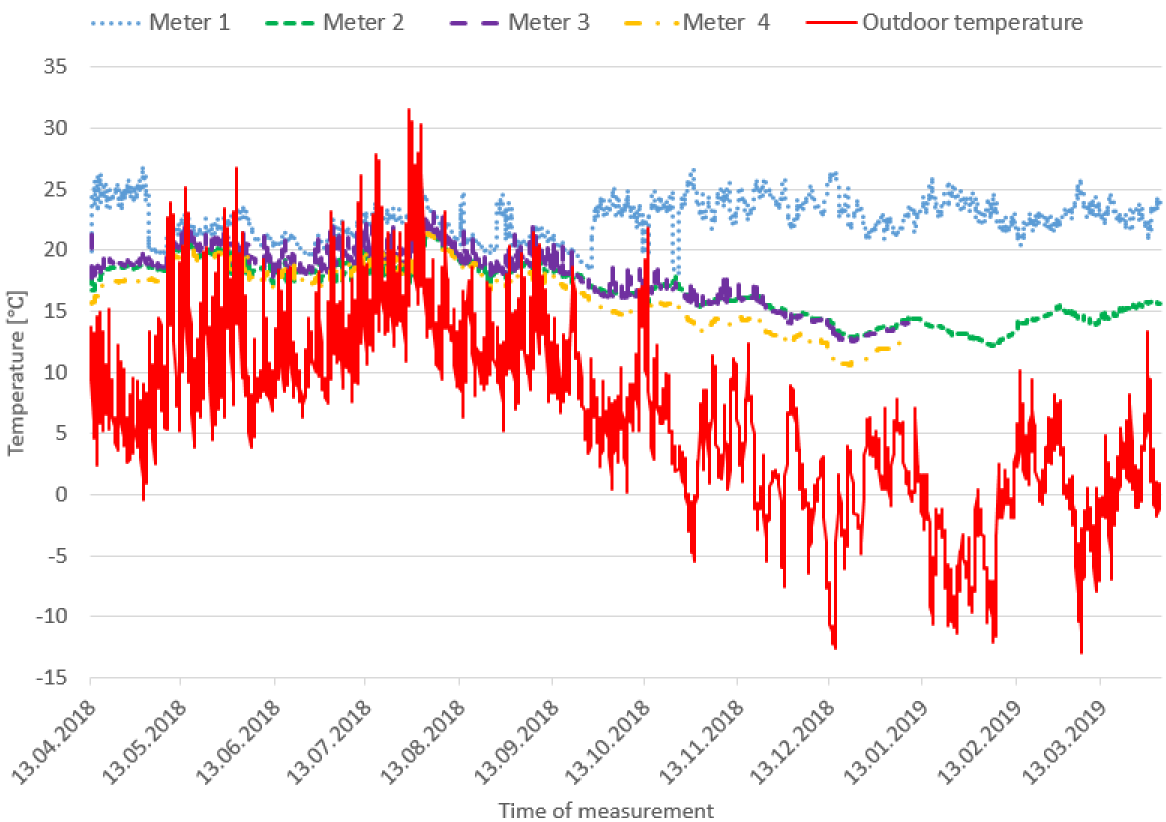

Figure 5.2: Relationship between indoor temperature at floor 10 and outdoor temperature

The temperature measurements are collected from Voll weather station, which is located approximately five kilometers away from the Gunnerus Library. A critical question is whether the outdoor environment measured at Voll is comparable to the environment at Gunnerus Library. It is difficult to estimate the difference between the two locations, although it is reasonable to assume some local differences. In other words, the outdoor temperature line displayed in the graph may not be accurate for the weather experienced at the Gunnerus Library.

The correlation coefficient between the indoor temperature and the outdoor temperature is calculated with the "Correl-function" in Excel. Table 5.1 gives the calculated correlation coefficient for all the meters placed on floor 10. The location of the meters is earlier illustrated in figure 4.3, section 4.3.

Table 5.1: Correlation coefficient for outdoor and indoor temperature

Meter	Correlation coefficient, r	Coefficient of determination, r^2
1	-0,46	0,21
2	0,80	0,64
3	0,80	0,63
4	0,77	0,59

Additionally, the measured data are also presented in two-dimensional scatter plots to visualize the relationship between the outdoor and indoor temperature. Linear regression analyses are made by inserting trend lines including the corresponding equations. Figure 5.3, 5.4, 5.5 and 5.6 displays the scatter plots with trend lines for meter 1-4.

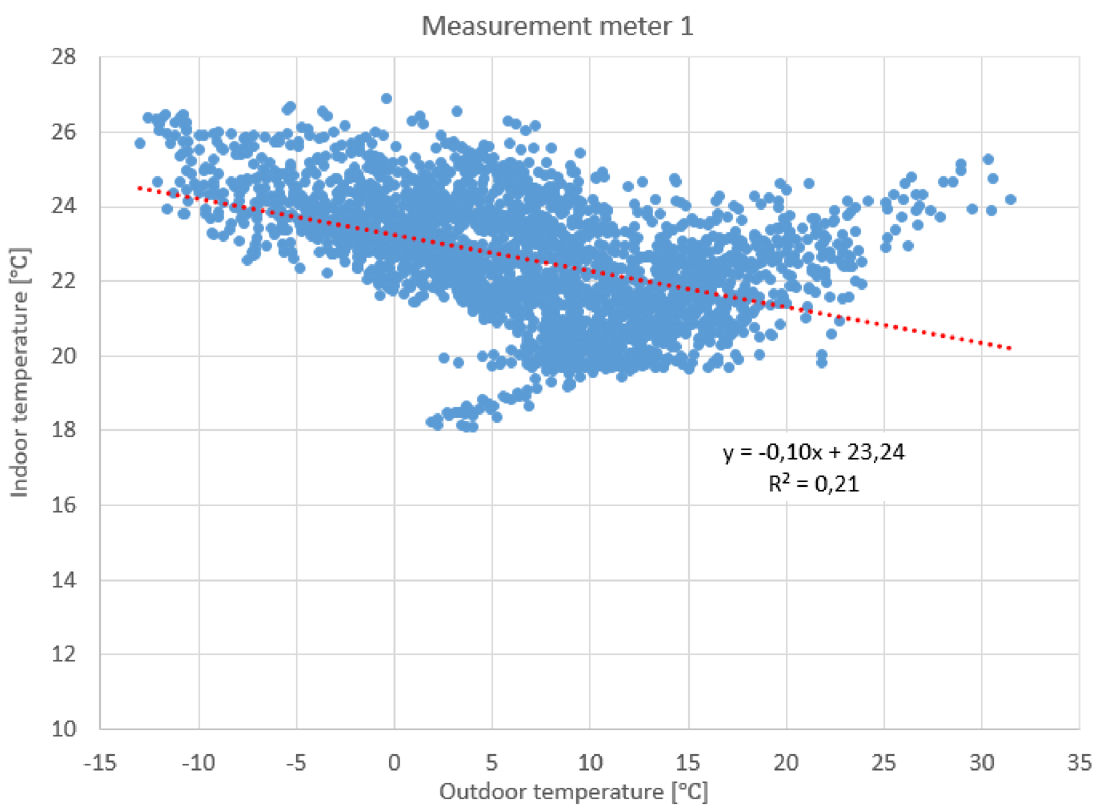

Figure 5.3: Relationship between the temperature at meter 1 and the outdoor temperature

Figure 5.3 displays the relationship between meter 1 and the outdoor temperature. As a recap and an important enlightenment, measurement meter 1 is located at the supply inlet in the storage area. Table 5.1 displays that the correlation coefficient between the outdoor temperature and the temperature at the supply inlet is calculated to be -0,46, which represents a weak/moderate negative correlation.

A negative correlation coefficient means that the variables move in opposite directions. This agrees well with the information given about the technical system at the library, referring to that the temperature of the supply air controls the temperature of the storage area. The negative correlation will in this case signify that as the outdoor temperature decreases, the temperature of the supply air will increase to compensate for the decrease.

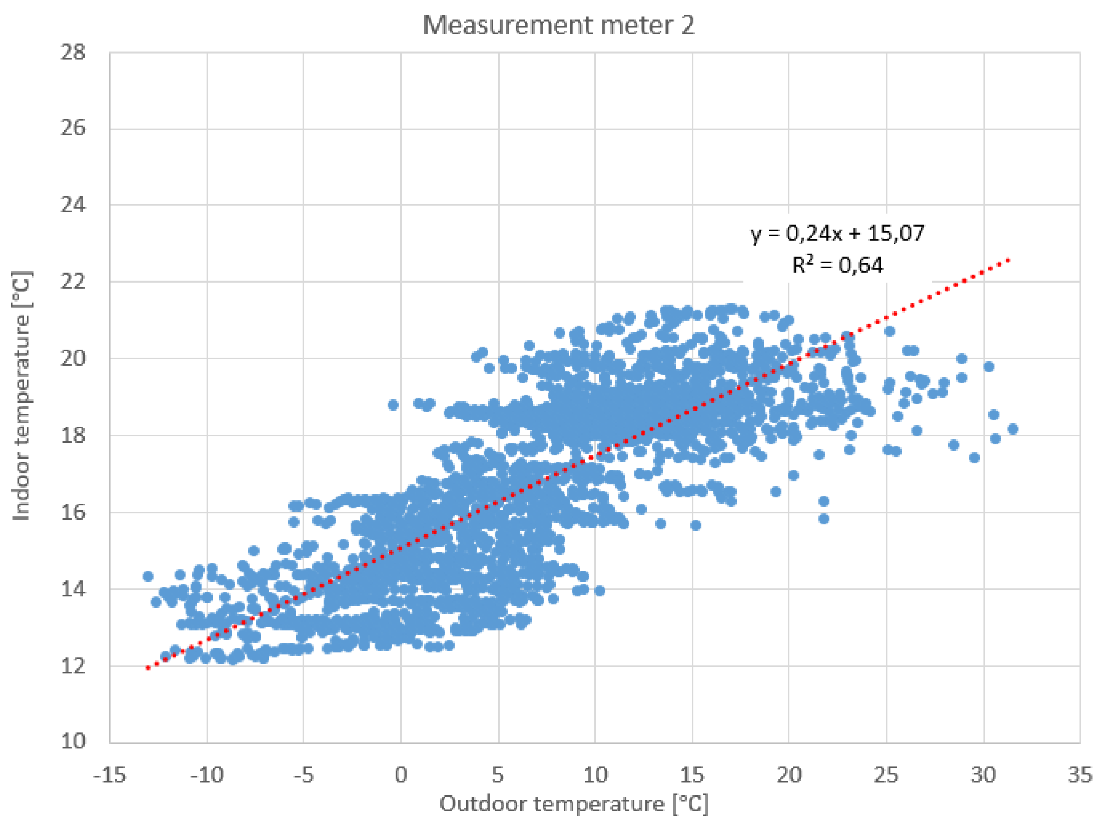

Figure 5.4: Relationship between the temperature at meter 2 and the outdoor temperature

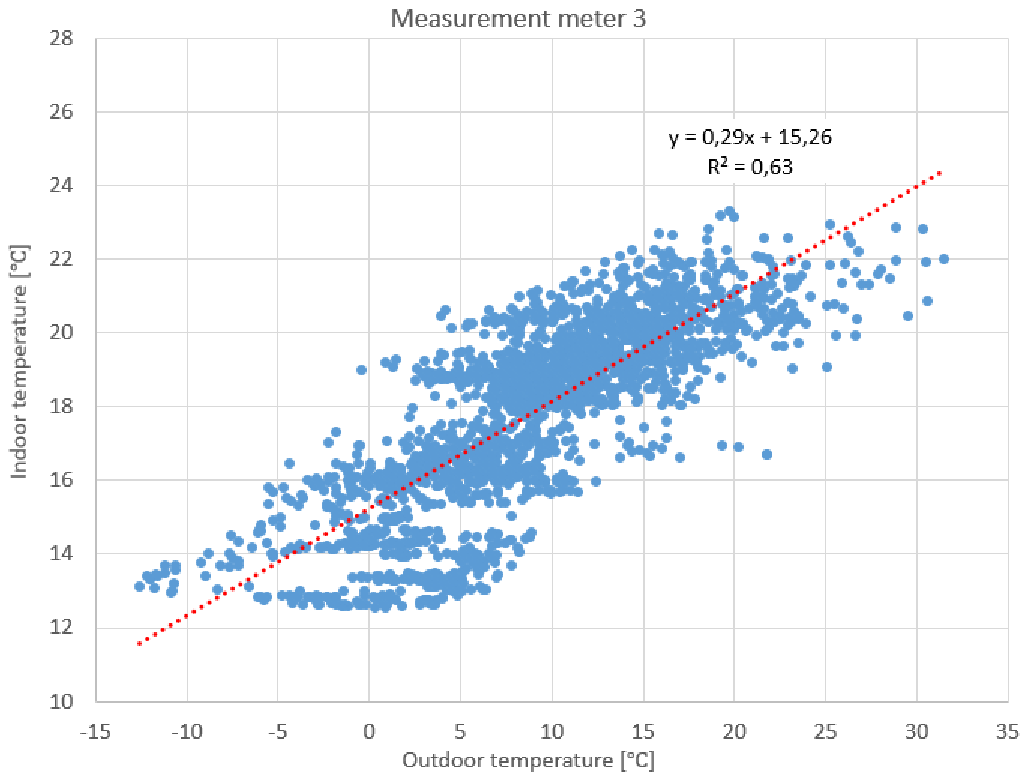

Figure 5.5: Relationship between the temperature at meter 3 and the outdoor temperature

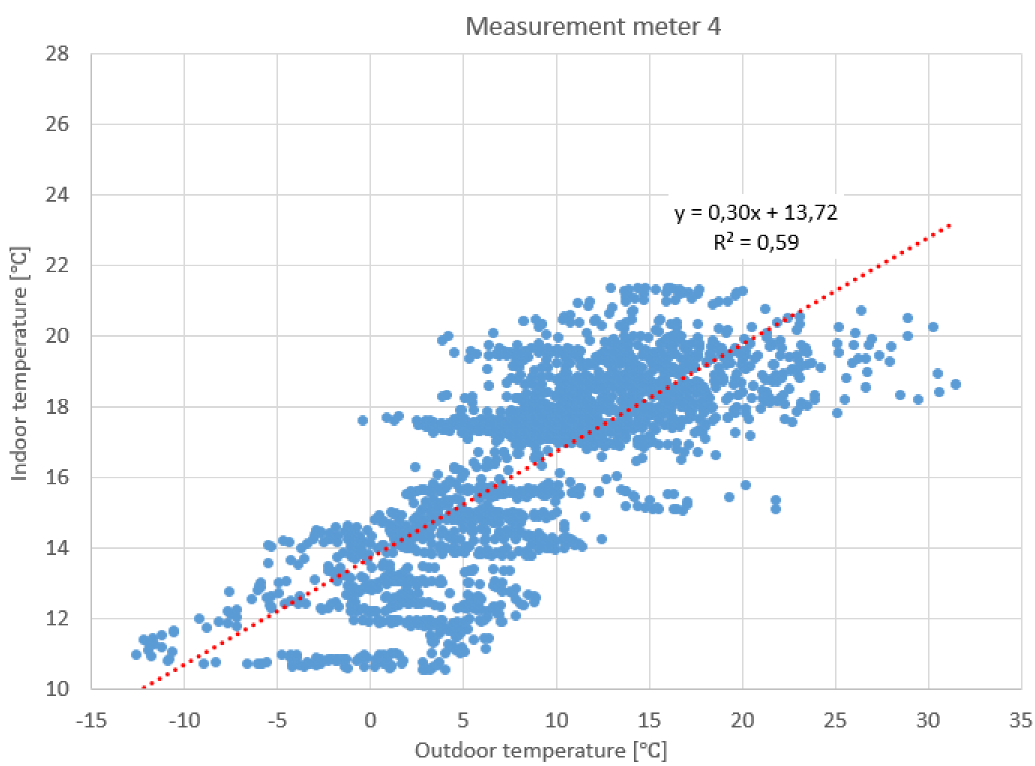

Figure 5.6: Relationship between the temperature at meter 4 and the outdoor temperature

On the contrary, figure 5.4, 5.5 and 5.6 show the relationship between the outdoor temperature and the measurements of other meters, 2-4. The figures show significant correlations with positive r-values > 0,7. The plots indicate similar patterns for meter 2, 3 and 4, with correlation factors of 0,8, 0,8 and 0,77, respectively. The patterns are evident referring to figure 5.4, 5.5 and 5.6. The squared R for the three meters is approximately 0,6, which signifies a moderate fit of the model.

When describing the relationship between two variables, the correlation is just one piece of the puzzle. The correlation is necessary, but not sufficient. Thus, other analyses should also be made to provide more information on the relationship. The correlation coefficient is based on means and standard deviations and is therefore sensitive to outliers. This means that extreme observations have strong impact on the correlation coefficient.

The overall result obtained by applying a simple linear regression analysis to the temperature, show that there is a significant influence of the outdoor temperature over the indoor temperature measured by meter 2, 3 and 4.

5.3 Long-term measurement of the thermal environment at floor 10

This section enlightens the results of the long-term measurements of temperature and relative humidity in the storage area at floor 10. The measurements are conducted and collected by Victoria Juhlin, paper- and book conservator at the library. The devices used to perform the measurements are Tiny Tag data loggers, which are the same as used in the other measurements associated with this thesis. Figure 4.3 in section 4.3 illustrates the placement of the data loggers, as well as giving a further description of the location.

Due to the change in the placement of two of the data loggers made in early January, it was not possible to gather measurements from a whole year for logger 3 and 4. The loggers placed in the supply inlet and exhaust outlet, however, have measurements from a whole year as their placement was permanent.

The evaluation and monitoring suggestions listed in section 3.3, recommends placing the data loggers in spots that reflect the climate experienced by the artifacts. Additionally, it is mentioned that the positioning of the loggers is a complex decision, which often is determined by the number of data loggers available. This is the case for the NTNU Gunnerus Library, which as of today only has four loggers per storage area. With limited number of data loggers, it is not possible to cover the total area of approx. 200 m^2. However, the loggers are spread and cover different parts of the area, including both the exhaust outlets and the supply inlet. Ideally, the data loggers should have been placed throughout the whole area, including at different heights.

Due to the unspecific nature of the different guidelines and standards, there are no exact values to follow for either set-points or fluctuations values for temperature and relative humidity. Recurring for the standards and guidelines is the importance to maintain stable conditions for both temperature and relative humidity. However, a prerequisite is that every storage environment is different and most of all dependent on the content in the storage. Therefore, it is desirable that the set-point values for the storage environment are evaluated and decided in collaboration with expertise and in-house knowledge.

According to Victoria Juhlin and Stein Olle Johansen, the desired climate condition to maintain in the storage area is 50 % relative humidity and 19 °C air temperature. This is within the recommended conditions for mixed storage given in the guidelines and standards presented in section 3.6.

The literature review of this thesis enlightens the two most strict classes of control, A and AA, given by ASHRAE. Class of control AA is the strictest, which allows no seasonal adjustments in system set-points for relative humidity. Taken the cold climate in Trondheim and the environmental aspect into consideration, class of control A is the chosen specification for further fluctuation analyses. The requirements for set-points and fluctuations are presented in table 5.2.

Table 5.2: Chosen requirements for system set-points and fluctuation limits

Condition	Set point	Short-term fluctuations	Seasonal fluctuations
Relative humidity	50 %	± 5 %	± 10 %
Temperature	19 °C	± 2 °C	± 5 °C

5.3.1 Analysis of fluctuations

As the visual inspection of the storage area indicated varying conditions, it is looked deeper into the fluctuations of temperature and relative humidity. This section present analyses of the measurements of temperature and relative humidity from the measurement meters located at floor 10. The measurements are evaluated up against the seasonal fluctuation range presented in table 5.2. Seasonal changes refer to changes in conditions over a period of one month or more, preferable are measurements including all seasons.

Short-term fluctuations are fluctuations within a period of 12-24h. The measurements gathered in this thesis are only logged every third hour. As a result of this, the measurements are not representative to give a sufficient overview of the short term fluctuations. Measurements logged in a more frequent interval are needed.

Temperature

Figure 5.7 presents the temperature readings for meter 1-4 at floor 10 with the corresponding set-point temperature and seasonal fluctuation range of 19 ± 5 °C.

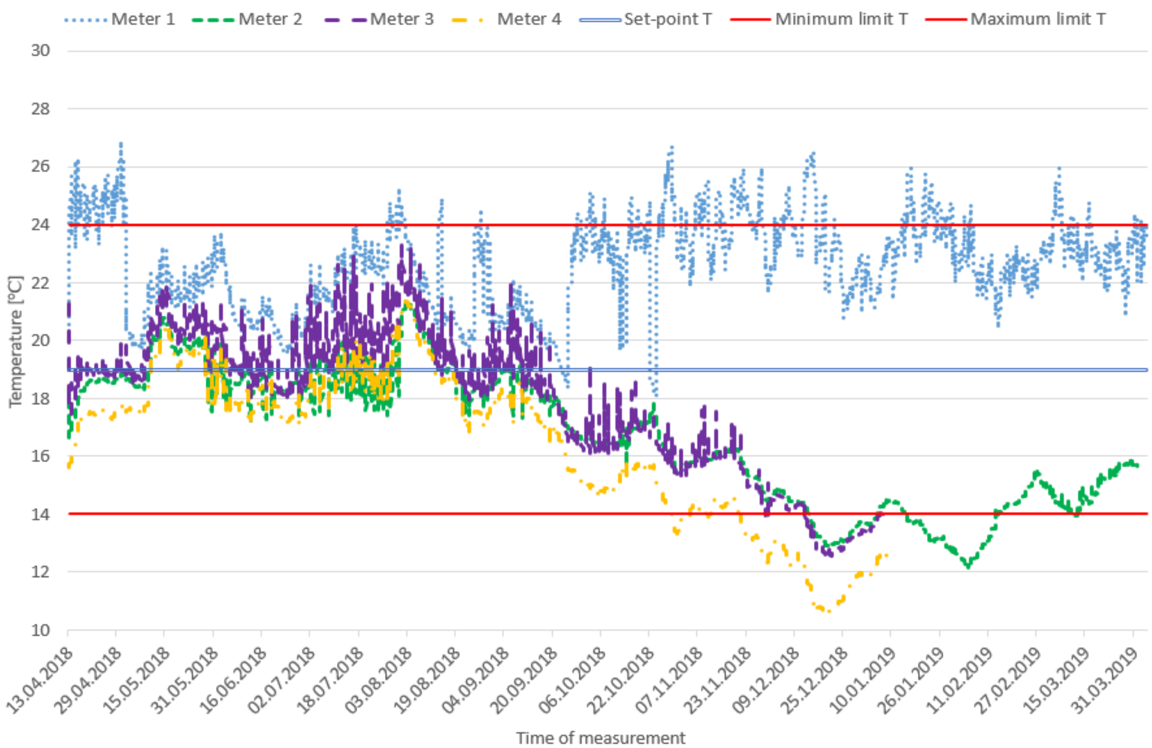

Figure 5.7: Temperature readings for meter 1-4 at floor 10

Table 5.3 gives the percentage of the temperature measurements that is outside the seasonal fluctuation range.

Table 5.3: Percentage of the temperature measurements outside the seasonal fluctuation range

Temperature	Meter 1	Meter 2	Meter 3	Meter 4
Percentage outside the comfort zone	20 %	15 %	9 %	20 %

Disregarding the fluctuations, the overall impression of the graph is that the temperature out of most times stays within the fluctuation range. However, the graph emerges that the temperature follows a seasonal pattern. The readings show fluctuations at a steadily higher level in the summertime, while in the wintertime there is an evident decrease in temperature in the storage areas.

The readings representing meter 1 show a different and much more fluctuating trend than the other meters. Figure 5.7 displays that after 20.10.2018, the readings for meter 1 often exceeds the maximum limit, while the other meters show a declining trend. As stated in section 2.3, meter 1 measures the temperature of the supply air that controls and adjusts the temperature in the storage area. Consequently, the readings for meter 1 lies at a higher level during the cold seasons when the storage room is in need of heating. Table 5.3 show that the temperature readings for meter 1 are outside the range 20 % of the time. The content stored in the area close to the supply inlet experiences a fluctuating climate and is in danger of degradation due to these sudden changes.

In periods where the temperature is too high, the cooling and dehumidifier system is turned on. This is evident on the graph, referring to the heavy temperature fluctuations from June to August. Although the readings rarely exceed the maximum temperature limit, it is interesting to see that the readings at most times are fluctuating around on the uppermost layer of the range.

It is also worth noticing the readings representing meter 4. As informed in figure 4.3 and table 4.3, meter 4 is located in direct contact with the external wall. The readings are at a noticeable lower value than for the other meters, which may be related to the influence of the outdoors. The difference appears more evident as the outside temperature decreases. Furthermore, the temperature in the area surrounding meter 4 is out of range 20 % of the time and the content experiences inadequate conditions for safe preservation.

Relative humidity

Figure 5.8 presents the measurements of relative humidity by meter 1-4 at floor 10, with the corresponding set-point value and seasonal fluctuation range of 50 ±10 %.

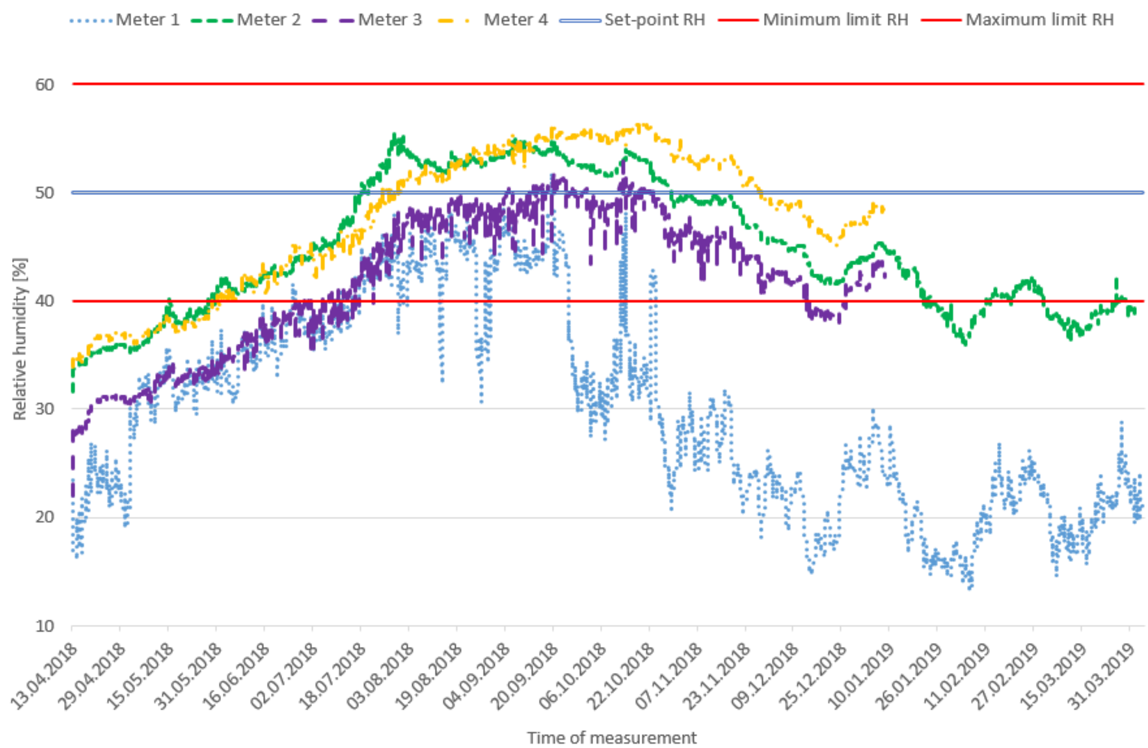

Figure 5.8: Relative humidity readings for meter 1-4 at floor 10

Table 5.4 gives the percentage of the measurements that is outside the fluctuation range for relative humidity.

Table 5.4: Percentage of the relative humidity measurements outside the seasonal fluctuation range

Relative humidity	Meter 1	Meter 2	Meter 3	Meter 4
Percentage outside the comfort zone	80 %	27 %	37 %	18 %

First and foremost, the relative humidity is dependent on the temperature of the air. In addition, the humidity in a room varies as humidity is either supplied or extracted from the air. Regarding the storage areas at Gunnerus Library, there are humidity through the envelope and the dehumidifier associated with the cooling system that have an effect on the humidity level. Moreover, the presence of the staff will also play a role in the matter of humidity increase. Considering that the frequency of visits is assumed to be limited, and not accounted for, it is hard to draw any conclusions of the impact caused by visits of the storage areas. Figure 5.8 displays substantial variations in the state of the air, with a maximum relative humidity above 55 % and minimum relative humidity below 30 %. It emerges from the graph that the relative humidity for all meters is too low and out of range for a significant part of the measurement period. Table 5.4 presents the percentage of the measurements that are outside the range, referring to 80, 27, 27 and 18 % respectively for meter 1-4. In association with this, the content of the storage area is at risk of degradation associated with low humidity.

Recurring from figure 5.7 is the deviant trend for meter 1. The low relative humidity in figure 5.8 grounds in the rather high temperature readings displayed in figure 5.7. Table 5.4 show that the supply air is not within the fluctuation range 80 % of the time. More specifically, below the minimum limit of 40 % relative humidity. It is worth noticing that the relative humidity never exceeds the 65 % limit, which is the limit where mold begins to reproduce.

In the late months of summer, the readings for meter 2-4 are more or less stabilized, followed by an evident decreasing trend as the cold period occurs. As pointed out in the analysis of the temperature, there is a noticeable difference in the trend for the meter placed directly on the external wall. The graph representing meter 4 shows that the relative humidity level follows the same trend of decreasing, although at a higher level compared to the other meters. The higher level of humidity is in correlation with the rather low temperature in figure 5.7, and can be seen in the context of external influence.

5.3.2 Comfort zone

As the of the air includes both temperature and relative humidity, it is necessary to consider them both when investigating the indoor environment. The comfort zone of the storage area is illustrated in figure 5.9, and presents the zone that is considered to be safe for preservation of the mixed materials in the storage.

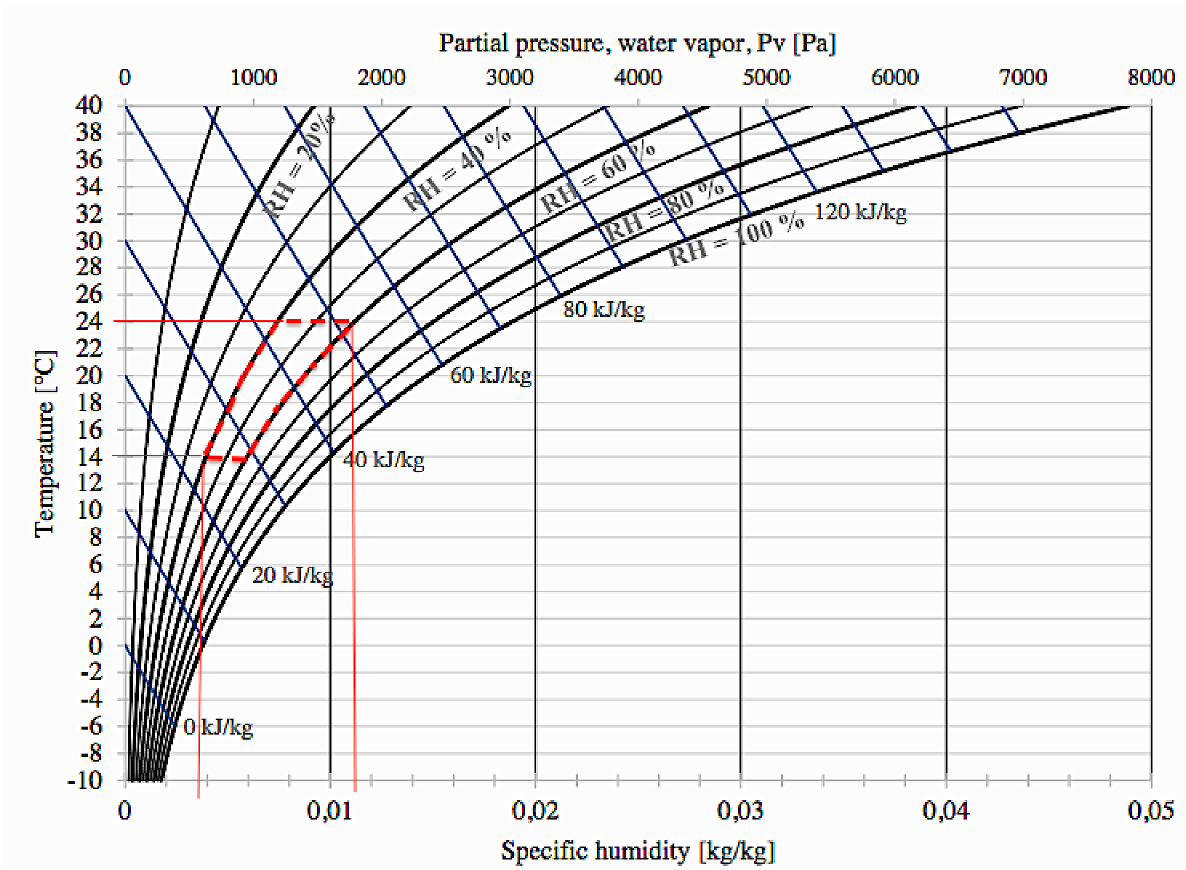

Figure 5.9: Mollier chart presenting the comfort zone of the storage area

The annual measurements are processed in Excel by using "if" and "and" formulas to merge together the results of the temperature and relative humidity fluctuations. Table 5.5 shows the percentage of the measurements that is outside the zone of 50 ± 10 % and 19 ± 5 °C.

Table 5.5: Percentage of the annual measurements outside the comfort zone, T and RH combined

Temperature and relative humidity	Meter 1	Meter 2	Meter 3	Meter 4
Percentage of the environment outside the comfort zone	81 %	36 %	42 %	39 %

The table displays that a substantial part of the measurements is outside the comfort zone, which means that the environment is inadequate for safe preservation. The measurements for meter 1-4 are out of the comfort zone, respectively, 81, 36, 42 and 39 % of the time.

The area surrounding meter 1 and meter 3 are the ones exposed to airflow from respectively the supply air and the cooling system. Table 5.5 indicates that the environment surrounding meter 3 is not distinctly affected by the airflow from the cooling system, as the percentage for meter 2-4 is quite similar. The area surrounding meter 1, however, experiences big variations in both temperature and relative humidity, which leads to the air being outside the comfort zone 81 % of the time.

In consequence of that, it is the content stored in the area surrounding the supply inlet that experiences the worst conditions throughout the year. Figure 5.8 emerges that the content is out of most times in danger of mechanical degradation due to too low relative humidity.

The environment in the areas surrounding meter 2-4 is inadequate approximately 40 % of the time. By comparing figure 5.7 and 5.8 it emerges that the content is most exposed in wintertime and that relative humidity is out of most times the critical parameter.

5.4 Vertical thermal gradients

Analysis of the long-term measurements of air temperature and relative humidity showed varying environment throughout the room. For that reason, potential vertical thermal gradients are surveyed. The following sections present the results of the measurements performed with the mobile car. Further, the results are presented as color-contour figures in order to visualize the temperature variations throughout the storage area. Prior to this, it is given an insight into the variations in the outdoor conditions prior to and during the measurement period.

5.4.1 Outdoor environment prior and during the experiment

As the experiment was conducted on three separate days, variations in the outdoor environment may influence the measurement results. Figure 5.10 shows the outdoor conditions of temperature and relative humidity from March 18th to March 31th. Additionally, the actual time frame for the measurements conducted with the mobile car is added to the graph. The hourly outdoor conditions of temperature and relative humidity are collected from the weather station located at Voll in Trondheim. As the measurements are from Voll, they do not give an accurate representation of the experienced weather at the NTNU Gunnerus Library.

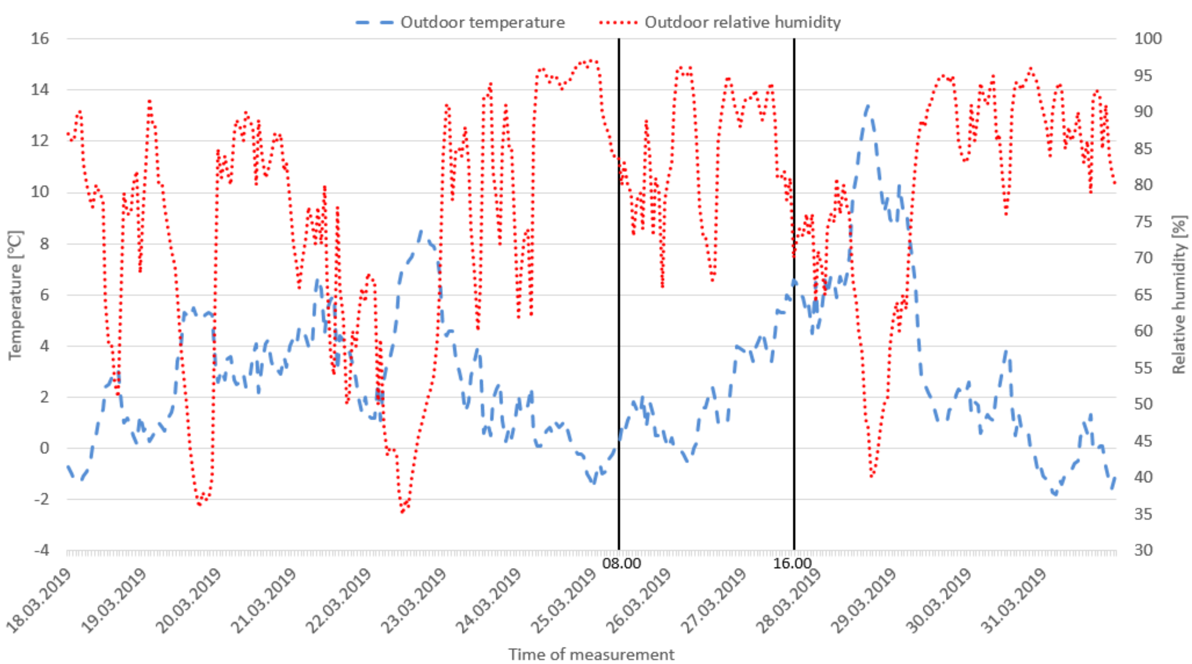

Figure 5.10: Weather readings from 18-31 March

It occurs from the graph that the values varies to some extent during the measurement period. Between 25-27th of March, the temperature varies from a minimum of 0 °C to a maximum of

6 °C. The weather conditions in the period before the measurements were conducted may also influence the result and are therefore included in the graph. By analyzing the readings, the daily variations are evident showing a fluctuating graph representing the climatic changes. A small increase in temperature is to be seen for the 25-27th of March.

5.4.2 Measurements of thermal gradients

The mean values of the temperature measured at the different measurement points with the mobile car are visually illustrated in color-contour figures; one for each passage. The Matlab-script used to plot the figures, as well as the input data, is attached to Appendix B. To make the deliberation of the result more understandable, the illustration of the passages and the measuring points is earlier shown in figure 4.2 in section 4.2.2.

Figure 5.11 displays the measured temperature for passage A measured March 25th.

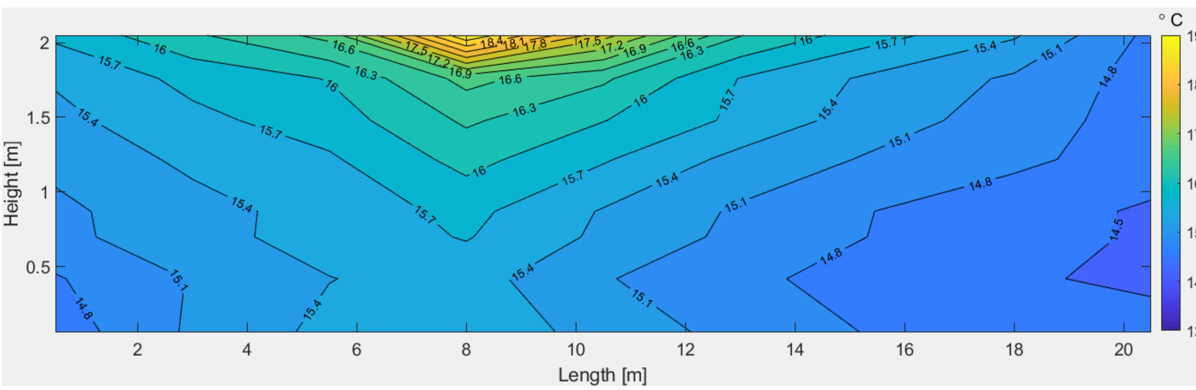

Figure 5.11: Measurements of thermal gradients, passage A

By reviewing the color-contour figure for passage A, it emerges that the most evident increase are to be seen in the area close to the supply air inlet, more precisely the area representing the measuring point A4. A4 shows a maximum temperature of 19 °C at ceiling height and a temperature of 15 °C at floor height, giving a ΔT= 2 °C/m height. The surrounding area is also somewhat affected and shows a moderate increase in temperature. This indicates that the supply air supplies air with a temperature of 19 °C, which agrees with the target temperature for the storage area.

Disregarded the temperature increase caused by the supply air, the overall impression is that the temperature is too low in relation to the target condition of 19 °C. The temperature varies between 14-15 °C at floor level, showing a slight increase towards the center. Additionally, the temperature also shows a moderate increase with the height of the room.

Figure 5.12 presents the results obtained from the monitoring of passage B, March 26th.

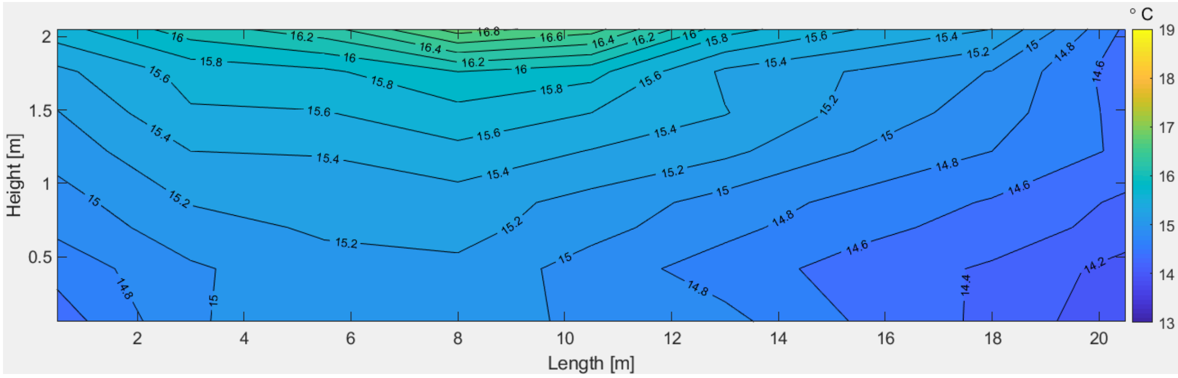

Figure 5.12: Measurements of thermal gradients, passage B

It emerges that the increase seen in figure 5.11 for passage A, also appears in figure 5.12 for passage B, although showing a less distinct increase. The temperature is noticeably higher in the area surrounding B4, which is the area assumed to be affected by the supply air inlet.

As for passage A, passage B also has rather low temperatures throughout the area. The temperature increases toward the center of the room as well as with the height. Hence, the areas with the lowest temperature appear in the corners of the passage. The highest temperature difference with the height is 1 °C/m height, found in the area surrounding B4.

Figure 5.13 displays the temperature measurements for passage C that were conducted March 27th.

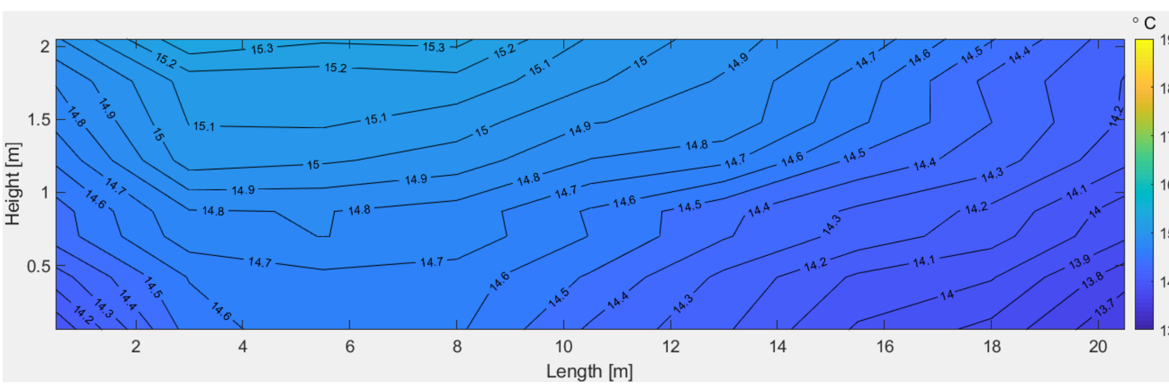

Figure 5.13: Measurements of thermal gradients, passage C

Out of the three passages, passage C shows the most stable conditions. The temperature has a slight increase towards the center, and also with the height. Overall the temperature is rather low and stable varying between 13,5-15,5 °C, referring to a well mixed temperature distribution and a maximum ΔT= 0,5 °C/m room height.

Additionally, it is worth noticing that the temperature at floor height around measuring point C9 represents the lowest measured temperature of all the measurement points. This area is a corner that is surrounded by outer walls, and may therefore be more exposed to external influences. Another reason may also be that this area is located as far away from the supply inlet as possible, which results in the air being stagnant and not sufficient distributed.

5.4.3 Overview of passage A, B and C

When comparing the three passages, it becomes clear that they show tendencies to follow the same trends. Recurring for the figures is that they show increasing temperature towards the center of the room, as well as an increased temperature with the height. Additionally, the coldest areas are to be found at floor height close to the short-walls, the corners in particular. In other words, the temperatures representing A9, B9 and C9 and A1, B1 and C1 show the lowest values, with decreasing temperature from passage A to C.

As the increase is presumed to be caused by the supply air, the impact decreases the further from the inlet the measurements are taken, respectively passage A, B and C. The maximum ΔT for the three passages are respectively 2, 1 and 0,5 °C/m room height. This indicates that the result agrees with the assumption that the supply inlet does not cover the whole area, and that one single supply inlet is not sufficient to provide stable temperature throughout the storage area.

Regarding the overall temperature, figure 5.11, 5.12 and 5.13 respectively shows a decreasing trend, and does not seem to be affected by the small increase in outdoor temperature during the measurement period seen in figure 5.10. Ideally, the measurements of the three passages should have been performed simultaneously. In that way, the measurements would have been entirely comparable.

Another aspect to notice on the figures is that there is no change in temperature in the areas close to the cooling system, referring to the measuring points A6, B6 and C6 and A7, B7 and C8. This indicates that the system was not operating during the measuring period, which is the expected outcome due to both the time of year and season but also since the temperature throughout the storage is too low. It would have been interesting to see the temperature distribution in periods where the cooling system was operating, and in particular how the cooling would affect the areas close to the inlets.

The color-contour figures can be used to find out which areas in the storage area who experiences inadequate conditions for preservation, or in this case the most inadequate conditions. By means, the most valuable content in the storage can be placed in the least exposed areas.

However, the measurements of the thermal gradients in the storage area are not continuously monitored. The one-day measurements may therefore not be representative for the annual variations in conditions. On the other hand, the result indicates varying temperatures in length, height and width of the area and the overall temperature in the storage area is low. As a result of this, it is reasonable to presume that the environment throughout the year also refers to varying conditions although more continuous monitoring is required.

6. Suggestions to improve the indoor environment

The analysis of the results gathered in this master thesis makes it clear that the climate at the NTNU Gunnerus Library is not optimal to secure adequate storage environment for materials of such cultural value. This chapter introduces suggestions to improve the indoor environment in the storage areas. However, the suggested solutions may not be possible to implement. This grounds in facts stated earlier in the thesis, for instance, that the old shelving system has bearing effect, space limitation inside the storage areas and the fragility of certain historic artifacts.

Some of the suggestions are based on the case studies presented in chapter 3. It may be complex to compare study cases, as they all vary in location, usage and historical value of the building, climate specifications and other assumptions. Nevertheless, one can use the obtained knowledge and take their recommendations and suggestions into consideration.

6.1 Ventilation system

The results of the thermal measurements conducted in the storage area show varying conditions throughout the storage area. This indicates that the recirculated air ventilation is not perfect, which means that the content stored in the area experiences fluctuating environment and are in danger of degradation.

Italian researchers at the University of Naples recommend, in their paper concerning "HVAC systems to control microclimate in museums", an all-air system with a centralized air-handling unit which keeps filtration, dehumidification, humidification, maintenance and monitoring away from the collections. This system allows for strict control of temperature and relative humidity, as well as avoiding the presence of undesirable water pipes. This system may be an appropriate choice for the NTNU Gunnerus Library.

The case studies presented in this thesis agree on the importance to maintain a stable thermal environment. The existing ventilation system with only one supply air inlet does not achieve an even air distribution. The storage area of approximately 200 m^2 has a rectangular shape, and the analysis of the indoor environment indicates variations in length, width and height of the area. The color-contour figures presented in section 5.4.2 show evident signs that the supply air has a rather local influence. Therefore, it is recommended to install more inlets in order to secure proper air distribution at lower supply air velocity. Lower velocity is advantageous because it results in less mechanical stress on the books close to the inlets.

The four storage areas share the present HVAC system. The project work prior to this thesis concluded that the indoor environment varies for the different floors. By dividing the storage areas into separate systems, the indoor environment of each floor could be optimized for the preservation of the specific content in each area. Both overheating of the area and temperatures below the required value of 19 °C was observed. Therefore, the HVAC system should be flexible, and allow for both heating and cooling all year around.

6.2 Passive solutions

One possible improvement is to change the division of the shelves and how the materials are positioned on the shelves. Particularly, in relation to placing the content at the recommended distance to external walls, floor, ceiling and the air inlets/outlets. The result presented in section 5.3.1, shows that the environment close to the external wall is more exposed to more extreme fluctuations.

Another suggestion is that the historic artifacts should be given the time to acclimatize before being taken out and used. The environment inside the storage area is in contrast to the environment the artifacts are taken out to. This exposes the artifacts for a climatic shock and the possibility for damage. For long-term preservation, the case study concerning the Hermitage Museum in Amsterdam recommends that the most sensitive objects should be placed and stored separately in display cases.

The study cases presented in this thesis agree that planning and positioning of a continuous monitoring system of the thermal environment of the area are important. To achieve a better overview and to optimize the management system, it is advisable to install more permanent data loggers in each storage area at the NTNU Gunnerus Library.

7. Conclusion

The NTNU Gunnerus Library is one of the most important cultural heritage libraries in the Nordic countries and houses collections and artifacts of great value and importance. The combination of materials in the storage areas causes the target condition to be a compromise, which has proven to be challenging to meet with the current climate regulation system.

The relationship between the outdoor and indoor temperature is surveyed through scatter plots and calculations of the correlation coefficient. The temperature readings of meter 1, representing the temperature of the supply air, indicate a weak/moderate negative correlation in comparison to the outdoor temperature. As the supply air controls the temperature of the storage area, a negative correlation signifies that as the outdoor temperature decreases the supply air temperature increases to compensate for the change. The scatter plots for meter 2-4 show significant correlation with positive r-values > 0,7. These results indicate that there is a strong relationship between the measured indoor temperature and the outdoor temperature.

Analyses of the seasonal fluctuations show a wide range of thermo-hygrometric values to which the storage area at floor 10 at the NTNU Gunnerus Library is exposed. The comfort zone, which is the condition that secure safe preservation of artifacts, used in the analysis is 50 ± 10 % relative humidity and 19 ± 5 °C air temperature. The results indicate that the environment is outside the comfort zone 81, 36, 42 and 30 % of the time, respectively for measurement meter 1-4. The meters are located respectively in the supply air inlet, close to the cooling system, by the exhaust outlet and directly on the wall.

Color-contour figures visualize the temperature variations at different lengths, widths and heights of the storage area. The recurring pattern for the figures is an increasing air temperature towards the center of the room, as well as with the height. The evaluation of the figures emerges evident higher air temperatures in the area close to the supply air inlet, which decreases with increasing distance to the inlet. The maximum ΔT is respectively 2, 1 and 0,5 °C/m height for passage A, B and C. This indicates that the supply air inlet does not provide even air distribution for the whole storage area, showing a rather local influence.

The results indicate that the current climate regulation system does not achieve the indoor environment that is required to meet the requirements for safe preservation. In order to improve the indoor environment at the NTNU Gunnerus Library, it is suggested an all-air system with a centralized air-handling unit as well as installing more supply inlets to provide an even air distribution throughout the area. Additionally, the storage areas should have separate systems, thus the demand of each of the areas could be fulfilled. To be able to optimize the management system, it is suggested to plan a continuous monitoring system of the thermal environment.

8. Further work

Further work can be carried on based on experiences and results gathered in this master thesis. Monitoring of thermo-hygrometric parameters is a time-consuming task. In order to achieve a reliable and useful overview of the indoor environment, it is necessary to consider measurements showing all the seasons. Thus, continuous measurements of at least one year are preferable. It is suggested to install more climate loggers inside the areas. By this action, it will be possible to monitor the climate in the area more precisely, and the possibility to detect undesirable microclimates will increase.

Relative humidity strongly depends on temperature, therefore, the comparisons of internal and external conditions should be carried out based on calculated values of moisture content. As for the correlation between indoor and outdoor temperature, the information obtained from the regression analysis is not sufficient to describe the relationship between two variables. Other analyses should also be conducted to provide more information on the relationship.

This thesis has used a simple version of machine learning to analyze data and to survey the indoor environment at the NTNU Gunnerus Library. However, other simulation software, such as IDA ICE and EnergyPlus, should be looked into, in order to examine the environment of the storage areas.

Short-term fluctuations are fluctuations within a period of 12-24h. The measurements gathered in this thesis are only logged every third hour. As a result of this, the measurements are not representative to give an accurate overview of the short-term fluctuations. This should be looked deeper into with measurements logged in a more frequent time interval.

The color-contour figures showed no signs of change in the areas close to the cooling system. However, the measurements were taken in a period where the system was not operating. It would be interesting to see how the cooling system both affects the environment surrounding the inlets and the environment in its entirety. Therefore, more measurement periods of the thermal gradients should be performed.

Furthermore, the outcomes of this thesis need to be compared with similar studies, which are comparable with climate conditions, environmental requirements and other conditions related to the case study.

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A. Visual inspection

More pictures from the visual inspection made at the storage areas at the NTNU Gunnerus Library are shown in figure A.1, A.2, A.3 and A.4

Figure A.1: Supply air inlet

Figure A.2: Exhaust outsets

Figure A.3: Cooling system

Figure A.4: Packed book shelves

B. Matlab script

This attachment includes the Matlab-script that were used to find the thermal gradients in the storage area at floor 10 at NTNU Gunnerus Library. In addition, the 9x8 matrix input data for each of the three passages is presented.

Figure B.1 show the Matlab-script used for the color contour figures.

```
clc
clear all

xax=[0.5 3 5.5 8 10.5 13 15.5 18 20.5]; %9 stk
yax=[0.06 0.42 0.70 0.87 1.22 1.48 1.76 2.05]; %8 stk
Length=21; %m
Height= 2.1; %m
%A1=load('tempmonday.txt'); %Passage A
%A1=load('temptuesday.txt'); %Passage B
A1=load('tempwednesday.txt'); %Passage C
f1=figure('units','centimeters','position',[0 0 Length Height]);
contourf(xax, yax, A1,[13:0.1:19], 'showtext', 'on');
xlabel('Length [m]');
ylabel('Height [m]');
set(gca, 'fontsize',14);
caxis([13,19]);
title(colorbar, '{\circ} C','fontsize',14);
```

Figure B.1: Matlab-script for color contour figures

Figure B.2, B.3 and B.4 show the input data for the three passages, measured March 25-27th.

```
%Temperature measurement, Monday

14.628  15.152  15.481  15.643  15.271  15.006  14.771  14.533  14.629
14.773  15.119  15.392  15.523  15.125  14.867  14.669  14.539  14.435
15.015  15.301  15.519  15.721  15.338  15.020  14.783  14.643  14.452
15.032  15.292  15.519  15.785  15.375  15.055  14.795  14.649  14.451
15.179  15.467  15.660  16.103  15.733  15.306  15.056  14.857  14.677
15.317  15.622  15.850  16.348  16.011  15.635  15.223  14.971  14.642
15.435  15.787  16.017  16.699  16.352  15.688  15.329  15.054  14.671
15.763  16.251  16.699  18.973  17.625  16.315  15.807  15.436  14.719
```

Figure B.2: Input data for passage A

```
%Temperature measurement, Tuesday

14.49   14.97   15.17   15.20   14.91   14.86   14.58   14.35   14.04
14.67   14.97   15.13   15.15   14.91   14.70   14.52   14.37   14.12
14.85   15.12   15.23   15.28   15.07   14.86   14.66   14.52   14.32
14.91   15.21   15.23   15.30   15.13   14.92   14.73   14.58   14.36
15.08   15.40   15.42   15.55   15.39   15.25   14.99   14.80   14.56
15.19   15.58   15.59   15.73   15.60   15.41   15.13   14.90   14.53
15.35   15.67   15.76   16.00   15.87   15.36   15.18   14.99   14.48
15.72   16.11   16.32   16.89   16.69   15.88   15.60   15.40   14.56
```

Figure B.3: Input data for passage B

```
%Temperature measurement, Wednesday

14.018  14.541  14.685  14.617  14.384  14.215  13.985  13.870  13.601
14.254  14.607  14.677  14.652  14.487  14.277  14.083  14.009  13.737
14.445  14.759  14.802  14.762  14.597  14.410  14.261  14.139  13.917
14.453  14.793  14.804  14.758  14.587  14.425  14.279  14.174  13.946
14.617  15.051  15.015  14.955  14.796  14.725  14.475  14.350  14.124
14.727  15.105  15.115  15.047  14.904  14.871  14.618  14.401  14.186
14.809  15.143  15.137  15.166  15.015  14.887  14.652  14.370  14.195
14.985  15.387  15.317  15.332  15.089  14.951  14.777  14.508  14.229
```

Figure B.4: Input data for passage C