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Indoor environment in modern Norwegian buildings in connection with moisture-related parameters

Master's Thesis in Structural Engineering and Building Technology

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Summary:

With recent standards, Norwegian dwellings started to have balanced mechanical ventilation systems, and since the new regulations applied, there was not a sufficient number of available studies on moisture, humidity levels in dwellings. Identifying the indoor environment of modern Norwegian residential buildings in connection with moisture-related parameters is the key to this thesis. The findings will serve a purpose of revealing the ventilation of urban residential buildings which can handle moisture-related problems, microbial growth and overheating while lowering the relative humidity related problems in order to maintain a better indoor environment. This study has a purpose of bringing answers to the following questions:

- How is the indoor environment in connection with moisture and temperature in modern Norwegian buildings?
- How do users perceive the indoor environment in modern Norwegian buildings?
- How does moisture differ in different types of rooms?

Keywords			
Relative humidity	Temperature	Moisture excess	Indoor air quality

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Oslo Metropolitan University,

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Abstract

The data collected for this thesis was real data measured in residential apartments. The focus and objective of this project was called healthy, energy-efficient urban home ventilation (NFR 2020-2024); where this thesis was a part of that research made in collaboration with SINTEF Community.

Relative humidity can be as low as 10% in Norway due to the cold winters, which can have a negative effect on people and equipment indoors. This paper has its aim in answering how the indoor environment is in connection with moisture and temperature associated with each room and the peaks of its humidity in modern Norwegian residential buildings, it also has a focus on how the residents of the apartments perceive the indoor environment.

This research aimed to answer these questions based on firstly field experiments where sensors were placed in the apartments for a duration of a week to measure relative humidity, temperature and CO_2 as well as pressure in main rooms of the apartments, secondly an online survey which was aimed at the apartment residents of the field experiments and thirdly computer simulations of the indoor air environment.

The findings showed that, in general, relative humidity levels observed in the monitored apartments was relatively low, e.g., the mean values lower than 26% for every room without a humidifier. While the mean moisture excess was found as lower than 1.36 g/m^3 for every room without a humidifier which was lower than what is found in the literature by other researchers. Additionally, the findings showed a moderate positive correlation between cooking events and moisture excess levels. Furthermore, the WUFI®PLUS simulations further strengthened the field experiment results and gave insight into the whole year results.

Sammendrag

Denne oppgaven inneholder reelle data målt og samlet inn fra leiligheter.
Fokus og mål for dette prosjektet ble kalt sunt og energieffektivt by ventilasjon (NFR 2020-2024); der denne oppgaven var en del av forskningen laget i samarbeid med SINTEF Community.

Relativ luftfuktighet kan være så lav som 10% i Norge på grunn av de kalde vintrene, noe som kan ha negativ innvirkning på mennesker og utstyr innendørs. Denne artikkelen har som mål å svare på hvordan innemiljøet er i forbindelse med fuktighet og temperatur knyttet til hvert roms maksimale og minimale fuktighet i de moderne norske boligbygningene. Hvordan beboerne i leilighetene oppfatter innemiljø er også satt i fokus.

Denne undersøkelsen tok sikte på å svare på disse spørsmålene basert på først og fremst feltforsøk hvor sensorer ble plassert i leilighetene i en ukes varighet for å måle relativ fuktighet, temperatur og CO_2 samt trykk i hovedrommene i leilighetene, for det andre en nettbasert undersøkelse som var rettet mot beboerne av leilighetene til felteksperimentene og for det tredje datasimuleringer av innendørs inneklima.

Funnene viste at det generelt var relativ fuktighetsnivåer observert i de overvåkede leilighetene relativt lave, for eksempel middelverdiene lavere enn 26% for hvert rom uten luftfukter. Mens det gjennomsnittlige fuktighetsoverskuddet ble funnet lavere enn 1,36 g / m^3 for hvert rom uten en luftfukter som var lavere enn det som finnes i litteraturen av andre forskere. I tillegg viste funnene en moderat positiv sammenheng mellom matlagingshendelser og fuktighetsoverskuddsnivåer. Videre styrket WUFI®PLUS-simuleringene resultatene fra feltforsøket ytterligere og ga innsikt i hele årsresultatene.

Nomenclature

Symbol	**Meaning**	**Unit**
G	Moisture production rate	g/h
h	Enthalpy	kj/kg
n	Air change-rate	h^{-1}
m	Mass	kg
m_a	Mass of dry air	kg- dry air
m_v	Mass of water vapour	kg- water vapour
M_g	Molecular mass of a gas	kg/kmol
E_s	the saturated vapour pressure	mb
P	Pressure	Pa
P_{tot}	Total air pressure	Pa
P_{sat}	Saturation pressure	Pa
P_c	Critical pressure	Pa
P_i	Partial pressure	Pa
P_v	Partial pressure of water vapour	Pa
P_d	Partial pressure of dry air	Pa
ν	Water vapor concentration	kg/m^3
ρ	Density	kg/m^3
R	Universal molar gas constant	J/(kmol·K)
R_d	Specific gas constant for dry air	J/(kg·K)
R_v	Specific gas constant for water vapour	J/(kg·K)
φ	Relative humidity	%
T	Temperature	K
T_d	Dry bulb temperature	°C
wbt	Wet-bulb temperature	°C
T_{dew}	Dew point temperature	°C
V	Volume	m^3
v_s	Specific volume	m^3/kg
$\dot{V}$	Volumetric flow rate	m^3/h
ω	Specific humidity	kg-vapor/kg-dry air
ωe	Specific humidity outdoor	kg/kg
ωi	Specific humidity indoor	kg/kg
AH	Absolute humidity	g/m^3
Δv	Internal moisture excess	g/m^3
Δx	Internal moisture excess	kg/kg

Key abbreviations of report assignment

Abbreviations	Meaning
CO_2	Carbon dioxide [ppm]
RH	Relative humidity [%]
AH	Absolute humidity [g/m^3]
MBV	Moisture buffer value [$kg/m^2 \cdot \%RH$]
MC	Moisture content [%]
RH	Relative humidity [%]
U	Thermal transmittance [$W/m^2 K$]
λ	Thermal conductivity [$W/m \cdot K$]
R	Thermal resistance [$K \cdot m^2/W$]
MP	Moisture production [kg/day]
ME	Moisture excess
PCM	Phase change material
IAQ	Indoor air quality
HVAC	Heating, ventilation, and air conditioning
NS	Norwegian standard
ISO	International Organization for Standardization
BS	British standard
MC	Moisture content [%]
MBV	Moisture buffer value [$kg/m^2 \cdot \%RH$]
r_s	Spearman's rank-order correlation coefficient [-]

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1. Introduction (MAIN)

This chapter gives an understanding of the problem and the background of the research object. It finishes with the research questions, limitations, and the structure of the report.

1.1. Motivation

There is growing popularity in building highly insulated airtight houses; this artificial environment creates problems with the indoor air having too low relative humidity. This problem is partly caused by ventilation rates of mechanical ventilation and the rise of heating (Chiba et al., 2007). Low or high humidity in the indoor environment is closely related to many health problems; it is also connected to energy consumption and construction durability. So that controlling the relative humidity is very important towards attaining a comfortable and healthy indoor environment (Zhang & Yoshino, 2010). Nordic climates can have their relative humidity as low as 10% during their dry and cold winters. Dry air is a concern that is frequently the cause of complaints. The low humidity has negative effects on things such as eye irritation, skin dryness, and static electricity, which is not preferable for electrical equipment. Low air humidity could also have negative effects on respiratory health. Norwegian Institute of Public health recommends a relative humidity higher than 20% due to the effect low humidity has on respiratory health (Lind et al., 2019).

Humidification of air is in general not recommended due to the danger of Legionella and other microbial development inside the humidification system, higher energy consumption and maintenance cost for humidification systems, as well as risk of condensation on windows or building envelope (Lind et al., 2019). Sunwoo et al. (2006) recommend having a relative humidity higher than 30% to avoid dry skin and dry eyes when relative humidity is under 30% and in addition nasal mucous membrane when RH is under 10%. In comparison, the Norwegian standards have set recommended lower limit for having residential apartments relative humidity at 25% and the upper limit at 60% when humidification and dehumidification systems are installed (Standard Norge, 2019).

On the other hand, research had shown through mean acceptability votes of 36 subjects selected for an experiment that dissatisfaction of test subjects increased when relative humidity increased to 50% and even more when at 70% (Fang et al., 1998). The high indoor relative humidity is also associated with mould growth that can lead to allergies and respiratory discomfort (Bornehag et al., 2001, 2004), as well as the risk of house dust mite infestation and condensation on cold surfaces, which in return can lead to microbial growth and chemical processes (Bornehag et al., 2001). Colder regions can also have indoor dampness problems, where damages related to dampness exposure is up to 5% to 30%; this percentage is, however, considerably smaller than in warmer regions (Jaakkola & Jaakkola, 2004).

Considering that populations spend up to 90 % of their time in their homes (Klepeis et al., 2001; Wierzbicka et al., 2018), together with the need for hygrothermal analysis to build healthy buildings with great indoor air quality and to demonstrate satisfactory performance of structures (Kalamees et al., 2006). makes research on the indoor environment essential to have a safe indoor environment.

1.2. Scope

The topic of this thesis is based on the project from SINTEF Community, called Healthy-efficient Urban home ventilation. With recent standards, Norwegian dwellings started to have balanced mechanical ventilation systems, and since the new regulations applied, there was not a sufficient number of available studies on moisture, humidity levels in dwellings.

The topic's goal was to identify the indoor environment of modern Norwegian residential buildings in connection with moisture-related parameters. The focus of this study is mostly on studying moisture associated with each room and the peaks of its humidity in the modern Norwegian residential buildings so that it is possible to determine and reveal useful findings for further research to repurpose in order to reveal the ventilation of urban residential buildings which can handle moisture-related problems, microbial growth, and overheating while lowering relative humidity related problems.

The scope of the study is limited to 10 different apartments and apartment sizes between 30 - 115 m^2 for the monitoring of indoor environment to been conducted on, furthermore only newer apartments (built/renovated after 2012) which operated with balanced mechanical ventilation will be assessed. The location of all selected apartments is limited as Oslo, Norway. The data from the field experiments will be collected during the time frame of February 2021 – May 2021. Each volunteer household to the study will be requested to complete a short questionnaire in order to evaluate perceived indoor environment and estimate the moisture production by each apartment. Furthermore, several WUFI ® PLUS simulation will be conducted in order to evaluate whole year situation together with a humidifier and without a humidifier. The authors wanted to use WUFI®PLUS simulation to get a close resemblance of relative humidity and temperature to the results of field measurements in order to create simulations for the period of

1.01.2021 – 1.01.2022, by using the premade simulation. It must be noted that validity by using WUFI®PLUS was not the intention.

1.3. Research question

Identifying the indoor environment of modern Norwegian residential buildings in connection with moisture-related parameters is the key to this thesis. The findings will serve a purpose of revealing the ventilation of urban residential buildings which can handle moisture-related problems, microbial growth and overheating while lowering the relative humidity related problems in order to maintain a better indoor environment. In order to provide a path through the research three research questions have been created.

- How is the indoor environment in connection with moisture and temperature in modern Norwegian buildings?
- How do users perceive the indoor environment in modern Norwegian buildings?
- How does moisture differ in different types of rooms?

These research questions will help to identify the typical load profiles from cooking and showering events. This will include the effects of moisture regeneration and buffering. The typical user profile will be created from the monitored and gathered dynamic data from the dwellings. Building simulation software will then be tested for its ability to simulate field data from the input data.

1.4. Limitations

This thesis had its focus on dwellings that had BRA between 30-115 m^2. Whether the apartments are newly refurbished or newly built also plays a role in choosing them.

Due to the Covid-19 situation followed with strict rules towards visiting other people' homes, made it very difficult to measure all ventilation rated in each monitored apartment. So that only two apartments ventilation rate was measured, where selected sample apartment was located in the same building project as most of the apartments were located in.

One household/participant did not answer to the questionaries, although the field measurement data from the apartment was utilized. No questionnaire answers were given by the household. The questionaries did therefore not reflect on this apartment.

Ten apartments were tested, but due to the limited time and sources no more than these apartments were possible to test.

2. State of Art

2.1. Indoor Environment

Nowadays, the indoor environment is defined by environmental factors such as thermal comfort, indoor air quality, lighting quality and acoustical quality. Thermal comfort or indoor climate is one of the main factors that comprise parameters such as humidity, air velocity and temperature. Another crucial factor is indoor air quality which is a complex phenomenon that consist of fresh air supply, odour and indoor air pollution, etc. (Bluyssen et al., 2009).

The most important factor in evaluating the thermal comfort in a building is considered to be the indoor temperature. If the people in a particular environment feel satisfied in terms of comfort and do not desire to be colder or warmer, then the temperature can be considered suitable (Frumkin et al., 2006). The comfort temperature is strongly related to measured mean temperature (Nicol & Humphreys, 2002). In recent years, there has been an increase in the trend of collecting data on indoor temperatures in dwellings, and this may help to gain a better understanding of preferences, patterns and trends in populations (Teli et al., 2018). For instance, Teli et al. (2018) stated the daily mean temperatures in Sweden as 22 °C, where around 80% of the values were between 20 °C and 25 °C. Also, Geving & Holme (2012) had conducted a field experiment in 117 Norwegian houses in order to measure indoor air humidity and temperature levels and reported the weekly mean temperatures as 21.5 °C when outdoor temperatures were under 5 °C. Also, Table 1 shows the summary of the mean temperatures from other regions created by Teli et al. (2018).

Table 1. Mean temperatures of dwellings and standard deviation from other regions in heating season (Teli et al., 2018)

Location/year	**T_{in} mean [°C]**	**Standard Deviation**
Tokyo, Japan	19.6	2.8 K
United Kingdom	19.0	2.5 K
Harbin, China/2000-01	20.1	2.4 K
Beijing and Shanghai/2012-13	21.4	2.7 K
Sweden/2007-08	22.0	0.7 K

Limits for design temperatures also differ between different standards and regulations. Design temperatures for residential buildings given in ISO Standard 17772-1:2017 are set lower limit to 16°C and upper limit to 25°C (International Organization for Standardization, 2017). Also, The WHO recommends 21°C as the lower limit for living rooms and 18°C for bedrooms (World

Health Organization, 2007). While Norwegian Building Authority recommends air temperature to be kept below 22°C when there is a need for heating (Direktoratet for byggkvalitet (TEK 17), 2017). Even though, contrary to the recommendations set out in the standards or regulations, there are also studies showing that occupants feel more comfortable in different temperatures. For instance, Zaikina et al. (2019) reported that air temperature of 25°C was evaluated as positively by 65% of respondents while Norwegian Building Authority’s recommendation points air temperature to be under 22°C. In addition, Tweed et al. (2014) showed that people have various expectations when it comes to thermal comfort. Therefore, design temperature values recommended in regulations are not suitable for every person: while some people accept the recommended temperatures as comfortable, some prefer higher and some lower temperatures. Han et al. (2009) showed that the thermal sensory responses of residents of urban dwellings during the cold winter months are different from those in rural dwellings. Moreover, Zalejska-Jonsson & Wilhelmsson (2013) reported that residents in the southern part of Sweden showed greater sensitivity to problems with thermal comfort, particularly problems with indoor temperature.

Additionally, indoor humidity is required in the evaluation of building performance (Arumägi et al., 2015). There are studies in the existing literature which concluded that indoor humidity-environment is intimately correlated to health problems (Zhang & Yoshino, 2010). Toftum et al. (1998) conclude that high humidity in conjunction with high air temperatures conducts to discomfort. Also, Toftum et al. (2002) reported that a RH over 65% leads to discomfort. Moreover, Nugrahanti et al. (2019) stated that mould development would start at a RH of 80% - 95%, and it might lead to serious health problems. However, discomfort for building occupants might also come along with low humidity (Derby et al., 2017). There are several studies that focused on the effects of low humidity on human health and comfort as well as IEQ. Reinikainen & Jaakkola (2003), Sato et al. (2003) and Wolkoff & Kjærgaard (2007) indicated that too low RH associated with discomfort such as dry skin, throat and mucous membrane and irritation of eyes. Also, Wittchen & Jensen (2019) reported that they received complaints about dry air from some occupants during the heating season. Moreover, Derby et al. (2017) have conducted a literature review on the effects of low humidity on health, comfort and IEQ and reported that several reviewed studies stated that due to the lowered humidity, increase in skin dryness, eye irritation occurs. Additionally, Lind et al. (2019) reported that at 14% RH, more subjects complained about burning and itchy eyes.

2.2. Moisture production

Water vapour is a gas in the atmosphere whose amount varies according to time and place and is expressed as moisture in literature. The addition of water vapour from a source to the surrounding air can be called moisture production. Based on the size and type of the addition of moisture, the process of moisture production always changes the state of the air resulting in an increasement in the relative humidity towards the dew point of the existing air.

There are a large number of activities affecting indoor moisture production. These moisture generative activities in dwellings depend on several conditions. First and foremost, moisture production will be affected by occupant behaviour together with the existence of technical appliances and installations (Pallin et al., 2011). To estimate the total indoor moisture load, incident frequencies of human behaviour is a necessity (Christian & Trechsel, 1994). Depending on occupants' user behaviour, moisture loads will also vary on weekdays and weekends. As seasonal changes can be expected, it is also essential to define variations over a longer period of time (Kalamees et al., 2006).

As aforementioned, there are several sources affecting indoor moisture, and humans are one of the greatest sources of moisture generation. Table 2 shows the estimated rates of moisture production from humans, taking into account the type of physical activity. In the table, activities differ between sleeping to hard activities. It must be noted that all activity results in moisture production rates are based on mean values of fully grown men (Johansson et al., 2015). Also must be noted that the sources may vary depending on room type and the moisture production rates from different sources that may be found in different rooms in dwellings are a crucial input to estimates of indoor humidity levels (Yik et al., 2004). Table 3 shows the most common moisture-generating sources that may be found in each room of an apartment. As can be seen, each room has its distinctive sources, while some of the sources appear in more than one room.

Table 2. The estimated rates of moisture production from humans, taking into account the type of physical activity (Johansson et al., 2015).

Moisture production – Perspiration and Respiration [kg/h/person]			
Type of Activity	*(Christian & Trechsel, 1994)*	*(Chartered Institution of Building Services Engineers, 1999)*	*(Yik et al., 2004)*
Sleeping			0,043
Light activity	0,03-0,12	0,04-	0,065
Medium activity	0,12-0,20	-	0,079
Hard Activity	0,2-0,3	-0,1	0,102

Table 3. The most common moisture-generating sources may be found in each room of an apartment (Johansson et al., 2015).

Type of the room	Moisture sources
Living room	Humans, pets, aquarium, plants, ironing.
Closet	-
Bathroom	Bathtub, tumbler drier, humans, showering, bathing.
Bedroom	Humans, pets, ironing, plants.
Foyer	Humans, pets.
Master bedroom	Humans, pets, ironing, plants.
Kitchen	Dishwashing machine, humans, food preparation, hand dishwashing, plants.

2.3. Moisture generation rates

The performance of indoor moisture production rate has a significant impact on the indoor moisture level (Lu, 2003). Moisture production in a residential is mostly covarying with human's activities. By both perspiration and respiration, humans produce an effect on indoor moisture supply. Moisture generation from humans depends on the indoor activity taking place as the activity pattern of individuals in a dwelling must be predicted (Johansson et al., 2015). As moisture generation depends on activities, some activities can be associated with the type of rooms. Recent studies about moisture production mostly focus on how moisture production rates vary on the type of rooms. The latest study, which had a focus on moisture production in bedrooms, has been performed by Ilomets et al. (2017). The moisture production rate in bedrooms can vary depending on a time of the day and the activity type; since the rate of people being present at night-time will increase in accordance with the intended use of the bedroom, moisture production will increase correspondingly. Ilomets et al. (2017) conclude that average night-time moisture generation in master bedrooms during cold days was found as 72 g/h with a standard deviation of 50 g/h. According to the authors, the temporary unused bedrooms or the moisture buffering effect might be the reason for the unexpected low average moisture generation in some dwellings. Another research paper created by Johansson et al. (2015) has an estimation of moisture production rate from sleeping as 30 g/h while in another study conducted by Yik et al. (2004), the moisture generation rate of a human while sleeping found as 43.2 g/h according to the latent heat values from ASHRAE Handbook (Handbook–Fundamentals, 2001). Apart from these, in another study conducted by Geving et al. (2008) has expressed the mean value of moisture supply in bedrooms under -5°C outdoor temperature as 1.62 g/m^3 with a standard deviation of 0.66 g/m^3. In order to gain a better view of what is found in the literature, the overview of moisture production rates from various activities from different studies is presented in Table 4.

Activities that have the biggest moisture generation rates mostly happens in bathrooms such as showering, bathing, laundry appliances and floor mopping. For instance, Geving & Holme (2012) found that the mean weekly internal moisture excess in bathrooms was considerably greater than all other zones for the whole outside temperatures. Also, Møller & de Place Hansen (2017) conclude that bathrooms have a greater average moisture supply (g/m^3) than other room types. Recent studies reached the conclusion that in bathrooms, there are peaks or a peak for the internal moisture excess and RH in a day (Geving et al., 2008; Geving & Holme, 2012). The reason for the peak/peaks is most likely the showering/bathing activities. Johansson et al. (2015) tabularised metadata on moisture production from taking a shower where values vary between 0.20 [kg/5min] to 0.38 [kg/5min]. Even though achieved values by most of the studies are varying between 0.20 [kg/5min] to 0.38 [kg/5min], there are some other studies that achieved higher numbers. For instance, Yokoo et al. (2007) found the average moisture production from bathing as 1100 g. The reason for higher moisture production probably due to the fact that Yokoo et al. (2007) took an average of different bathing styles such as bath in tub and showering.

Another zone where the other dominant moisture generative activities (food preparation, dishwashing, etc.) happen is the kitchen. Food preparation is one of the dominant indoor moisture sources, which includes preparing breakfast, dinner, and lunch. The moisture production from food preparation is commonly defined as a specific amount without information about the duration of the activity (Johansson et al., 2015). There are few studies that quantified the amount of moisture generated by each meal (Angell & Olson, 1988; Yik et al., 2004). (Johansson et al., 2015) tabularised metadata on moisture production from food preparation where it is obvious that there is a great difference between the values from different sources. Moisture release differs greatly depending on the cooking techniques (Angell & Olson, 1988). For instance, most of the Chinese cooking methods generate a great amount of moisture: some techniques such as stir-frying and boiling generate moisture intensively for a short period while steaming, and soup boiling generates intensively for a long period (Yik et al., 2004).

Another important source of moisture is washing clothes and drying. If a laundry is carried out in an automatic washing machine, the moisture added by washing is assumed to be zero, it is discharged directly into a drain (Angell & Olson, 1988). Instead, depending on the type of drying method, a possible moisture generation into the indoor environment may occur during the drying process of the clothes. Although the washing procedure does not normally generate moisture, determining the frequency of use of the appliance is still important as it can be used to estimate the laundry drying demand (Johansson et al., 2015). Zemitis et al. (2016) conducted research in order to measure moisture generation from cloth washing, plants and humans respiratory and they conclude that the average moisture generation from indoor cloth drying as 1220 g/day for one person. Another study conducted by Yik et al. (2004) shows that the average moisture production from clothes drying as 1666 g/load. While according to the standard BS 5250:2002, the moisture production from cloth washing and drying indoors is estimated to be 1500 g/person per day (The British Standards Institution, 2002).

There are great numbers of moisture generative sources in a dwelling, and each and every one of them has distinctive moisture production rates. In order to gain a better view of what is found in the existing literature, the overview of moisture production rates from various activities from different studies is presented in Table 4. As can be seen in the table, moisture production rates of the same activities differ between the results obtained from different sources. Since there is plenty of conducting each activity, it makes it hard to analyse or expound the moisture production. Also, it must be noted that by the time technology and people’s behaviours change and people’s changing lives with technology will also create changes in moisture production.

Table 4. The overview of moisture production rates from various activities found in different studies

Indoor moisture sources	Moisture production rates found from literature				
	(Kalamees et al., 2006)	***(Yik et al., 2004)***	***(Johansson et al., 2015)***	***(Yokoo et al., 2007)***	***(Zemitis et al., 2016)***
People	0.9 kg/day		72.0 g/h		
• Asleep		0.043 kg/h/person			
• Light activity		0.065 kg/h/person			
• Medium activity		0.079 kg/h/person			
• Hard activity		0.102 kg/h/person			
Pets					
• Dog	0.4 kg/day		2.48-53.6 g/h		
• Cat	0.1 kg/day		3.30-9.08 g/h		
Cooking	0.8 kg/day				
• Breakfast		0.52 kg/event			
• Lunch		1.75 kg/event			
• Dinner		1.75 kg/event	38.3 g/h		
Dishwashing	0.4 kg/day/family of 4				
• By hand		144 g/day			
• Dishwashing machine			0.2-0.4 kg/event		
Bathing		530 g/event		900-1300g/event	
• Showering	0.3 kg/5min		42.1 g/h		
Drying clothes	1 kg/load	1.66 kg/load	78.4 g/h		1220 g/day/person
House plants	0.4 kg/day/5pcs	~0.02 kg/day/pcs	0.04 - 0.15 kg/day/pcs		

2.4. Effect of building materials on indoor moisture variability

Indoor humidity levels have a significant effect on thermal comfort, occupant health and IEQ (Derby et al., 2017). Humidity levels in indoor environment differ considerably during the day and seasons (Nore et al., 2017). Hygroscopic materials can absorb moisture from the air when their relative humidity increases and release moisture into the air when their relative humidity decreases (El Diasty et al., 1992). The indoor humidity fluctuations can be reduced with the help of materials that have the ability to store and release moisture (Nore et al., 2017).

There are several studies that propose experimental methods in order to describe the influence of building materials on indoor RH. Time (1998) and Padfield (1998) proposed the methods for characterising the moisture buffering effect. Later, Hansen (2000) proposed a method for the evaluation of the moisture buffering effect based on simple measurements. Simonson et al. (2002) reported that moisture transfer between wood-based structures and indoor air considerably reduces the highest indoor humidity (at around 35% RH) also increases the minimum indoor humidity (up to 15% RH). Moreover, Mitamura et al. (2001) performed full-scale measurements on moisture buffering in building materials. Also, Rode et al. (2007) developed a test protocol proposal for the NORDTEST method in order to define the practical MBV and also conducted a Round Robin test on eight different building material systems and materials in order to find their performance of moisture buffering.

A review of studies that had a focus on experimental and numerical approaches on the moisture buffering performance of building materials has been carried out by Kreiger & Srubar III (2019). They conclude that hygroscopic materials should exhibit low desorption temperatures and dehumidification capacities in order to have the best performance for moisture buffering. Also, they categorised moisture buffering performance of non-conventional (natural) materials and reported that most of them have performance as excellent. The authors also mentioned that engineered materials have more consistent MBVs than natural materials. Moreover, Yu et al. (2013) mentioned that wood-based panels easily absorb or release moisture when ambient temperature and relative humidity fluctuate. Likewise, Nore et al. (2017) reported that wide areas of exposed wood finishes have significant efficacy by their impressive moisture buffering performance in order to keep the relative humidity in a closer range. In order to gain a better understanding of MBVs, a summary of reported MBV, density and porosity of different materials and their testing methods created by Kreiger & Srubar III (2019) presented in Table 5.

Table 5. Summary of reported MBV, density and porosity of different materials and their testing methods (Kreiger & Srubar III, 2019).

Material	**n**	**MBV ($g/\Delta RH/m^2$)**	**Method**	**Porosity (%)**	**Density (kg/m^3)**
Bamboo Fiberboard	6	3.0 ± 0.79	Nordtest	N/A	404 ± 85
Barley Straw	1	3.2	ISO 24.353	92	108
Birch Panel	3	0.85 ± 0.22	Nordtest	N/A	600
Brick	3	0.48 ± 0.19	Nordtest	N/A	1600
Carnauba Wax	1	1.1	Nordtest	N/A	N/A
CEB	7	1.9 ± 0.54	Nordtest	N/A	1800
CEB + Barley Straw	4	2.6 ± 0.10	Nordtest	N/A	1735 ± 71
Cellulose	1	3.1	Nordtest	N/A	N/A
Cement	2	0.37 ± 0.16	UMBV	N/A	1925 ± 153
Ceramic	1	0.26	Not Specified	N/A	1740
	1	0.95	Nordtest	N/A	1500
Clay Plaster + Fiber	4	1.7 ± 0.02	Nordtest	41 ± 2.8	1544 ± 144
Clay. Sand Plaster	9	0.31 ± 0.05	Not Specified	N/A	N/A
Concrete	2	0.85 ± 0.51	UMBV	N/A	1346 ± 1279
	2	0.70 ± 0.42	Not Specified	N/A	N/A
	10	0.88 ± 0.56	Nordtest	70.6	1335 ± 762
Corn Pith	1	3.0	ISO 24.353	98%	48.1
Earth Plaster	1	2.9	Nordtest	N/A	1848
Earth Plaster + Fibre	6	3.0 ± 0.31	Nordtest	N/A	1362 ± 242
ELS	5	0.90 ± 0.37	Nordtest	22.3 ± 2.2	2076 ± 65
Fibre Wallpaper	1	0.15	Not Specified	N/A	300
Gypsum	1	1.1	UMBV	N/A	874
	4	0.33 ± 0.18	Not Specified	N/A	N/A
	10	0.45 ± 0.30	Nordtest	N/A	977 ± 204
Gypsum. Lime Plaster	3	0.14 ± 0.06	Nordtest	N/A	900
Hemp Concrete	7	1.89 ± 0.32	Nordtest	76.4 ± 2.7	713 ± 645.5
Hemp Fibre	1	3.3	ISO 24.353	97	41.1
Hemp Lime	1	2.3	ISO 24.353	83	286
Hemp Line Assembly	19	1.5 ± 0.70	Nordtest	N/A	610 ± 453
Laminated wood	3	0.46 ± 0.08	Nordtest	N/A	430
MIL-100 (Fe)	1	15	Nordtest	N/A	N/A
Mortar + Fiber	1	3.0	Nordtest	N/A	N/A
Painted Gypsum	1	0.33	Not Specified	N/A	N/A
PCM	1	0.08	Nordtest	N/A	N/A
	9	0.81 ± 0.43	Not Specified	80	793 ± 351
Pise	1	2.1	Nordtest	24.2	1870
Plaster	3	1.1 ± 0.40	Nordtest	N/A	670
Plywood	1	1.0	UMBV	N/A	N/A
Rammed Earth	1	0.88	Nordtest	N/A	1980
Rape Straw Concrete	1	2.4	Nordtest	75.1	1954
Sand. Lime Plaster	1	0.90	Nordtest	N/A	1650
Sodium Polyacrylate	1	9.0	Nordtest	N/A	N/A

Spruce Board	4	1.2 ± 0.06	Nordtest	N/A	430
Spruce Board (sealed)	4	0.35 ± 0.25	Nordtest	N/A	N/A
Spruce Plywood	5	0.57 ± 0.08	Nordtest	N/A	N/A
Vermiculite Board	1	0.19	Not Specified	N/A	746
WSE Mortar Assembly	2	0.92 ± 0.04	UMBV	N/A	637 ± 21
Wood	1	0.4	Not Specified	N/A	N/A
Wood	1	1.2	Not Specified	N/A	N/A
Fiberboard	2	2.4 ± 0.47	Nordtest	N/A	458 ± 4
Wood Fiber	2	2.3 ± 0.50	ISO 24.353	91 ± 7.1	136 ± 108

Although most research has focused on the moisture buffering effect of each material alone, also, there are some studies that have focused on the influence of moisture buffering from entire interior hygroscopic materials on indoor moisture supply. For instance, Pallin et al. (2011) developed a simulation model in regard to the moisture buffering effect of interior materials. They performed simulations for 1000 random Swedish dwellings with and without moisture buffering from hygroscopic materials. They concluded that the moisture buffering effect of hygroscopic material surfaces affects the moisture supply in a dwelling. Figure 1 shows an example of the results from simulations which presents the hourly variations of the indoor moisture supply based on simulation of 1000 dwellings for the duration of one year.

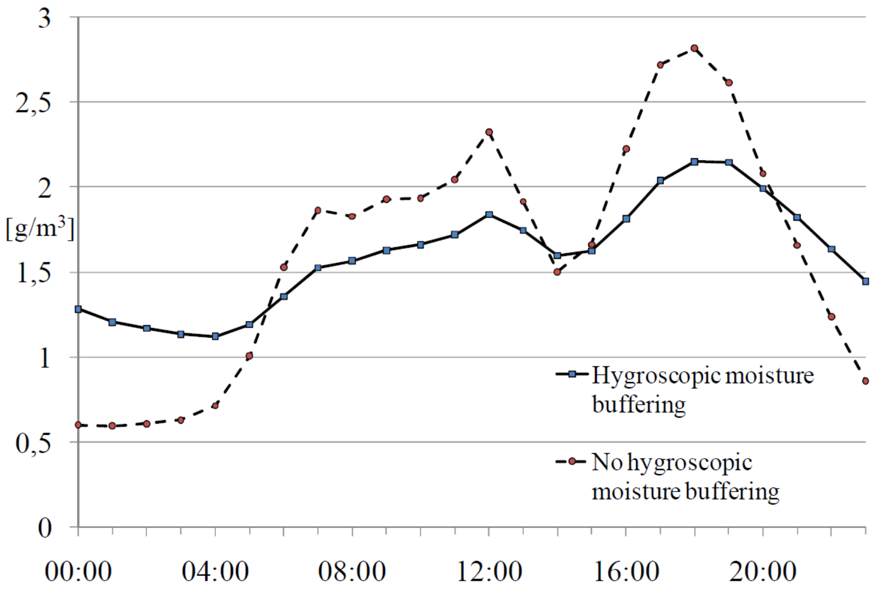


Figure 1. The hourly variations of the indoor moisture supply with and without the effect of moisture buffering from hygroscopic materials, based on simulation of 1000 dwellings for the duration of one year (Pallin et al., 2011).

2.5. Effect of ventilation on indoor moisture levels

Ventilation involves the penetration of air from outside into a building to create an acceptable indoor environment. In some cases, ventilation utilised to control the indoor thermal environment by adjusting the humidity and providing cooling or heating (Carrer et al., 2015). Ventilation should be adequate to either remove moisture generated indoors and pollutants or dilute their concentrations to satisfactory levels for the health and comfort of the occupants and should be efficacious to maintain the integrity of the building (Seppänen & Kurnitski, 2009).

It is possible to provide ventilation in several mechanical and natural methods. These methods usually give better results in improving health however also might have undesirable effects due to improper design, installation, operation and maintenance (Seppänen & Kurnitski, 2009). Chenari et al. (2016) have carried out a large-scale review on energy-efficient methods for ventilation in buildings and reported many studies and their findings related to undesirable effects (SBS symptoms, respiratory illness, allergies, etc.) as a result of inconvenient installation, maintenance, design and operation of ventilation. Ventilation which used to control humidity, can eventuate in too high or too low humidity levels, under particular circumstances. In hot climates, indoor humidity may be lower than outdoor humidity. In such situations, the humidity will be brought in by ventilation, and usually, air conditioning will remove humidity (Seppänen & Kurnitski, 2009).

While the problem is high indoor relative humidity in temperate and hot climates, extremely low relative humidity may possibly be a problem when concerning cold climates. In cold climates, lowering room temperature, which increases relative humidity, may alleviate the skin symptoms (Reinikainen & Jaakkola, 2003). In the existing literature, there are so many studies that reported a correlation between ventilation rate and humidity. For instance, Fisk (2018), Hägerhed-Engman et al. (2009), and Howieson et al. (2003) have evinced that humidity indoors tends to react negatively to ventilation rates, meaning that increasing ventilation rates decreases indoor air humidity, and this results in lowering the health risks from mould, moisture or house dust mites. However, there are other studies that indicated the opposite findings, such that higher ventilation rates result in increasement of room humidity or moisture-related diseases (Singleton et al., 2017; Strøm-Tejsen et al., 2016). Consequently, studies from literature show that ventilation rates can affect building occupant health, moisture-related diseases, and humidity levels indoors. Nonetheless, it is controversial whether the effects are negative. Findings are largely dependent on location, weather conditions, building designs, etc. (Tang et al., 2020).

3. Theoretical background

This chapter gives an elementary understanding of the physics behind humid air. It is divided into two main categories, which are humid air and indoor environment.

3.1. Humid air

Air has, in general, some amount of moisture in the form of water vapour under normal temperature and pressure circumstances. Humid air can be regarded as an ideal gas under normal pressure and temperature. The amount of water vapour in the air can be measured in different ways, such as (Geving & Thue, 2002):

- As the water vapour's partial pressure (P_v) expressed in the unit of Pa (N/m^2)
- As water vapour concentration (ν) (also called water vapour density) measured in kg/m^3
- Or as water vapour mass (x) per kg dry air, which uses the unit of kg/kg

The chemical composition of atmospheric clean and dry air consists mainly of the gases: argon (0,9%), oxygen (21%), nitrogen (78%). While other substances such as carbon dioxide, Neon, Helium, Methane, Hydrogen, Ozone are all at smaller levels but still present in the air. Additional substances can be found with human activities, which, through natural processes, can release substances in the air that is outside the scope of the ones mentioned (Nilsson, 2003).

3.1.1. Ideal gas

Dry air is to be considered as an Ideal gas, even without considering the gases which are present in the air. Both water vapour and dry air are far below the critical limits when considering the temperature and pressure range of the atmosphere and thus considered ideal gasses (Geving & Thue, 2002).

An ideal gas is a gas where all collisions between the atoms or molecules are perfectly elastic while there are no attractive intermolecular forces. Three variables define an ideal gas, and these are (Speight, 2017).

- Absolute pressure (P)
- Volume (V)
- Absolute temperature (T)

Equation 1 is the ideal gas equation. The ideal gas law is assumed applicable with an acceptable accuracy since temperature (T) is high when compared to critical temperature (T_c), and that the critical pressure (P_c) is high when compared to the lower pressure (P) (Michael J. Moran et al., 2010) (Ingebrigtsen, 2016).

$$\mathrm{P}_v = \frac{\mathrm{m}}{\mathrm{M}_g}\ \mathrm{RT} \qquad \textit{Equation 1}$$

In Equation 1, P stands for (Pa), which is the gas pressure, and the gas volume is V measured in (m^3), the mass of the gas is m measured in (kg), While M_g is the molecular mass measured in ($kg\cdot kmol^{-1}$), T is the absolute temperature in the unit form of Kelvin (K), and lastly, R which is the universal molar gas constant with the value of 8.31441 ($J\cdot kmol^{-1}\cdot K^{-1}$), (Geving & Thue, 2002).

The Dalton model is compatible with the ideal gas concept as being made up of molecules that services negligible forces on themselves and whose volume is relative to the volume occupied by the gas is negligible. The Dalton model is applicable due to atmospheric air containing both dry air, and water moisture were both behave as ideal gases. The Dalton model supposes that the components in a mixture of gas exert an ideal gas behaviour as though it was solitary at volume (V) and temperature (T). In the Dalton model, P_i stands for the single individual pressure of a single gaseous compound, while P_{tot} is for all of them combined. The Dalton model is shown in Equation 2. The Dalton model is generally a specific case of additive pressure rule to relate the pressure, temperature, specific volume of gas mixtures (Michael J. Moran et al., 2010).

$$\sum_i P_i = P_{tot} \qquad \textit{Equation 2}$$

The partial pressures sum equals mixed pressure. The components partial pressure, P_i, is the actual pressure that the moles of the component would exert if the component would to be alone at volume (V) and the mixture temperature (T). So that the Equation 2 can be applied as components for the humid air or the water vapour as one. Daltons model (Equation 2) can be applied to the equation of state in Equation 3; here, the equation of state is presented for a component (Michael J. Moran et al., 2010).

$$P_i \cdot V = \frac{m_i}{M_i} \cdot R \cdot T \qquad \textit{Equation 3}$$

3.1.2. Relative humidity

The relative humidity is a term that describes the existing water vapour in a gaseous mixture containing water vapour and air in terms of percentage. The definition of the relative humidity of an air and water mixture is the ratio of the saturated vapour pressure of water at the specific temperature to the partial pressure of water vapour in the mixture (Castillo, 2011). There is an upper limit of the amount of water vapour the air of a given temperature can hold, and at this limit, it is said that the air is saturated. The content of moisture due to saturation is given in g/m^3, and its designation is P_{sat} where the “sat” stands for saturated. This is basically the upper limit of how much water vapour the air can hold, and the temperature at the saturation point is called the dewpoint. The amount of water vapour the air can hold rises with temperature, but should the temperature of saturated air suddenly fall, the air would then no longer be able to hold as much water vapour as previously possible, so that the excess water vapour is then released as air moisture or condensation on surfaces (Edvardsen, 2014). The refrigerating and air conditioning standard (ASHRAE) has recommended the relative humidity to be maintained within the region of 40% - 60%; this is the desired comfort range for human beings (Qin et al., 2020). The relative humidity (RH) Equation 4 divides P_v by P_{sat} for the given temperature and multiplies it by 100 (Vaisala, 2013) (Edvardsen, 2014).

$$RH = \frac{P_v}{P_{sat}} \cdot 100\% \qquad \textit{Equation 4}$$

As the total pressure has not entered the definition of relative humidity when the temperature is above 100°C, the same definition is possible. But as the normal ambient pressure (saturation pressure) is above 1013 hPa, RH cannot reach 100% when unpressurised. This is also the case when the temperature is below 0°C, condensation occurs at a lower humidity than 100%, and therefore the vapour is saturated against ice. In these two scenarios, relative humidity at 100% is impossible (Vaisala, 2013).

Relative humidity (RH) is a critical factor for how fast the excessive moisture in materials is dried out. The amount of moisture a material has, wants to gradually come to equilibrium with the surrounding relative humidity level of the air. But a driving force through water vapour transport by diffusion becomes present when there are different air humidity levels on each side of a material. Indoor condensation may occur due to air leakages, and this condensation is reliant on the air’s dew point temperature, which is a measurement for how much water vapour there is in the air, and it gives the temperature where the air by cooling reaches 100% RH. The risk of condensation rises with the dewpoint temperature and the water vapour content (Geving & Thue, 2002).

3.1.2.1.Outdoor

Humans can generally not control relative humidity outdoors. This is, however, what nature does through the changes in temperatures, seasonal variations and the local climate in the region. Figure 2 shows the outdoor relative humidity for the last ten years in Oslo, Blindern. The max, average and min relative humidity during the last ten years has been 100%, 74.6, and 13, respectfully. The 100% is likely during rain when the relative humidity can directly be 100%. Simultaneously specific humidity is found to be at a maximum of 13,5 gr/kg, and the minimum 0.9 gr/kg, where the maximum for specific humidity is during summer months and the minimum is during winter months. In the Mollier diagram seen in Appendix D, it is possible to see that air can hold more moisture in the summer months. This is due to the temperature being higher during the summer months and thus containing more humidity. And vice versa during winter.

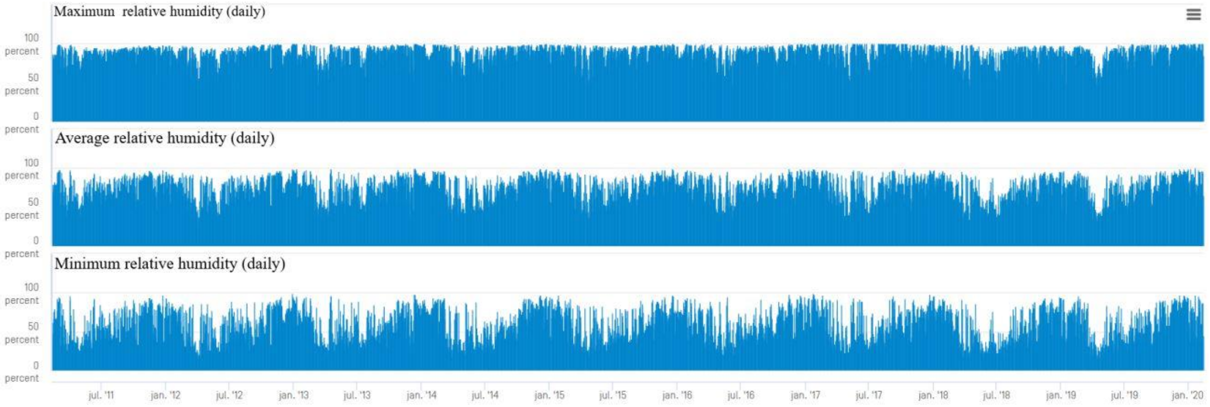


Figure 2. Daily outdoor relative humidity Oslo. Blindern. Daily max, average and minimum for the last ten years

3.1.2.2.Indoor

Cold climates have low humidity issues. While low humidity indoors can potentially lead to itchy, dry skin and noticeable discomfort in humans' nose and eyes. Relief from this discomfort can be found by providing the indoor environment with minimum moister, which has also been found to be improving healing in medical spaces. The dewpoint in humidified spaces can be as high as 50°C, which lowers condensation risk, but as low as 25°C without humidification (Miles & Furgeson, 2008).

3.1.2.1.Measuring relative humidity

Measuring relative humidity (RH) indoors can show whether there is bad ventilation or unnormal moisture production. One of the downsides with measuring RH can be that the equipment needs to be calibrated quite often as well as needing stable temperature without gradients while the measurement is ongoing. Most of the RH measuring equipment that directly measures RH either uses an electrolyte to measure the resistance or to measure the capacity using polymer film. Where both the resistance and the capacity changes in accordance with the relative humidity. Some of the relative humidity measuring equipment can give inaccurate measured data for RH higher than 95%. The RH measuring equipment measuring precision is in the region of ± 2 % if the surrounding RH is between 0 – 90 % and temperature at 25 °C. And regular calibration is required to document the precision of the measurements.

So, it is possible to get precise measurements already after a couple of minutes when measuring RH inside a room, provided that the temperature around the sensor is the same as the surrounding air. It is wise to let the equipment stay inside indoor temperature before usage if the equipment and its sensor have been exposed to lower temperatures during wintertime transportation. Other temperature sources need to be avoided. It is essential to measure the air temperature simultaneously with the RH measurements. If the moisture supplement is of additional interest, the air temperature outdoors must be measured additionally (Geving, 2011).

3.1.2.2.Mollier Diagram

Psychrometric graphs, a graphical representation of the properties of humid air, have been developed to facilitate engineering calculations. Such a chart with enthalpy as a coordinate has been used for the first time by Richard Mollier (McQuiston et al., 2004, p. 55). The physical properties of air are defined and described in Table 6.

Mollier diagram is an essential tool for engineering purposes such as studying and estimating the changes of humid air. Mollier diagram provides a graphical representation of the relationship between temperature, water content and enthalpy with a minimum of thermodynamic assumptions in connection with humid-air issues and calculations in ventilation technology (McQuiston et al., 2004).

Table 6. The physical properties of air and their description

Name	**Unit**	**Designation**	**Description**
Dry-bulb temperature	°C	T_d	Air temperature measured with a standard thermometer (Field & Solie, 2007, p. 294).
Wet-bulb temperature	°C	wbt	If a damp and porous rag is placed around the sensor on a standard thermometer, it will cool down because the water evaporates, and the thermometer will show a temperature that is lower than the dry temperature. This temperature defines the wet-bulb temperature of air (Per F. et al., 1998, p. 10)
Relative humidity	%	RH	Definition of relative humidity is the ratio between the actual amount of water vapour in the air at a certain temperature and the maximum amount of water vapour the air can contain at this temperature (Field & Solie, 2007, p. 294).
Moisture content	%	MC	A measure of the actual total amount of water held in the air as a form of vapour (Field & Solie, 2007, p. 294).
Dew point	°C	T_{dew}	Dew point is the temperature at which moisture in the air starts to condense when the air is cooled or at which droplets are too large to hang in the air (Field & Solie, 2007, p. 294).
The total heat	kJ/kg		The total heat energy in the air
Specific volume	ft^3/lbm or m^3/kg	v_s	The specific volume is defined as the opponent of the density (M. J. Moran et al., 2014, p. 14)

Even though there are different type of developed modern-day charts, they still retain the enthalpy coordinate. There are five Mollier-type charts developed by ASHRAE to cover the required variable range (McQuiston et al., 2004, p. 55). The simplified version of a Mollier diagram is shown in Appendix D.

3.1.3. Air density

Under calculation, the air density and dry specific mas are often used, meaning the mix of dry air and water vapour. Density, in simple terms, is mass divided by volume (kg/m^3) (Ingebrigtsen, 2016). Equation 5 shows the air density for dry air. It is a function of temperature (T) at the measured height and the function of the pressure of dry air (P_d). The R_d is equal to 287.06 $J \cdot kg^{-1} K^{-1}$ is the constant of the ideal gas of dry air (Ulazia et al., 2019).

$$\rho = \frac{P_d}{R_d \cdot T} \qquad \textit{Equation 5}$$

The density of dry air is not the same as the density of humid air. Furthermore, the density of air may decrease in different climatology, such as with a high-rise building located in a cold climate. If more accurate measurement needs to take place, the formula for a humid atmosphere must be utilised (Equation 6) (He et al., 2021).

$$\rho = \frac{P_d}{R_d \cdot T} + \frac{P_v}{R_v \cdot T} \qquad \textit{Equation 6}$$

$$P = P_d + P_v \qquad \textit{Equation 7}$$

Where:

ρ is the density (kg/m^3)

P_v is the water vapour partial pressure (Pa)

P_d is the partial pressure of dry air (Pa)

R_d is the specific gas constant for dry air = 287.05 J/(kg·K)

R_v is the specific gas constant for water vapour = 461.495 J/(kg·K)

T is the temperature (K)

P_d and P_v are partial pressures that respectively denote the dry air pressure as well as the pressure of water vapour. An equation suggested by Herman Wobus is presented in Equation 8; was used for calculating saturated vapour pressure. Even though there are several ways to do the calculation of saturated vapour pressure, the Wobus Polynomials were used to get the partial pressures and presented in Table 7, which was supposed to give the values within 0.02% of the real value. The polynomial was fitted from data from the Smithsonian Meteorological Tables, which is valid for the temperature range of -50 to 100 °C (Doswell, 1982).

$$E_s(T) = \frac{e_{s0}}{P(T)^8} \qquad \textit{Equation 8}$$

$$P(T) = c_0 + T \cdot (c_1 + T \cdot (c_2 + T \cdot (c_3 + T \cdot (c_4 + T \cdot (c_5 + T \cdot (c_6 + T \cdot (c_7 + T \cdot (c_8 + T \cdot (c_9)))))))))$$

Equation 9

where:

$$e_{s0} = 6.1078$$

Table 7. Herman Wobus Polynomial Coefficients

Coefficient	Value
c_0	0.99999683
c_1	$-0.90826951 \cdot 10^{-2}$
c_2	$0.78736169 \cdot 10^{-4}$
c_3	$-0.61117958 \cdot 10^{-6}$
c_4	$0.43884187 \cdot 10^{-8}$
c_5	$-0.29883885 \cdot 10^{-10}$
c_6	$0.21874425 \cdot 10^{-12}$
c_7	$-0.17892321 \cdot 10^{-14}$
c_8	$0.11112018 \cdot 10^{-16}$
c_9	$-0.30994571 \cdot 10^{-19}$

The dry air pressure (P_d) is the difference between the atmospheric pressure (P_{atm}) and the pressure of water vapour (P_v), with this, all the parameters for Equation 6 have been satisfied. In order to find dew point temperature (T_{dew}) Equation 10 has been used (Wanielista et al., 1997).

$$T_{dew} = \left(\frac{\varphi}{100}\right)^{1/8} \cdot (112 + 0.9T) + 0.1T - 112$$

Equation 10

Where:

T is the temperature [°C]

φ is the RH [%]

Equation 6, Equation 7, Equation 8, Equation 9 and Equation 10 are utilised in order to calculate ρ, where ρ is dependent and based on field measurements of RH, P, T as well as P_d were the latter can be deduced from P_v and P (He et al., 2021).

3.1.4. Specific humidity

Humidity ratio (ω) is, at times, also referred to as specific humidity (ω). Where the humidity ratio is defined as the ratio of the mass of the water vapour to the mass of dry air (kg vapour/kg dry air), it is a way to describe the actual present amount of moist air. It is possible to calculate the humidity ratio using Equation 11 when the mass of water vapour to the mass of dry air is known ((M. J. Moran et al., 2014) p.754-755).

$$\omega = \frac{m_v}{m_a} \qquad \textit{Equation 11}$$

The humidity ratio can be illustrated in partial pressures and molecular weights by solving Equation 11 for m_a and m_v, respectively, and substituting the resulting expressions into Equation 3 to obtain Equation 12. This equation is applicable for the same temperature and the same volume ((M. J. Moran et al., 2014) p.754-755).

$$\omega = \frac{m_v}{m_a} = \frac{M_v \cdot P_v \cdot V/R \cdot T}{M_a \cdot P_a \cdot V/R \cdot T} \qquad \textit{Equation 12}$$

And by introducing Equation 7, as well as noticing that the ratio of the molecular weight of the water to that of dry air, M_v/M_a has a number value of approximate 0.621979. It becomes possible to write Equation 13 ((M. J. Moran et al., 2014) p.754-755).

$$\omega = 0.621979 \frac{P_v}{P - P_v} \qquad \textit{Equation 13}$$

3.1.1. Absolute humidity

Absolute humidity is not functionally dependent on the temperature; it is, however, dependant on the volume of air. It measures the amount of water vapour in the air expressed by air density, as seen in *Equation 14*. Absolute humidity exhibits the strongest indoor to outdoor correlation, and it is the outdoor measurement that is the least prone to errors (Nguyen et al., 2014). It is also the furthermost important measure of humidity for estimating the consequence humidity has on the human body. Evaporation from the human raspatory tract is dependent on absolute humidity and not relative humidity. Furthermore, absolute humidity has an exponential relationship with temperature (Fielder, 1989).

If an ideal gas behaviour is assumed, absolute humidity can be calculated using Equation 15. That includes humidity ratio and air density, while Equation 14 is general (Vaisala, 2013).

$$AH = \frac{Mass\ of\ water\ vapour}{Volume\ of\ air}[\mathrm{g/m^3}]$$ *Equation 14*

$$AH = \omega \cdot \rho\ [\mathrm{g/m^3}]$$ *Equation 15*

3.1.2. Air movement

Air movement has good and bad consequences. The idea is to create the climate shell and installations in such a way that the good traits are achieved instead of the bad ones. It is essential to know how building tightness works with different installations of the building. Increased air change and air circulation often creates better air quality but at the expense of increased energy consumption. Air movement is dependent on the difference in air pressure and possible flow paths. The pressure inside the building can be crucial to gain the correct climate and avoid damages. Air movement of moist air through the outer shell is dependent on over and under pressure. It is when the control of indoor air movement is lost that problems might appear. Resolving the problem can be done by either improving the building tightness or controlling indoor pressure. Table 8 shows examples of positive and negative consequences of welcomed and not welcomed air movement plus good airtightness (Bankvall, 2013).

Table 8. positive and negative consequences of air movement and good airtightness (Bankvall, 2013)

	Positive consequences	**Negative consequences**
Moisture	Drying, removal of moisture. Air movement in cracks, Creeping grounds etc. to remove moisture, smells or radon	Damages from moisture convection, moist air-flow.
Energy	Lower energy use through the right air supply and right dimensioned ventilation. The possibility to add/remove heat with the ventilation air.	Increased energy usage, air movement in isolation, transmission loss. Increased energy used through ventilation in the form of fanwork and air heating.
Air quality	Well working ventilation system, right air movement. Old air is exchanged with new fresh air. Heat, moisture, smells, gases and particles are removed.	Inadequate function of the ventilation system through unwanted or extra air movement. Spreading of smells, particles, gases, including radon
Thermal comfort	Air movement for: fresh, comfortable indoor air, suitable outdoor	Drag. Cold floors

	temperatures; for example, to avoid cold air by the window, better thermal comfort. Abduction of heat and evaporation of moist skin

Air pressure drives air movement, which is in return based on three forces which are (Bankvall, 2013):

- Thermal driving forces followed by the temperature differences, meaning the density differences between cold and warm air.
- Wind that creates wind pressure differences around a building
- Fans that create unalike pressure settings in and around a building

3.2. Indoor Environment

The indoor environment contains a combination of dead (nonviable) and live (viable) microorganisms, fragments in the form of allergens, toxins, volatile microbial organic compounds as well as other chemicals. The concentration of these chemicals and compounds are presumed or known to be elevated in damp indoor environments, which may affect the health of the people working or living there. Fungi and dust mites favour damp environments and particularly play a big role in this. Dampness is an indicator of poor ventilation and can escalate bacterial growth and an increase in other harmful indoor pollutants. Excessive moisture can also lead to chemical emissions from building materials (Heseltine & Rosen, 2009).

3.2.1. Moisture content of materials

Most of the building materials that are used today are porous and thus considered to be made of solid matrix and pores filled with air. Moisture is then in the air of the pores as water vapour. Because of this, water takes on different forms in the material. Such as absorbed water molecules that are on the surface of internal pore walls, as capillary condensed liquid water located in the fine pores, or as bulk water in the coarse pores, but also water that has been chemically bound inside the material. This phenomenon important if an assessment of damage due to high moisture content is being conducted (Butcher, 2006).

The moisture content of a material is dependent on the relative humidity of surrounding air, the materials, previous occurrence of moisture accumulation, and the materials pore structure. And the accumulation of moister is mostly down to capillary forces. There are various ways to describe the moisture content of a material, such as the ratio of the weight of absorbed moisture to the dry weight of the material, u (kg/kg), or by the relationship of the volume of absorbed moisture by the volume of material, ψ (m^3/m^3). Or by the weight of absorbed moisture by the volume of material, w (kg/m^3) (Butcher, 2006).

3.2.2. Health issues related to buildings with dampness problems

WHO states that indoor air plays a massive role as a health determinant as populations spend a substantial amount of time indoors. When sufficient moisture becomes available, microbial pollution becomes an essential element of indoor air pollution. The cause is hundreds of species of fungi and bacteria, especially filamentous fungi (mould), getting to grow indoors when sufficient moisture becomes available. Exposure to these microbial contaminants has been clinically associated with allergies, respiratory symptoms, immunological reactions, and asthma. The problems associated with indoor air are health problems for humans with low income, middle income, and high-income countries. Inadequate ventilation and dampness are the reasons for many biological agents in the indoor environment, and almost all indoor materials can gain the growth of microbes such as fungi, bacteria and mould, which can subsequently emit cells, spores and fragments and volatile organic compounds into the air. Dampness can also lead to the degradation of indoor materials that also can pollute the air. This is the reason for dampness being a strong sign of risk towards respiratory symptoms (e.g. wheeze and cough) and asthma. Importantly moisture management requires proper control of ventilation and temperature so that excess humidity can be avoided, and the presence of any biological agent indoors is due to inadequate ventilation and dampness (Heseltine & Rosen, 2009).

A building should be made with the idea that relative humidity should never exceed 75% RH due to mould growth so that high moisture and any water during construction should be avoided. Organic materials are more prone to mould growth than other inorganic materials, and experiments have shown that materials with 50% RH are very resilient to mould growth if exposed to 90% RH for a limited amount of time (Møller et al., 2017).

Interior RH is the product of ventilation rates and moisture production, and the hygrothermal conditions of the interior surfaces of the buildings envelope are a complex function of the outdoor and indoor temperature but also relative humidity and the construction itself. Therefore, predicting mould growth on interior materials is dependent on all these parameters (Møller et al., 2017).

3.2.3. Comfort

Comfort is described as how the mind expresses satisfaction with the environment. Many factors come into play here, such as thermal, acoustic and visual comfort. As for thermal comfort, it connects to the global human psychology and physiology of 37°C (310K). Humans release heat to the environment by convection, conduction, radiation, transpiration, precipitation and breathing. All these six mechanisms have their heat exchange determined by Air temperature, air temperature gradients, radiant temperature, radiant asymmetry, contact temperatures, relative air velocity, air turbulence and relative humidity (Hens, 2012).

Predicting the occupier’s perception of comfort is demanding and complex because the occupiers will need to feel comfortable with the temperature, humidity levels, ventilation rates, air movement. The problem still lies with the person’s preferences and perception because it may vary with gender, geographical location, metabolic rate, clothes worn, task performed and the surface temperature of the surrounding surfaces in a certain situation. Most guidances thus states that if, according to occupier surveys and/or the use of predicted mean vote (PMV), the acceptable standard is achieved when 80% of the buildings occupiers are comfortable (Keeping & Shiers, 2017).

3.2.4. Ventilation

The main role of ventilation is to provide optimum air quality for the occupants, although it is not only used for heating, cooling, and adding fresh air to the occupants, but it is also used to remove potentially harmful pollutants from the air. Since ventilation is essential for removing harmful pollutants, it is vital to have higher ventilation rates, and these points are usually associated with good health (Butcher, 2006).

The amount of ventilation that is required to gain air quality is dependent on (Butcher, 2006):

- Occupants density
- Occupants activities
- Pollutant emission within a given space.

Insufficient ventilation can lead to long term damage due to moisture problems. Ventilation can, in combination with moisture buffering materials, keep the indoor relative humidity at a very stable level. Adequate ventilation is used to make sure to have a good IAQ and keep the indoor RH at a target level. Ventilation strategy can have a considerable impact on the building’s energy performance, especially if the building is modern and well insulated. Newer buildings heat loss can have air renewal to be accountable to as much as half of its heat loss (Woloszyn et al., 2009).

3.2.4.1.Mechanical ventilation

Mechanical ventilation is very much used throughout the world, especially in larger buildings as well as buildings located in the city's centres. They have evolved as a means to deliver fresh air and thermal comfort. Mechanical ventilation is applied by the process of a network of ducts and driving fans. In a larger office building, the supply of air is usually thermally conditioned by cooling and heating as well as being filtered. Some key variations are (Butcher, 2006):

Supply-only ventilation

This technique uses mechanical fans to supply fresh air from the exterior that can be pre-cleaned. This is in combination with the passive vents for the extraction of air. This method creates a positive indoor pressure because the air is pressed into space. As well as having reduced air entering from the fabric leakage cracks.

Extract-only ventilation

This system uses mechanical fans to extract or suck the air out of the space. This is done in combination with passive vents that let air pass through them. Furthermore, this system results in a building that is negatively pressured relative to ambient outdoor pressure. Because of the air being sucked out from indoors to the exterior. This system has its advantage in wet or in polluting spaces, where the pollutants can be captured before they are emitted into the atmosphere.

Balanced mechanical ventilation

This system is based on two different fan systems, where one system provides fresh air from the exterior, and the other system is used for extract air from the indoors to the exterior. In this system, both the advantages from the separate systems are present (i.e., cleaning of extract air combined with the possibility for recovering the thermal losses from the extract air, to use for supply air preconditioning, and also air supply filtration). This system does, on a negative note, operate at a double mechanical cost. The balanced mechanical ventilation systems do have a neutral influence on pressure distribution inside the building. This makes it easier for air infiltration, which can add to the total number of air changes. This is in contrast to the mechanical supply and extract ventilation systems that pressurise or de-pressurise the building respectfully.

It is possible to limit interstitial condensation as well as contaminants from the exterior if the ventilation system is operating at an overpressure (supply-only ventilation) (Butcher, 2006).

Heat recovery

Heat recovery can be explained through the process of heat (and at times latent load) recovered through the extract air stream so that the recovered air from the extract can be used to precondition the supply air stream. Meaning that heat recovery can recover thermal losses instead of releasing them to the atmosphere. The bigger the temperature difference is between inside and outside, the bigger the cost and energy difference becomes with the heat recovery. This means that it is more viable in cold climates. However, more energy might still be needed with heat recovery under sub-zero temperatures due to additional defrost and heating as a precaution for condensation and frost (Butcher, 2006).

The greatest problem towards the widespread use of mechanical ventilation heat recovery has been identified to be the lack of both building airtightness and maintenance. Air infiltration ads directly to the energy consumption without the benefits of heat recovery because infiltrated air bypasses it. Airtightness is, therefore, a crucial factor for using heat recovery. Other points on heat recovery are that it can increase the overall pressure drop and subsequent fan power. As well as being influenced by the duration of the heating and cooling season and the operating times (Butcher, 2006).

There are typically four different heat recovery systems which are seen in Table 9 (Butcher, 2006):

Table 9. Heat recovery systems characteristics (Butcher, 2006).

System	Efficiency (%)	Pressure drops (Pa)	Separate air stream	Adjacent ducts needed?
Run-around coil	40-50	200-500	Yes	No
Plate heat exchanger	40-70	250-500	Yes	Yes
Thermal wheel	60-85	200-500	No	Yes
Double accumulator	85-95	150-200	No	Yes

Table 9 shows which of the heat recovery systems is more efficient, and has the least pressure drop, also separate air stream or adjacent ducts needed.

3.2.4.2.Humidification through the ventilation

Humidification through the ventilation system only occurs in special systems. Its purpose is to elevate the relative humidity indoors. Its area of use is typically museums, archives, orchestras, publishers and painting plants. There are generally two main types of humidification regarding HVAC and a further three subcategories by water. The main systems are (Ingebrigtsen, 2016):

- Humidification by damp
- Humidification by water
- Humidification by atomised water (all the added water is soaked up by the air)
- Humidification by recycled water, without heat being added/removed
- Humidification by recycled water, with heat being added/removed

3.2.4.3. HVAC cold climate

The design of HVAC systems located in cold climates needs to pay attention to several factors in order to attain an indoor environment that has a minimum moisture and humidity issue. These factors are indoor temperature and humidity requirements, outdoor dry-bulb/wet-bulb temperatures, building pressurisation, the quality of building envelope, insulation of pipe and coil, airside economizers, among others (Miles & Furgeson, 2008).

3.2.4.4.HVAC heat recovery

Heat recovery is rather important in cold climates such as the Scandinavian climate. The heat from the extract air that is already heated is recycled to heat the supply air to acquire a favourable indoor temperature. A lower energy requirement is needed when using heat recovery for mechanical ventilation (Ingebrigtsen, 2016).

Heat recovery can be divided into four different categories:

- Regenerative heat recovery
- Recuperative heat recovery
- Active heat recovery
- Passive heat recovery

Table 10 shows which heat recovery categories most used in Norway.

Table 10. Most used heat-recovery systems in Norway (Ingebrigtsen, 2016).

Regenerative / Recuperative	Type of heat recovery	Active or passive
Regenerative	Rotating heat recovery	Passive
	Chamber exchanger	Passive
	Circulating air	Passive
Recuperative	Heat pump	Active
	Platechanger (cross / countercurrent)	Passive
	Battery heat recovery	Passive
	Heatpipe exchanger	Passive

Regenerative:

This type of heat recovery is also referred to as cyclical. It Transmits both tactile and latent heat. Moisture condensates inside the extract air to evaporate in the supply air. This has advantages such as more stable indoor humidity in the building, as well as having no need for the condensation drain due to a low chance of freezing. The disadvantage of this system is odour transmission, as well as the transmission of dangerous gases. The disadvantages are, however, limited to cases of something creating these problems inside the extract air of ventilation.

Recuperative:

This type of heat recovery is also referred to as statical, and it only transmits tactile (dry) heat. The air currents are physically separated, and notably, no moisture is added. The advantage of these systems is highly ensuring that no dangerous gases or odours are added to extract and supply air. The negative consequences of this are the extract airs ability to freeze under high relative humidity combined with low temperatures outside; the need for drainage will also be needed due to condensation water. This type of heat recovery system does not transmit humidity, so that low relative humidity can be an indoor issue during the winter months.

Active heat recovery

Active heat recovery means that the system uses a heat pump together with a compressor that needs power. Moreover, since it uses power, it is active.

Passive heat recovery

Passive heat recovery systems do not use electricity to gain heat. However, some passive systems use smaller amounts of electricity but are still called passive such as the rotating heat recovery system (Ingebrigtsen, 2016)**.**

3.2.4.5.Humidity controlled ventilation system (RHC)

Ventilation systems that let RH control their air flow were designed so that an increase in energy performance becomes possible without letting moisture damage take hold in the building. These systems work have a humidity sensitive membrane in their outlet and sometimes inlet. This system lets the air-flow get higher when RH gets high and decreases when indoor air gets dry. The energy performance of these systems is, however, also based upon the moisture buffering capacity of indoor materials. However, with doors closed RHC system showed in tests that it did not save energy but rather resulted in a better indoor environment with respect to relative humidity and the risk of moisture damage. So that a constant flow ventilation system was adequate when open doors (good mixing of air). (Woloszyn et al., 2005).

3.2.4.6.Units of ventilation

The ventilation rate can be described in several ways, which can cause confusion; there is no standardised ventilation measurement unit. However, there are some common units nonetheless that include ((Butcher, 2006) paragraph number 4.1.4):

- ***Air-flow rate***: It is most often expressed as a volumetric flow rate as m^3/s or L/s. It is at other times expressed as an hourly rate per unit area as $(m^3 \cdot h^{-1})/m^2$ or as the rate per person, i.e. $(L \cdot s^{-1})$/person. Occasionally the mass flow rate can be portrayed in terms of mass flow rate, e.g. kg/s.
- ***Air-change rate***: This is defined as the rate of ventilation divided by the volume of the ventilated space. The most typical way of expressing this is in terms of units of air changes/hour. This will then be shown as h^{-1} or ac/h, ACH. The volume can then express the entire building or a given room.

3.2.4.7.Minimum ventilation rates for indoor air quality, in relation to kitchen and bathroom

Minimum ventilation rates according to (Direktoratet for byggkvalitet (TEK 17), 2017) § 13-2. Ventilation in a residential building, are shown in Table 11.

Table 11- Minimum ventilation rates for kitchen and bathroom (Direktoratet for byggkvalitet (TEK 17), 2017)

Room	Basic ventilation	Forced ventilation
Kitchen	36 m^3/h	108 m^3/h
Bathroom	54 m^3/h	
Bedroom	26 m^3/h (per planned bed)	

1. Extraction requirement is met when the extraction volume is minimum, as specified in Table 11
2. When using forced ventilation, the amount of air supplied must still be equal to the extract volume specified in Table 11

Bedrooms need a minimum of 26 m^3/h of fresh air, per planned bed when the bedroom is in use. While rooms that are not intended for permanent residential use need 0.7m^3/h fresh air per hour for every m^2 (Direktoratet for byggkvalitet (TEK 17), 2017).

In private dwellings, the extract ventilation is placed in wet rooms such as the kitchen or bathroom, the result of this ads suction to the wet rooms to prevent moisture generation, which can build up in wet spaces. This potentially prevents the moisture, cooking fumes or other pollutants to reach the living area and thus contributes to removing the risk of condensation (Butcher, 2006).

4. Research method

4.1. Testing Environment

Over 90% of the tested apartments were located at district Bjerke in Oslo, Norway, with the address being Spireaveien Oslo, Norway, as shown in Figure 3 (Google maps, n.d.). With the distinction being two apartments, where one was located at Pilestredet in Oslo, Norway, and the second was located at Mørtelverksbakken in Oslo, Norway. Emphasis on using climatic data near the tested apartments has been in focus.

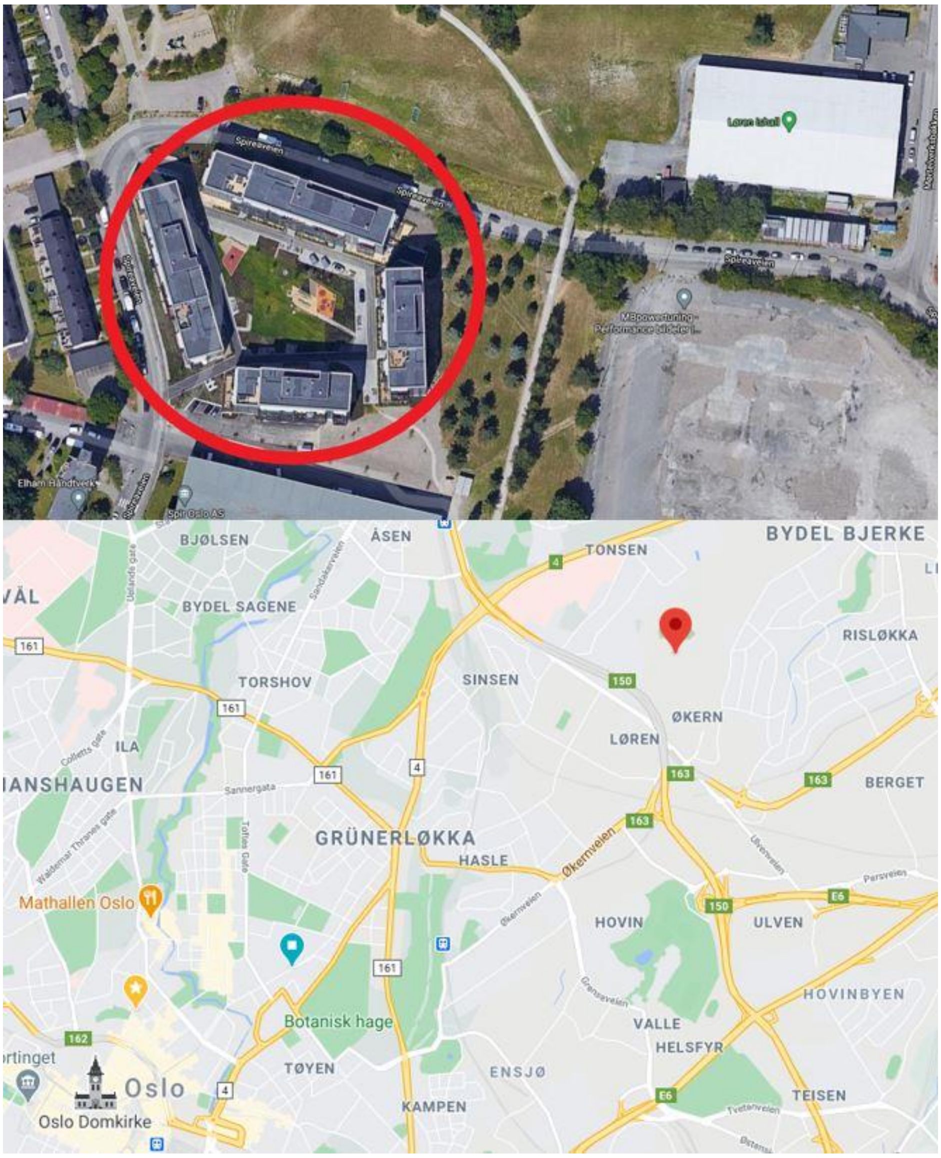


Figure 3. Location of apartments in district Bjerke, Oslo, Norway (Google maps, n.d.)

This is why Blindern weather station in Oslo, Norway, was utilised for climate data (*Blindern, Meteorological Station*, n.d.). Blindern weather station was created in January 1931 and has an id: SN18700 (*YR-Historiske værdata for Oslo (Blindern)*, n.d.)

Table 12. Details of Blindern weather station (Blindern, Meteorological Station, n.d.)

Meteorological station	**Longitude** (deg min sec)	**Latitude** (deg min sec)	**Altitude** (metres)
Blindern: 0313 Oslo Henrik mohns plass 1, Norway	10° 43’ 14” E	59° 56’ 34” N	97

In this research, weather station data was combined with the data from the measurements of the given apartments. So that, exterior conditions such as temperature and RH were known during the measurement of apartments.

A widely used empirical climate classification can describe the Oslo climate. Which is the climate classification system found by Wladimir Köppen to identify aridity in terms of temperature – precipitation index (meaning that it is assumed the evaporation is controlled by temperature) (Arnfield, n.d.) and is still the most popular climate classification system to this day. Classification A has the warmest climate, while E has the coldest climate. Oslo has gotten Dfb as a climate classification, where D stands for ’’temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month –3°C or lower’’ The second letter f stands for ’’no dry season’’, and lastly the third letter b stands for ’’temperature of each of four warmest months 10°C or above but warmest month less than 22°C’’.

4.2. User and building information

This study comprises measurements performed in urban homes located in Oslo, Norway. The apartments were selected according to the following criteria: the maximum BRA of 115 m^2 and buildings built/renovated after 2012. In order to gain a better understanding of the measurements, the characteristics of the selected apartments are summarized in Table 13.

Table 13. Summary of building characteristics of the 11 apartments included in the research.

Apartment	Year of Construction	Year of Renovation	Floor	Area (m^2)	Number of Occupants	Ventilation Type	Period of measurement
#1	1978	2012	5	30	2	Balanced	14/2/2021 - 22/2/2021
#2A	2017	-	4	60	3	Balanced	14/2/2021 - 22/2/2021
#2B							16/4/2021 - 22/4/2021
#3	2017	-	2	N/A	1	Balanced	22/2/2021 - 2/3/2021
#5	2017	-	-	45	1	Balanced	31/3/2021 - 7/4/2021
#7	2017	-	1	60	1	Balanced	13/3/2021 - 22/3/2021
#8	2017	-	4	87	1	Balanced	9/3/2021 - 21/3/2021
#10	2017	-	4	90	2	Balanced	22/3/2021 - 28/3/2021
#11	2017	-	3	85	4	Balanced	28/3/2021 - 4/4/2021
#12	2017	-	1	115	4	Balanced	8/4/2021 - 14/4/2021
#20	2019	-	N/A	67	3	Balanced	7/4/2021 - 15/4/2021

4.3. Experimental Setup

In order to achieve accurate results when conducting experiments, it is crucial to use instruments to measure and monitor data. The values of temperature (T), relative humidity (RH), pressure and CO_2 levels indoors were measured with two different sensor types from a brand called Airthings at 5-min intervals over a period of 7 days. Also, the values of supply air flow rates and mechanical extract ventilation air flows in the rooms were measured with two different equipment sets. The first equipment set was Kimo K35 measuring funnel and Velocicalc® Air Velocity Meter 9545 anemometer with hot wire, and the second one was Swemaflow 125 air flow hood. More details of sensors and their placements are given in this chapter.

4.3.1. Relative humidity, temperature, CO_2 and pressure sensors

By using two different sensor types, time-varying relative humidity, temperature, and CO_2 levels indoors were monitored in the selected apartments. The sensor type and manufacturer were as follows:

- Temperature, Relative Humidity and Pressure: *Indoor Air Quality Monitor with Mold Risk Indication / Wave Plus Radon and Indoor Air Quality Monitor*
- CO_2 Levels: *Wave Plus Radon and Indoor Air Quality Monitor*

For the measurements of each apartment, one set, which includes two pieces of Wave Plus, four pieces of Wave Mini and one piece of Airthings Hub, have been used. The room temperature, relative humidity, CO_2 and pressure measurements were conducted with a 5-minute interval over a period of 7 days. The measured temperature range of the Airthings Wave Plus sensors was between 4°C to 40°C with an accuracy of ± 1 °C/F, while the measurement range for relative humidity was between 0 and 85% with an accuracy of ± 1%. The accuracy of temperature measurements for Airthings Wave Mini was ±0.5 °C at 25 °C / ± 1 °C from 0-60 °C while the accuracy of relative humidity measurements was ± 3 % at 25 °C within 20-80 % RH. Also, the measured pressure range was the same for both sensors, and it was 500-1100 hPa with a resolution of 0.02 hPa and accuracy of ± 0.15 hPa. Lastly, the measured CO_2 range for Airthings Wave Plus sensors was 400–5000 ppm with an optimum accuracy as ± 30ppm ± 3% within 15 – 35°C / 60 - 95°F. Each sensor has been placed at the breathing height (between 1.5 m – 1.8 m) and minimum 1 meter / 3 feet distance from the windows/vents and away from direct sunlight and heating units as suggested in Airthings manual (ASA, n.d.). An example of placement of the sensors in of the apartments is illustrated in Figure 4, and a picture of both sensors shown in Figure 5.

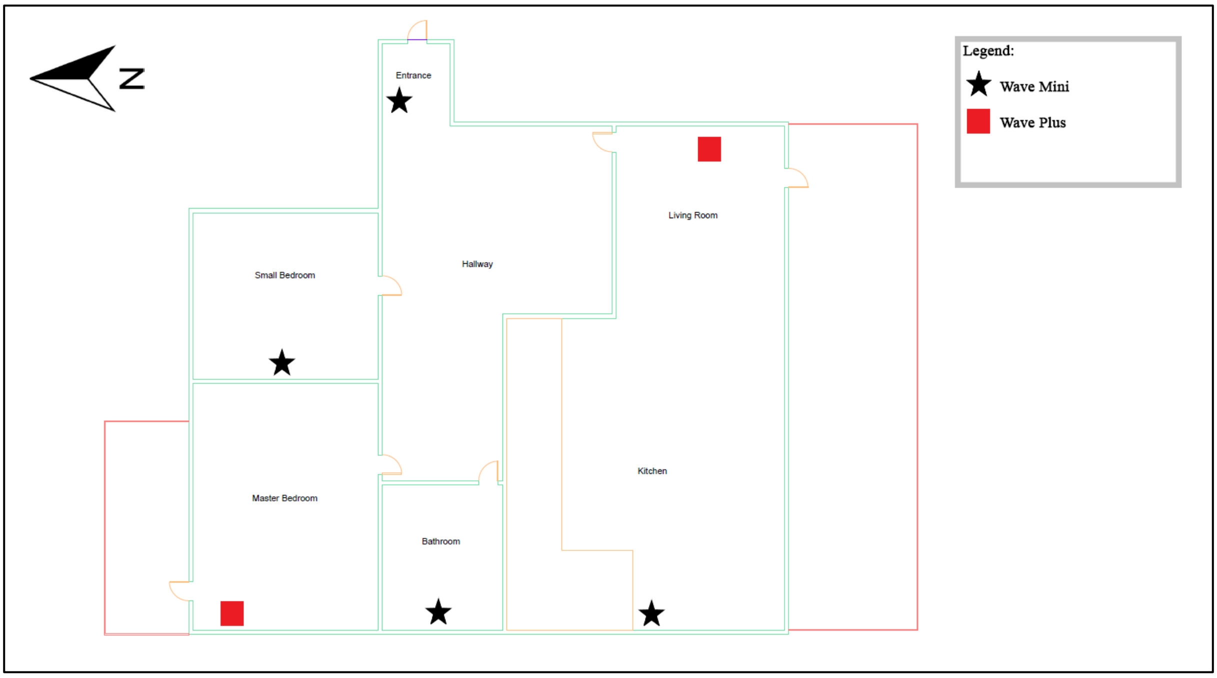


Figure 4. Illustration of placement of the sensors in the apartments

Figure 5. Picture of the both Airthings sensors and hub used in experiments

4.3.2. Extract and supply air flow rates sensor

In order to measure supply air flow rates and mechanical extract ventilation air flows in the rooms of the sample apartments, two different equipment set were used. The first equipment set was Kimo K35 measuring funnel and Velocicalc® Air Velocity Meter 9545 anemometer with hot wire, and the second one was Swemaflow 125 air flow hood. Velocicalc® Air Velocity Meter 9545 had a range of 0 to 6,000 ft/min (0 to 30 m/s) and an accuracy 1&2 ±3% of reading or ±3 ft/min(±0.015 m/s), whichever is greater, while its resolution was 1 ft/min (0.01 m/s). While, Swemaflow 125 air flow hood had a range of 2 to 125 l/s (7 to 450 m3/h, 4 to 260 cfm) and uncertainty of ±3,5% read value, min 0,4 l/s. Figure 6 illustrates the setup of the instrument set of Kimo K35 measuring funnel and Velocicalc® Air Velocity Meter 9545 anemometer with hot wire.

Figure 6. The measurement of supply air flow rates and mechanical extract ventilation air flows

4.4. Calibration of the sensors

In order to minimize measurement uncertainty, calibration of equipment is an essential process. In the process of time, sensors tend to deviate from accuracy. There is an ongoing need for service and maintenance by calibrating them to ensure that the measured values are correct.

Accurate results are crucial when calculating moisture excess and moisture production. Since the required equations presented, contain both relative humidity, temperature and air pressure, all measurements that include these parameters. More details of the calibration process and calculations are given in this chapter.

Calibration of temperature and RH sensors

The calibration of the Airthings Wave Plus and Wave Mini sensors was carried out using a climate chamber called *KB 8400 F/L* from the company *Termaks* in SINTEF Community laboratory, as shown in Figure 7 in an ongoing calibration procedure.

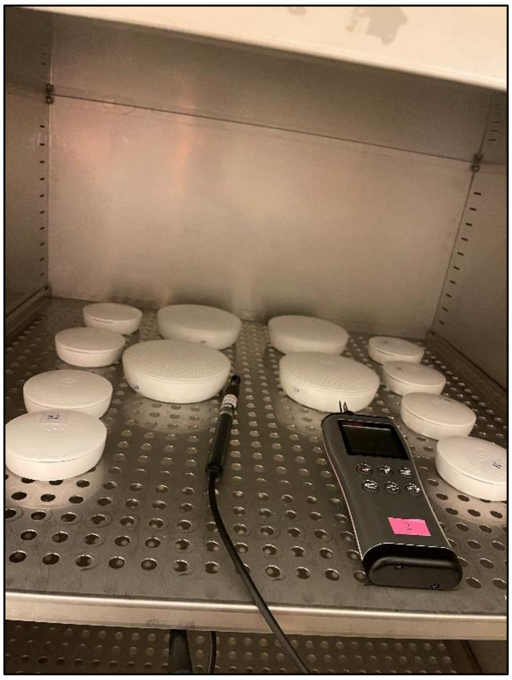


Figure 7. An ongoing calibration procedure of the Airthings sensors

In order to perform calibration, all of the sensors were set into the climate chamber together with a pre-calibrated probe called *HC2A-SG* from the company *Rotronic*. In order to ensure better accuracy, the climate chamber was set to 5 different combinations of temperature and RH. Table 14 shows the settings of the climate chamber in different time periods. Also, together with the sensors, the pre-calibrated probe also logged data, and for the calibration, both logged data from the probe and climate chamber compared with the logged data from Airthings sensors. The comparison graphs of temperature and RH values illustrated in Figure 8 and Figure 9, respectively.

Table 14. The settings of climate chamber in different time periods

Date	**Time**	**RH [%]**	**Temperature [°C]**
10/05/2021	17:20	40	22
11/05/2021	8:30	60	22
11/05/2021	11:07	75	22
11/05/2021	12:30	65	26
11/05/2021	13:59	62	30

As the outcome of the calibration, per cent error values were calculated by using Eq. 1 for each sensor and each setting. Three averaged per cent error values for temperature measurements where the measured temperature values <25°C, ≥25°C, and ≥28°C and three averaged per cent error values for RH measurements where the measured RH values <40, ≥40, and ≥55, respectively were used as a constant for each sensor in order to perform interpolation or extrapolation. The interpolation and extrapolation were done by excel and resulted either in a decrease or increase in the measured data. Appendix B shows the calculated per cent error constants used for interpolation or extrapolation for each sensor.

$$\%\,Error = \frac{|Theoretical\,Value - Experimental\,Value|}{Theoretical\,Value} \qquad Eq.\ 1$$

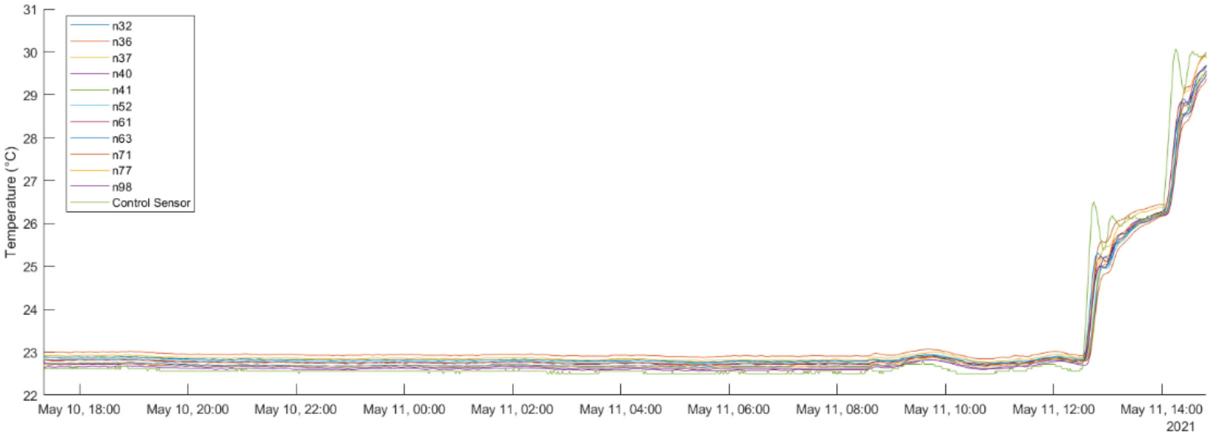


Figure 8. Comparison of the temperature values logged by the Airthings Sensors, with the average of the logged data from the probe and the climate chamber

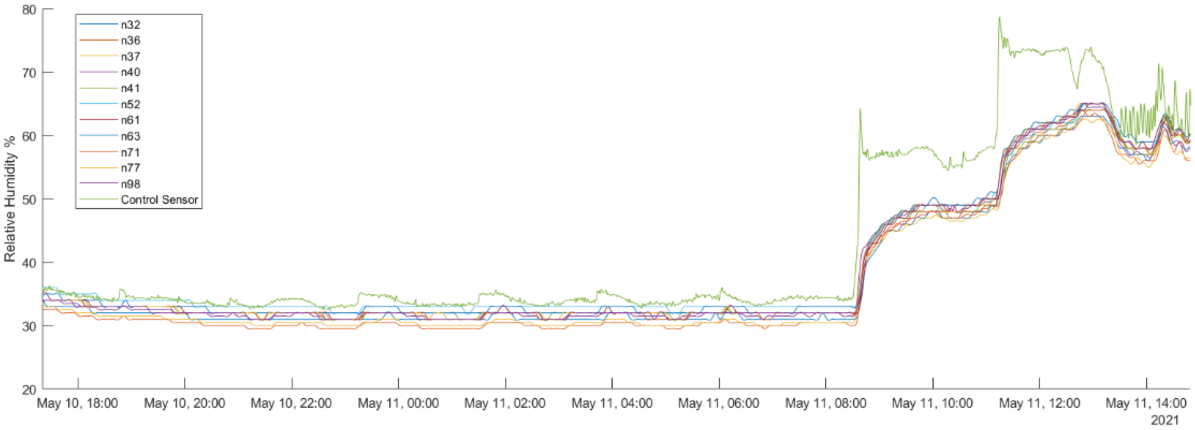


Figure 9. Comparison of the RH values logged by the Airthings Sensors, with the average of the logged data from the probe and the climate chamber

4.5. From experiment to data

The value for indoor moisture excess levels, Δv (g/m^3) (the difference between indoor and outdoor air-water vapour content, also known as vapour excess or moisture supply) was calculated based on the results of indoor temperature, RH and pressure measurements, along with the outdoor temperature, RH and pressure data collected from nearest meteorological station, using Equation 16. Absolute humidity values were averaged in accordance with exterior hourly averaged values.

$$\Delta v = v_i - v_e \ [g/m^3] \qquad \text{Equation 16}$$

Moisture production (moisture generation) G [g/h] in apartments was calculated based upon the calculated indoor moisture excess and measured air flow rate indoors, $\dot{V}$ [m3/h], using Equation 17.

$$G = v_i - v_e \cdot \dot{V} \ [g/h] \qquad \text{Equation 17}$$

The air flow rate indoors was measured only for two apartments, while one of them selected as a sample apartment from the building where most of the tested apartments were located. And measured values were used for moisture production calculations for the rest of the apartments. Also, the moisture production was calculated for a specific time period based on the time period of measurements (January-February-March-April-May) because the air flow rate was measured by using two different equipment sets during this specific period. The first equipment set was Kimo K35 measuring funnel and Velocicalc® Air Velocity Meter 9545 anemometer with hot wire, and the second one was Swemaflow 125 air flow hood. As the air flow rate was measured for only two apartments, the total supply/exhaust air flow rate from the sample apartment selected as the sum of the exhaust rates from the bathroom and kitchen.

4.6. Survey as a case study research

Case studies analyse modern phenomena, which can be investigated with a quantitative or qualitative examination. But by combining both of them, many new sources of evidence became available to the researcher, which in return is a significant strength for the case studies. So that the researcher can use both methods to understand and express the phenomena better. More advanced investigations become possible by using a mixed-method case study, especially when the perspective of the events are not that easily obvious (Yin, 2014). The case study aim is to analyse and understand the studied object in detail (Thomas, 2013).

The thesis has objectives that needed to be accomplished by a variety of methods. A case study does not prescribe a specific method to use for data collection (Yin, 2014)

All ten apartments from the field experiment were invited to do the questionaries, where they were explained how the process of the questionaries would proceed and how data would be collected. Questionnaires can provide case study researchers with data that has been gathered through quantitative or qualitative self-report. Such as opinions, beliefs, knowledge, attitudes toward something. This is a method for collecting data of a subset of a common survey technique in which gather information in the form of surveys, interviews, polls, written form or by oral responses such as scales documents or questionaries. There are two methods for the use of a questionary in case study research: 1. As the primary strategy for the collection of data. Or 2. As a combination with other case study methods, such as participant interviewing, observation or document analysis (Mills et al., 2021).

There are assumptions made towards the respondents of the questionaries, such as their ability to express their understandings of it. There could be doubts about the respondent's ability toward answering the questionaries. However, the questionaries should be completed to confirm or disconfirm it later so that one can acknowledge the validity through supplementary approaches. Validation could then be done by comparing to the reports of others. Questionaries can provide the researcher with high-quality empirical data that is needed to create high-quality case studies (Mills et al., 2021).

The authors needed more information to make a better assessment and to understand how the results were connected to the residents of the apartments in the field experiment. Questions regarding estimation of moisture production, occupancy level, moisture sources, characteristics of the apartment, health symptoms related to the indoor environment and Occupant behaviour were asked to provide a better evaluation of the results.

All answers to the questions were gathered by (NSD, 2021)website. It uses a notification form for processing personal data. The site follows the law for personal data and ensures that the collected data regarding people and society can be collected, stored, processed and shared legally, safely today and in the future. All answers to the questionaries were saved anomalously. The survey go-ahead was given by (NSD, 2021), as seen in Appendix A, permission was granted for the questionaries.

4.7. WUFI®PLUS Simulation

Computer simulations of the indoor air environment were carried out to validate the measured values from results and further understand some of the factors affecting the daily variations of indoor air humidity observed in field measurements. The digital software called WUFI®PLUS has been used to carry out the simulations. The simulations of WUFI®PLUS were used to verify in-field measurements of apartments.

WUFI®PLUS is a program that uses 3D room models to calculate the indoor temperature and relative humidity based on the hourly exterior weather climate, such as in the instance of this paper, temperature, relative humidity and solar radiation. Interior design conditions can be added before calculation. For more information, refer to the WUFI®PLUS manual (*WUFI-Pro-5_Manual.Pdf*, n.d.)

Four simulated scenarios with similar settings follow, except for one change in each scenario. Scenario one was without humidification. While Scenario two was, however, with humidification. Scenario one and two were conducted based on the time frame of field measurements of apartment two. Both scenario one and two started and ended when the field measurement of apartment two started and ended. The actual hourly weather data was utilised for this time period. Finally, scenario three and four were based on the same as scenario one and two. The only change for scenario three and four was that they simulated the conditions for the whole year, which was why the average weather data WUFI®PLUS comes equipped with was used instead.

No shading factor was added since the south wall (sunny side) was practically free of obstacles on the fourth floor where the apartment was located. However, balconies were added so that shading from them has been integrated into simulated calculations.

The initial relative humidity conditions for all components was set to 15% to match the conditions at the start of measurements. While the initial temperature was set to 20 degrees for the components. The initial material conditions change directly when the simulation starts.

The windows have a shading factor of 0.9 where 1 = no shading factor and 0 = total shading. Furthermore, solar gain and the radiation on the interior surface was not changed as it was 0.03[-]. No solar protection was added, and window overhang was added by the model rather than numbers.

Scenario one

The μ value for the bathrooms cement plate has been found at https://us.wedi.de/product-systems/shower-and-wet-room-systems/building-panels/vapor-85/.

4.7.1. Apartment assemblies

WUFI®PLUS simulation needed a setup verification. Hence a detailed procedure follows. Before the simulation could proceed, there was a need for an apartment model by creating different assemblies for the floor ceiling and walls. These layers were made based on typical assemblies/requirements given in Byggforsk. In addition, in dialogue with apartment owner to verify the type of assembly material.

The Byggforsk research series delivers recommendations and documented solutions for buildings, construction, design and management. Byggforsk delivers documented and robust solutions by meeting the requirements of (TEK) (Sintef, 2021). Each assembly used for the simulation are shown below as following:

- Figure 10 shows both the floor and the apartment ceiling due to the apartment being between two other apartments, with similar conditions as the measured apartment's interior. A vapour retarder is a must when laying parquet on concrete.
- Figure 11 shows the concrete wall connecting the apartments from the two sides with indoor conditions.
- Figure 12 shows inner walls made of insulation light metal frames and one layer of gypsum on each side.
- Figure 13 shows one of the two walls of the bathroom. It must be noted that tiles were added in surface setting.
- Figure 14 shows the one bathroom concrete wall connecting to the next apartment. It must be noted that tiles were added in surface setting.
- Figure 15 shows the bathroom floor between apartments. It must be noted that tiles were added in surface setting.
- Figure 16 shows the exterior wall on the south side, living room/kitchen
- Figure 17 shows the exterior wall on the north side of the apartment (bedrooms)
- Figure 18 shows the wall of the shaft opening towards the corridor.
- Figure 19 shows the wall of the shaft towards the bathroom. It must be noted that tiles were added in surface setting.

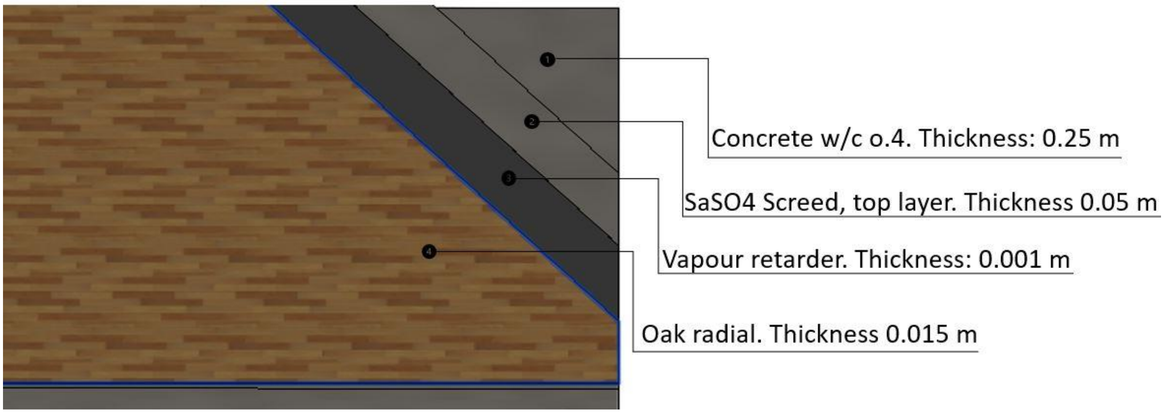


Figure 10. Floor and ceiling of the measured apartment. Byggforsk 541.505 Laying of parquet.

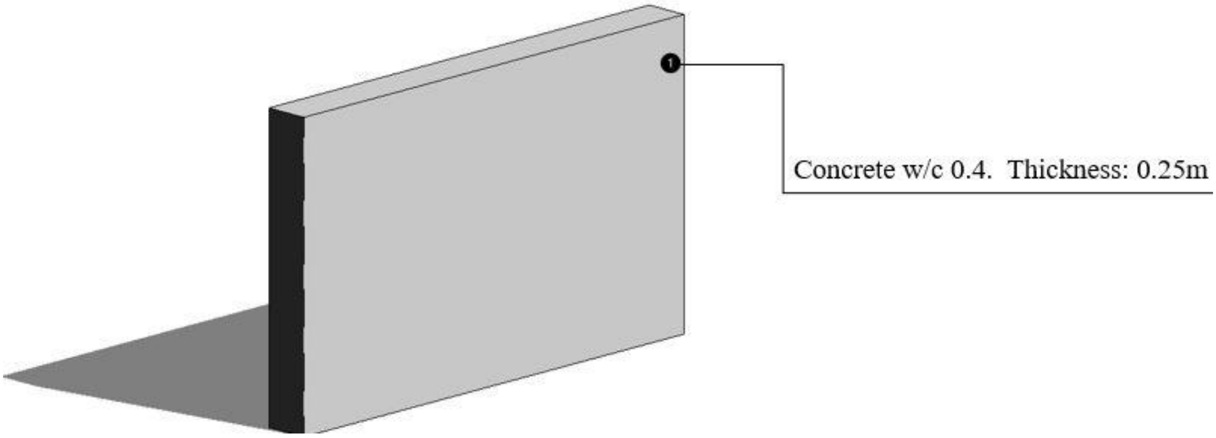


Figure 11. Wall connecting to the next-door apartment.

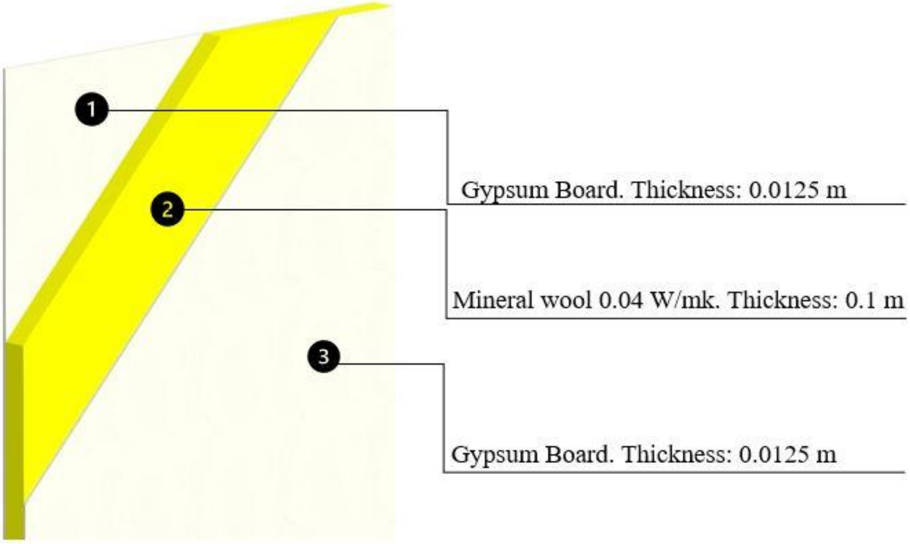


Figure 12. Inner walls of the measured apartment. Byggforsk 524.233 Interior walls with steel posts.

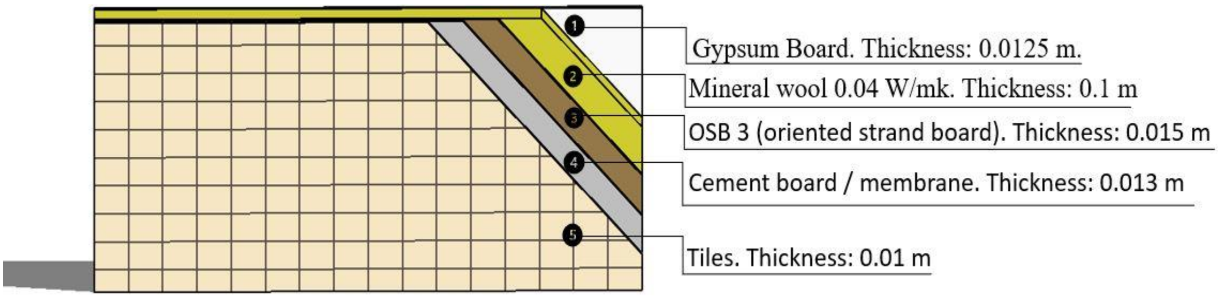


Figure 13. Bathroom walls. Byggforsk 543.506 Wet room walls with tiles.

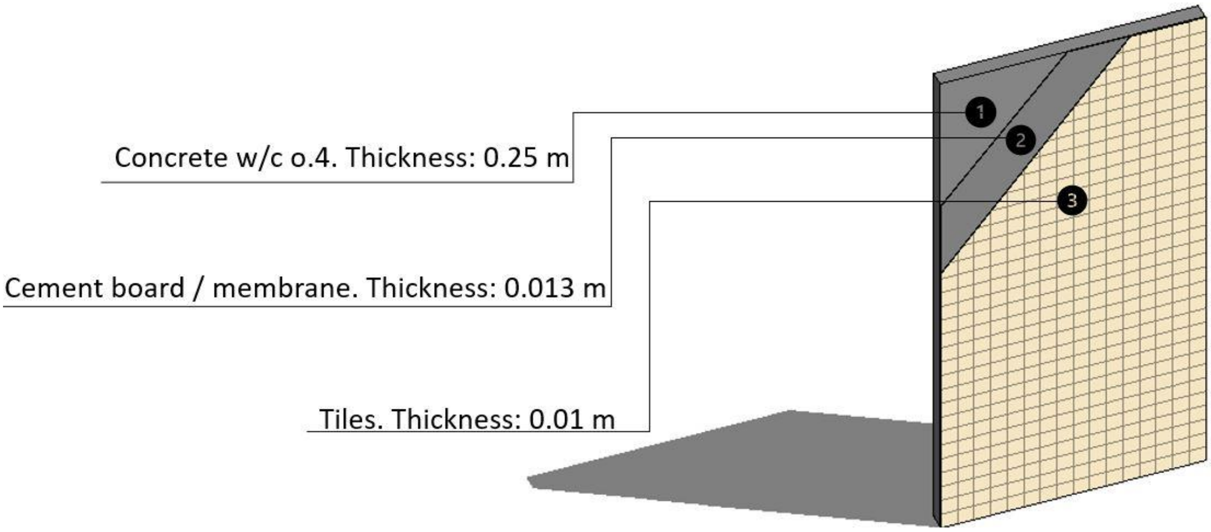


Figure 14. Bathroom concrete wall towards the next apartment based on Byggforsk 543.506 Wet room walls with tile cladding.

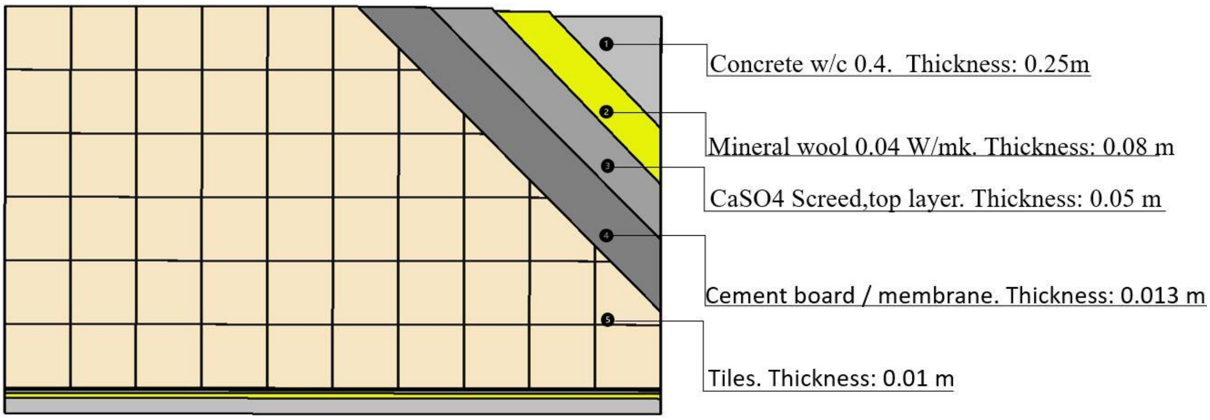


Figure 15. Bathroom floor between apartments. Byggforsk 541.805 Floors in bathrooms and other wet rooms

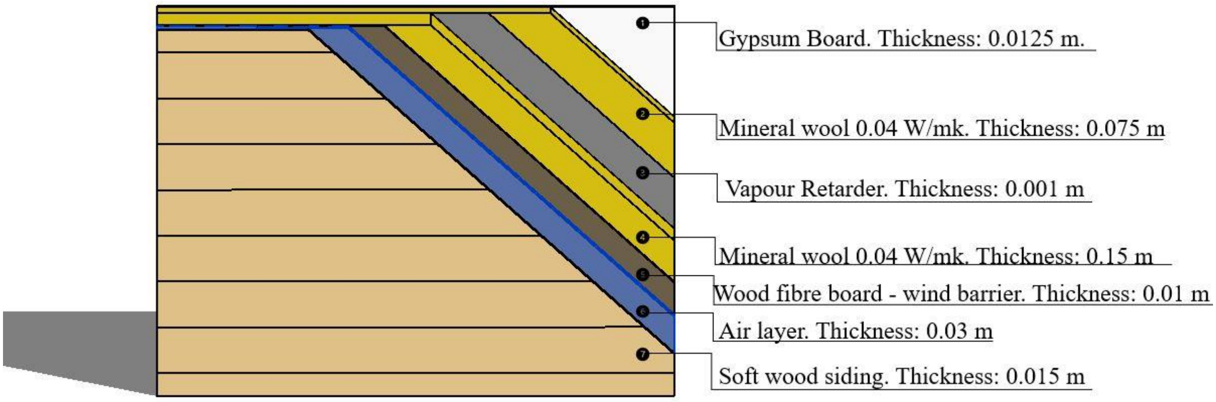


Figure 16. South exterior wall. Byggforsk 523.255 Exterior walls of half-timbering. Thermal insulation and sealing

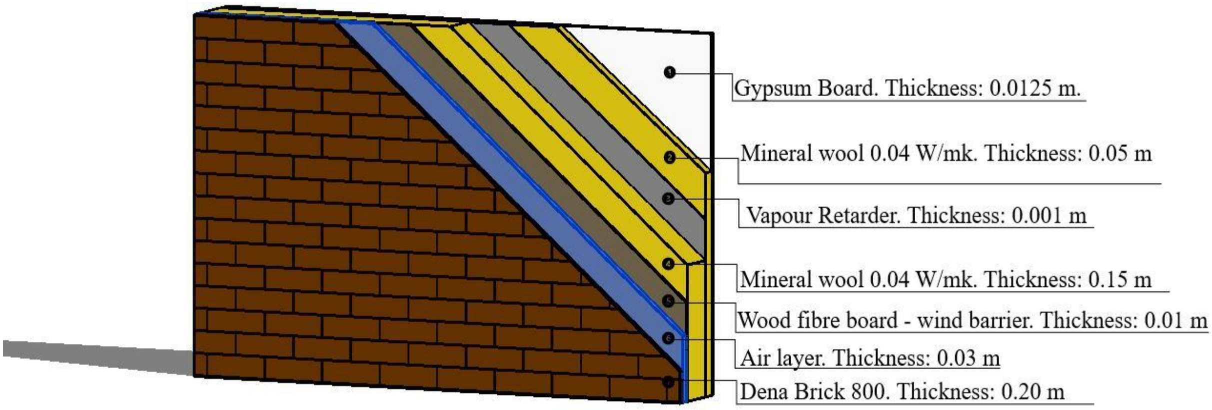


Figure 17. North exterior wall. Byggforsk 542,301 Brick glazing

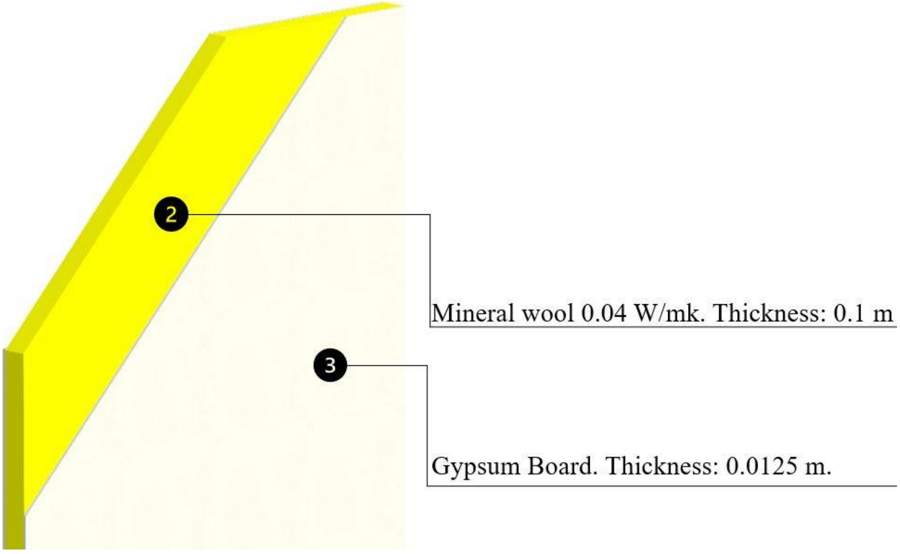


Figure 18. Wall of the shaft opening towards the corridor Byggforsk 524.233 Interior walls with steel posts.

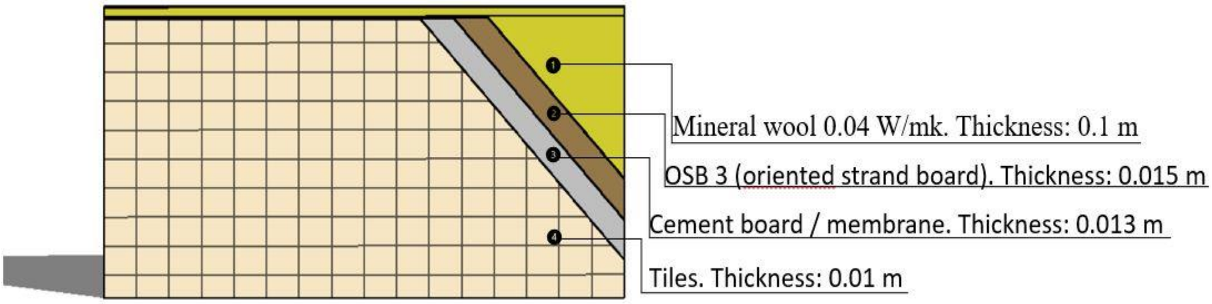


Figure 19. Shows the wall of the shaft towards the bathroom.

4.7.2. Climatic conditions of simulation

WUFI®PLUS simulation was used to evaluate the precision of field measurement. This meant that the weather file used in the simulation needed to be based on the climatic conditions during the occurring field measurements, which lasted seven days, starting with calculation period of February 14, 2021 at 14:00 – February 22, 2021 at 10:00 for scenario one. WUFI®PLUS comes equipped with a software tool that can create a weather file. The hourly climatic conditions such as temperature and relative humidity fluctuations were added to this weather file, with a start date of February 14,2021 at 14:00 and end date of February 22, 2021 at 10:00. (*Meteorologisk institutt. Norsk klimasenter*, 2021) was utilized to obtain the needed data for temperature and relative humidity. Data came from Blindern weather station.

Scenario two, however, which also lasted seven days, was done at a later date from April 16, 2021 at 19:00 to April 22, 2021 at 19:00. This time reflects on the field measurement done with a humidifier. Hourly climatic conditions of temperature and relative humidity fluctuations from (*Meteorologisk institutt. Norsk klimasenter*, 2021) were added to this weather file as well.

Scenario three and four was created for the whole year simulations, with WUFI®PLUS integrated weather file. The premade weather data in this integrated file was based on the average weather data of the last thirty years in Oslo, Norway.

The accuracy of all new hygrothermal simulations was set to very high, which was the highest accuracy setting in WUFI®PLUS.

4.7.3. Rooms and zones

Five different zones were made as the apartment had five different rooms, which was measured. The floor area of each zone is seen in Table 15, and the floor height was 2.4 m in all rooms except the corridor and bathroom, where the height was 2.1 m.

Table 15 shows the different rooms/zones and corresponding square metres and height. And Figure 20. Whole apartment design created in WUFI®*PLUS*

Table 15. Rooms/zones and corresponding square metres and height.

Room	Floor area [m^2]	Room height
Kitchen / Livingroom	22.344	2.4
Bathroom	4.42	2.1
Corridor	13.6395	2.1
Master bedroom	12.312	2.4
Small Bedroom	7.39	2.4
Shaft opening (closed environment)	Unheated and unused space	
Sum	**60.1**	

All layers got their orientation added following their actual orientation, where the façade of the wall in the kitchen/living room has south as its orientation. There were only two façades that had their side in exterior conditions, one of these facades was the one wall in the kitchen/living room, the other side was the exterior wall on the Northside of the apartment, which was shared with the master bedroom and the smaller bedroom. The whole apartment was located on the fourth floor. For this reason, the height above ground for all layers has been set to ten metres.

All rooms were interconnected by having a door opening between the rooms open. This allows air and moisture to be able to travel between the rooms more freely.

The thickness and U-values of the wall assemblies have been presented in Table 16. They were all based on the minimum requirements for U-value given in TEK 17 (Direktoratet for byggkvalitet (TEK 17), 2017). Furthermore, interior paint with SD value five and exterior paint with SD value ten (exterior walls) was added to the painted walls, which means all surfaces except tiles or brick.

Table 16. Thickness, Thermal conductivity, Water vapour diffusion resistance factor and U-values of the wall assemblies

Name of Assembly	**Layer**	**Thickness [m]**	**Thermal conductivity λ [W/mK]**	**Water vapour diffusion resistance factor μ [-]**	**U-value [W/m²K]**
North Exterior Wall Brick	Dena brick 800 (heat cond.: 0.28 W/mK)	0.2	0.28	15	0.165
	Air layer	0.03	0.59	0.15	
	Wind barrier-woodfibre board	0.01	0.18	9	
	Mineral wool	0.15	0.04	1.3	
	Vapour retarder (sd=100m)	0.001	2.3	100000	
	Mineral wool	0.05	0.04	1.3	
	Gypsum board	0.0125	0.2	8.3	
South Exterior Wall Wood siding	Softwood siding	0.015	0.09	200	0.163
	Air Layer	0.03	0.59	0.15	
	Wind barrier-woodfibre board	0.01	0.18	9	
	Mineral wool	0.15	0.04	1.3	
	Vapour retarder	0.001	2.3	100000	
	Mineral wool	0.08	0.04	1.3	
	Gypsum board	0.0125	0.2	8.3	
Interior Wall Bathroom	Gypsum board	0.0125	0.2	8.3	0,332
	Mineral wool	0.1	0.04	1.3	
	OSB 3 (oriented strand board)	0.015	0.1049	165	
	Cement board / membrane on edges	0.0125	0.255	170000	

	Tiles (added under surface settings)	0.01	(Added under surface settings)	200	
Interior Wall Bathroom Against Shaft	Mineral wool	0.1	0.04	1.3	0.305
	OSB 3 (oriented strand board)	0.015	0.1049	165	
	Cement board / membrane on edges	0.0125	0.255	170000	
	Tiles (added under surface settings)	0.01	(Added under surface settings)	200	
Interior Wall Against Shaft	Mineral wool	0.1	0.04	1.3	0.354
	Gypsum board	0.0125	0.2	8.3	
Interior bathroom wall between apartments	Concrete w/c 0.4	0.25	1.7	192	2.732
	Cement board / membrane on edges	0.013	0.255	170000	
	Tiles (added under surface settings)	0.01	(Added under surface settings)	200	
Interior bathroom floor between apartments	Concrete w/c 0.4	0.25	1.7	192	0.41
	Mineral wool	0.1	0.04	1.3	
	CaSO4 Screed, top layer	0.05	1.6	18	
	Cement board / membrane on edges	0.0125	0.255	170000	
	Tiles (added under surface settings)	0.01	(Added under surface settings)	200	
Interior Wall	Gypsum board	0.0125	0.2	8.3	0,347
	Mineral wool	0.1	0.04	1.3	
	Gypsum board	0.0125	0.2	8.3	
Interior Wall between apartments	Concrete w/c 0.4	0.25	1.7	192	3.154
Floor /Ceiling (between apartments)	Concrete w/c 0.4	0.25	1.7	192	1.984
	CaSO4 Screed, top layer	0.05	1.6	18	
	Vapour retarder (sd=100m)	0.001	2.3	100000	
	Oak Old	0.015	0.13	140	
Window	3-layer clear glazing (fixed setting in WUFI®PLUS)	0.035	1.269	-	0,788
Balcony Door	Hardwood	0.03	0.13	200	0,724
	Mineral wool	0.03	0.04	1.3	
	Hardwood	0.03	0.13	200	

Window	3-layer clear glazing (fixed setting in WUFI®PLUS)	0.035	1.269	-	0,788
Entrance Door	Hardwood	0.03	0.13	200	0,724
	Mineral wool	0.03	0.04	1.3	
	Hardwood	0.03	0.13	200	

As seen in Figure 20, the model had two balconies on the exterior south and north side.

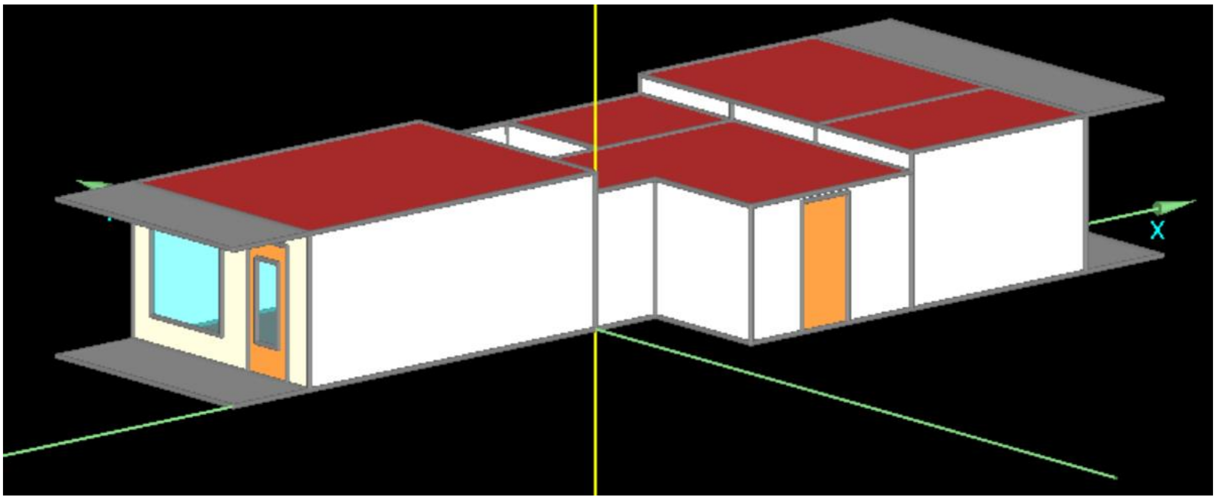


Figure 20. Whole apartment design created in WUFI®PLUS

4.7.4. HVAC system

The HVAC system had mechanical ventilation with a capacity of 10000 [m^3h) and district heating that only contained space heating with a capacity of 200 kW. This was, of course, for scenario one and were the only settings for the HVAC during the first run of the simulation. Both the mechanical ventilation and the space heating capacity were distributed based on the actual size of the rooms. Their value was listed in Table 17.

Table 17. Share zones of mechanical and space heating

Zone	**Space heating [%]**	**Space ventilation [%]**
Kitchen / Livingroom	37.1	37.1
Bathroom	7.3	7.3
Corridor	22.7	22.7
Master bedroom	20.6	20.6
Bedroom	12.3	12.3

Thermal bridges

TEK 17 has set the normalized thermal bridge value for standard buildings to be 0.07 ≥ 0 ($W/(m^2 \cdot K)$) (Direktoratet for byggkvalitet (TEK 17), 2017). This was utilized. The simulated apartment has a net area of 60.1 m^2. There are three exterior walls. Table 18 shows the perimeter of the three exterior wall and windows/doors thermal bridges. The length of the thermal bridge is seen in the rooms total perimeter.

Table 18. The perimeter of the thermal bridge

Room	Part	Circumference [m]
Livingroom/kitchen	Window	1.6+1.6+1.65+1.65= 6.5
	Balcony door	2.1+2.1+0.9 = 5.1
	Exterior wall	2.4+2.4+4+4= 12.8
Room total perimeter		**24.4**
Master bedroom	Balcony door	2.1+2.1+0.9 = 5.1
	Window	0.75 0.75+1.7+1.7= 4.9
	Wall (one corner)	4+4+2.4=10.4
Room total perimeter		**20.4**
Small bedroom	Wall (one corner)	2.16+2.16.2.4=6.72
	Window	0.9+1.3=2.2
Room total perimeter		**8.92**
Apartments total perimeter of thermal bridges		**62.64**

The linear thermal transmittance has been calculated to be 0.0672 W/(m·K). The calculation was carried out by multiplying 0.07 W/(m^2·K) from TEK 17 (Direktoratet for byggkvalitet (TEK 17), 2017) times the net area of apartment 60.1 m^2, before dividing it on the total perimeter of 62.64 m which has been calculated using NS 3031 (Standard Norge, 2014).

Both the 0.0672 W/(m·K) and the three rooms individual total perimeter were added to WUFI®PLUS, in the living/room, bedroom, and master bedroom. These rooms were the only rooms connected to exterior conditions.

4.7.5. Internal load (Occupancy)

Internal load and occupancy were created in WUFI®PLUS based on a discussion with the owner and the resident of the apartment. This was done to create a more realistic internal load in WUFI®PLUS, which resembled the actual scenario during the measurements. However, an entirely correct occupancy is not feasible since people behave differently day by day. The internal load was minorly tweaked during the measurements to find the right balance between the simulation and measurements. Furthermore, only the master bedroom was used for sleeping as the child of the apartment slept in the master bedroom. This was why the occupancy load for the small bedroom was at zero during the night. The occupancy loads for all the zones are in Table 19 to Table 26.

Table 19. Occupancy load of living room / kitchen weekdays

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Living room kitchen weekdays	00:00	0	0	0	0	0	0
	07:00	2 Adults + 1Child. (seated/ quiet)	192	96	184	93	1
	08:00	0	0	0	0	0	0
	16:00	2Adults + 1Child. (seated/ quiet)	192	96	184	93	1
	17:00	1Adults + 1Child. (seated/ quiet) + 1 Adult cooking	246	123	277	115	1.266
	18:00	2Adults + 1Child. (seated/ quiet)	192	96	184	93	1
	20:00	2 Adults (seated/ quiet)	144	72	138	70	1
	23:00	0	0	0	0	0	0

Table 20. Occupancy load of living room/kitchen weekend

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Living room kitchen weekend	00:00	0	0	0	0	0	0
	07:00	1Adults + 1Child. (seated/ quiet)	120	60	115	58	1
	10:00	1Adults +	120	60	115	58	1

	1Child. (seated/ quiet)					
11:00	0	0	0	0	0	0
16:30	1Adults + 1Child. (seated/ quiet)	120	60	115	58	1
17:00	1Adults + 1Child. (seated/ quiet) + 1 Adult cooking	246	123	277	115	1.266
18:00	2Adults + 1Child. (seated/ quiet)	192	96	184	93	1
20:00	2 Adults (seated/ quiet)	144	72	138	70	1
23:00	0	0	0	0	0	0

Table 21. Occupancy load of bathroom weekday

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Bathroom Weekday	00:00	0	0	0	0	0	0
	05:00	-	38,8	19.4	0	7	1
	06:00	-	48.8	24.4	172	12	1.2
	06:30	0	0	0	0	0	0
	21:00	-	23.2	11.6	0	18	1
	22:00	-	80	40	372	18	1
	23.00	0	0	0	0	0	0

Table 22. Occupancy load of bathroom weekend

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Bathroom Weekend	00:00	0	0	0	0	0	0
	07:00	-	23.2	11.6	0	8	1
	07:30	-	15.6	7.8	344	6	1
	8:00	0	0	0	0	0	0
	18:00	-	6.6	3.3	0	0	0
	20:00	-	13.2	6.7	0	0	0
	21.30	-	36,6	18.3	250	18	1
	22:00	-	72.2	36.1	250	20	1.2
	22.30	-	80	40	372	18	1
	23:00	0	0	0	0	0	0

Table 23. Occupancy load of corridor weekday / weekend

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Corridor	00:00	0	0	0	0	0	0
	07:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	07:30	0	0	0	0	0	0
	10:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	10:30	0	0	0	0	0	0
	16:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	16.30	0	0	0	0	0	0

	22:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	22.30	0	0	0	0	0	0

Table 24. Occupancy load of master bedroom weekday

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Master bedroom	00:00	2 Adults resting sleeping. Child resting sleeping.	128	64	91	70	0.7
	07:00	2 Adults resting sleeping. Child resting sleeping.	0	0	0	0	0
	20:00	2 Adults resting sleeping. Child resting sleeping.	32	16	23	18	0.7
	22:00	2 Adults resting sleeping. Child resting sleeping.	128	64	91	70	0.7

Table 25. Occupancy load of master bedroom weekend

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Master bedroom	00:00	2 Adults resting sleeping. Child resting sleeping.	128	64	91	70	0.7
	07:00	2 Adults resting sleeping. Child resting sleeping.	0	0	0	0	0
	20:00	2 Adults resting sleeping. Child resting sleeping.	32	16	23	18	0.7
	23:00	2 Adults resting sleeping. Child resting sleeping.	128	64	91	70	0.7

Table 26. Occupancy load of small bedroom weekday

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]

Small bedroom	00:00	0	0	0	0	0	0
	10:00	1 person sitting activity (office)	90	35	50	59	1.2
	16:30	0	0	0	0	0	0

4.7.6. Design conditions

This section in WUFI®PLUS controls the minimum and maximum temperature, relative humidity and CO2 concentration.

The minimum indoor temperature was set to 22 °C in all rooms, except for the bathroom, where the minimum temperature was 24 °C. Furthermore, as the HVAC had no cooling in the apartment, the maximum indoor temperature at 26 °C had no significance. However, it still needed to be set for the simulation. Furthermore, all temperatures mentioned were for the whole duration of the measurement.

There was no air humidification or air dehumidification, so that the settings under design condition for maximum and minimum relative humidity were not of significance.

4.7.7. Ventilation

In the settings of ventilation, it is possible to make changes to natural ventilation, mechanical ventilation and interzone.

All the inlets and outlets were measured using Kimo K35 measuring funnel and Velocicalc® Air Velocity Meter 9545 anemometer with hot wire, and the second measuring equipment was Swemaflow 125 airflow hood. Have been added to WUFI®PLUS, as seen in Table 27, to resemble the ventilation rate of the apartment accurately.

Table 27. Measured ventilation rates of the rooms

Room	Inlet / Outlet	Ventilation rate [m^3/h]
Living room/kitchen	Inlet	25
	Outlet	21
Master bedroom	Inlet	18
Smal bedroom	Inlet	11,5
Bathroom	Outlet	100

No natural ventilation rate was added to any room, but in the interzone setting, 1/h was added between the rooms. This was done to resemble the open doors of the apartment and that the different zones exchange some air between them.

4.7.8. Initial room conditions

The settings in the initial parameters were for the start of the simulation. All of these parameters were changed quickly as soon as the simulation starts.

-Initial temperature 20°C

-initial relative humidity 55%

-initial CO_2 concentration 400 ppmv

The distribution of solar gains on the interior surface was proportional to the area, and the solar radiation directly to interior air was 0.1 [-]

Attached Zones

There was only one room/zone that had the simulation setting as an attached zone. This room was the shaft between the living room/kitchen and the bathroom. It did not have any ventilation or heating, as well as not being a part of the internal conditions. Due to this, no results were made for this zone.

4.7.9. Scenario two

Scenario two was for confirming field measurements with a humidifier. Only changes to settings done in scenario two in comparison to scenario one will be highlighted. No other changes were made to simulation two.

Scenario two lasted seven days and was performed from April 16, 2021 at 19:30 to April 22, 2021 at 19:30. This time reflects on the field measurement done with a humidifier. Hourly climatic conditions of temperature and relative humidity fluctuations from (Meteorologisk institutt. Norsk klimasenter, 2021) were added to this weather file as well. Humidifier results for both the field measurement and the WUFI®PLUS were all based on the humidifier being on the corridor and distributing humidity to other rooms from there. There was always only one humidifier in use for scenario two.

The added humidification for scenario two was done through the HVAC settings in WUFI®PLUS. This section can assign the capacity for humidification. The capacity was set to 50 kg/h. Shared zones distribute the humidifier capacity based on the room size. The distribution of the share zone for the humidifier was identical as for ventilation and district heating, seen in Table 17 (share zones). Now that humidification was added, a change was needed in the setting of design conditions where the minimal relative humidity settings were located. This minimal setting for relative humidity was set to 40% for the corridor only, which is a good value according to (Standard Norge, 2019). The simulation time frame for scenario two was changed to the time of field measurement.

To match the field experiments maximum and minimum RH in the rooms with a humidifier. Added humidity to the different rooms of the apartment was added together with changes to interzonal settings to emulate the shared humidification between the rooms. Internal load and occupancy were changed so that more moisture could be added to the different rooms. By adding moisture, a closer resemblance to the field measurement was acquired. All occupancy loads for scenario two are listed in Table 28 to Table 46 in the same order as the simulation.

Living room/kitchen

Table 28. With a humidifier, occupancy load of living room/kitchen weekdays 16/04/2021 to 22/04/2021 (generic from WUFI®PLUS database)

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Living room kitchen weekday	00:00	0	0	0	0	0	0
	05:00	Database generic	0	0	0	0	0
	06:00	Database generic	48.8	24.4	90	12	1.2
	07:00	0	0	0	0	0	0
	18:00	36	18	8.611	0.006	0.006	0.8
	21:00	36	18	8.611	0.006	0.006	0.8
	22:00	Database generic	80	40	250	18	1
	23:00	0	0	0	0	0	0

Table 29. With a humidifier, occupancy load of living room/kitchen weekdays 17/04/2021 to 19/04/2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Living room kitchen weekday	00:00	0	0	0	0	0	0
	06:00	Database generic	48.8	24.4	40	12	1.2
	07:00	0	0	0	0	0	0
	18:00	36	18	8.611	0.006	0.006	0.8
	21:00	36	18	8.611	0.006	0.006	0.8
	22:00	Database generic	80	40	150	18	1
	23:00	0	0	0	0	0	0

Table 30. With a humidifier, occupancy load of living room/kitchen weekend 19/04/2021 to 22/04/2021.

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Living room kitchen weekend	00:00	0	0	0	0	0	0
	05:00	-	60	33	50	15	1
	12:00	-	60	33	50	15	1
	13:00	0	60	33	50	15	1

The exchange of air (interzonal) from the living room/kitchen to the corridor was set to 0.15 (1/h)

Bathroom

Table 31. With a humidifier, occupancy load of the bathroom for 16/4-2021 to 22/4-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Bathroom Weekday	00:00	0	0	0	0	0	0
	07:30	-	15.6	7.8	149	6	1
	08:00	0	0	0	0	0	0
	21:30	-	36.6	18.3	108	18	1
	22:00	-	80	40	108	18	1

	22:30	-	80	40	165.6	18	1
	23:00	0	0	0	0	0	0

Table 32. With a humidifier, occupancy load of the bathroom for 18/4-2021 and 21/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Bathroom Weekday	00:00	0	0	0	0	0	0
	07:30	-	15.6	7.8	108	6	1
	08:00	0	0	0	0	0	0
	21:50	-	36.6	18.3	82.5	18	1
	22:00	-	72.2	36.1	82.5	20	1.2
	22:30	0	80	40	82.5	18	1
	23:00	0	0	0	0	0	0

Table 33. With a humidifier, occupancy load of the bathroom for 20/4-2021 to 21/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Bathroom Weekend	00:00	-	15.6	7.8	70	6	0
	07:30	-	15.6	7.8	70	6	1
	20:00	-	15.6	7.8	70	6	1
	21:30	-	36.6	18.3	100	18	1
	22:30	-	80	300	300		
	23:00	-	15.6	7.8	80	6	1

Table 34. With a humidifier, occupancy load of the bathroom for 21/4-2021 to 22/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Bathroom Weekend	00:00	-	15.6	7.8	20	6	0.8
	06:00	-	48.8	24.4	50	12	1.2
	06:30	0	0	0	0	0	0
	12:00	-	80	40	135	18	1
	18:30	0	0	0	0	0	0

Table 35. With a humidifier, occupancy load of the bathroom for 16/4-2021 to 17/4-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Bathroom	00:00	-	48.8	24.4	55	12	1.2
Weekend	19:00	0	0	0	0	0	0

The exchange of air (interzonal) from the bathroom to the corridor was set to 0.8 (1/h)

Corridor

Table 36. With a humidifier, occupancy load of corridor weekday/weekend 16/4-2021 to 22/4-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Corridor	00:00	0	0	0	0	0	0
	07:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	07:30	0	0	0	0	0	0
	10:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	10:30	0	0	0	0	0	0
	16:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	16.30	0	0	0	0	0	0
	22:00	Person, child-Standing, Moderate Activity	93	46	76	119	2
	22.30	0	0	0	0	0	0

The exchange of air (interzonal) from corridor to other rooms
From corridor to living room/kitchen was set to 1.2 (1/h)
From corridor to the bathroom was set to 0.073 (1/h)
From corridor to the master bedroom was set to 0.8 (1/h)
From corridor to the small bedroom was set to 2.5 (1/h)

Master bedroom

Table 37. With humidifier occupancy load of the master bedroom for 16/04-2021 to 22/04-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Master bedroom	00:00	-	128	64	180	70	0.7
	07:00	0	0	0	0	0	0
	20:00	-	32	16	180	18	0.7
	22:00	-	128	64	180	70	0.7

Table 38. With humidifier occupancy load of master bedroom for 16/4-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Master bedroom	00:00	-	128	64	230	70	0.7
	07:00	0	0	0	0	0	0
	20:00	-	32	16	230	18	0.7
	22:00	-	128	64	230	70	0.7

Table 39. With humidifier occupancy load of master bedroom for 17/4-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Master bedroom	00:00	-	128	64	130	70	0.7
	07:00	0	0	0	0	0	0
	20:00	-	32	16	130	18	0.7

	23:00	-	128	64	130	70	0.7

Table 40. With humidifier occupancy load of the master bedroom for 19/4-2021 to 20/04-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Small bedroom	00:00	-	42	21	40	23	0.7
	07:00	0	0	0	0	0	0
	20:00	-	42	21	40	23	0.7
	23:00	-	42	21	40	23	0.7

Table 41. With humidifier occupancy load of the master bedroom for 21/4-2021 to 22/04-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Small bedroom	00:00	-	128	64	110	70	0.7
	07:00	0	0	0	0	0	0
	20:00	-	32	16	110	18	0.7
	22:00	-	128	64	110	70	0.7

The exchange of air (interzonal) from the master bedroom to the corridor was set to 0.06 (1/h)

Small bedroom

Table 42. Occupancy load of small bedroom 16/4-2021 to 22/4-2021

Room / zone	Time of day [hour]	Person Count	Heat convection [W]	Heat radiant [W]	Moisture [g/h]	CO_2 [g/h]	Human activity average [met]
Small bedroom	00:00	0	0	0	0	0	0
	10:00	1 person sitting activity (office)	90	35	700	59	1.2
	16:30	0	0	0	0	0	0

Table 43. Occupancy load of small bedroom 16/4-2021 to 16/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
	10:00	1 person sitting activity (office)	90	35	700	59	1.2

Table 44. Occupancy load of small bedroom 21/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Small bedroom	00:00	0	0	0	0	0	0
	10:00	1 person sitting activity (office)	90	35	850	59	1.2
	16:30	0	0	0	0	0	0

Table 45. Occupancy load of small bedroom 16/4-2021 to 17/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Small bedroom	00:00	0	0	0	0	0	0
	10:00	1 person sitting activity (office)	90	35	800	59	1.2
	16:30	0	0	0	0	0	0

Table 46. Occupancy load of small bedroom 21/4-2021 to 22/4-2021

Room / zone	**Time of day [hour]**	**Person Count**	**Heat convection [W]**	**Heat radiant [W]**	**Moisture [g/h]**	**CO_2 [g/h]**	**Human activity average [met]**
Small bedroom	00:00	0	0	0	800	0	0
	02:00	1 person sitting activity (office)	0	0	600	0	0
	12:00	1 person sitting activity (office)	90	35	300	59	1.2
	14:00	1 person sitting activity (office)	90	35	600	59	1.2

The exchange of air (interzonal) from the small bedroom to the corridor was set to 2.9 (1/h)

4.7.9.1.Scenario three and four

Scenarios three and four were to see the full-year effect of scenario one without humidifier and scenario two with humidifier, respectively. Scenario three had all the same settings as scenario one except for the time frame and weather file. While scenario four had all the same settings as scenario two except for the time frame and weather file.

The difference in the weather file was that scenario three and four had changes done to it in the form of it being for the whole year. The simulation timeframe was set to 1 January 2021 - 00:00 to 1 January 2022 - 00:00; the occupancy load was also for this period based on the day of the week, which means that the same occupancy load (week) was reoccurring throughout the year. The weather file was changed to the 30-year average from WUFI®PLUS database. No humidification was added to scenario three but added to scenario four in the corridor only. As scenario one and scenario two, respectively. Both scenario three and four contained central heating, as all scenarios did.

5. Results

5.1. Study period and overall climate

The total field experiment period was defined as February 14, 2021 – April 22, 2021. As it can be seen in Figure 21, the outdoor temperature during the measurement period was on average of 1.87°C, which is 0.08°C cooler than the 30 years average of 1.95 °C for outdoor temperature recorded at the Oslo Blindern weather station between the period of February and April 1990-2021.

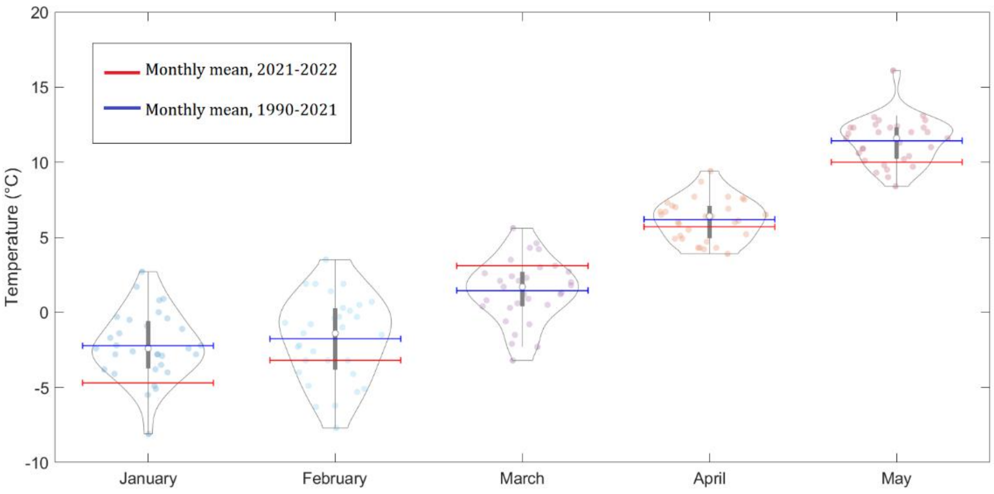


Figure 21. Outdoor climate 2021–2022 compared to 30-year average for outdoor temperature recorded at the Oslo Blindern weather station.

5.2. Participating households

A total of 10 households participated in this study. An overall description of their characteristics is shown in Table 47. It must be noted that the apartment called Apartment 2 was tested two times and presented as Apartment 2A and Apartment 2B, where A stands for a tested period of without humidifier while B for with humidifier. Since it was the same household, the second time with humidifier was not counted in calculations of mean values except for the row showing owning humidifier(s). The mean numbers of occupants per household were 2.4, with a mean age of 41.73 years. The mean BRA of the monitored apartments was 72.64 m^2. Also, the apartments were all in residential buildings, with a mean height of 6.5 floors. And, only two of the participants reported ownership of at least one humidifier.

Table 47. The characteristics of participating households

		Mean (Range)
Total household members		2.4 (1-4)
Age of household members		41.73 (26-60)
Rooms in home		3.2 (2-5)
Floors in building		6.5 (6-7)
BRA (m^2)		72.6364 (30-115)
Can turn heat on and off		
	Yes	10 (%100)
	No	0 (%0)
Own humidifier(s)		
	Yes	2 (%18.2)
	No	9 (%81.8)

5.3. Ventilation air flow rates

The ventilation airflow rates were measured only for two apartments (Apartment #1 & Apartment #2) where Apartment #2 was located in the same project area, which includes 4 buildings with similar characteristics where most of the tested apartments located, while Apartment #1 was the one that was not located in this area. As aforementioned, for the calculations for each apartment except Apartment #1, the total extract airflow rate measured in Apartment #2 was used as ventilation airflow rate. Table 48 shows the air supply and air extraction rates achieved in Apartment #1 and #2 and a comparison with design values recommended in TEK 17 (Direktoratet for byggkvalitet (TEK 17), 2017). It was apparent that measured values indiscriminatingly far away from recommended values from TEK 17 (Direktoratet for byggkvalitet (TEK 17), 2017). As shown in Table 48, Apartment #1 had a higher air supply than its air extraction, which causes under pressurisation, while Apartment #2 had the opposite situation, which causes over pressurisation. It must be noted that ventilation rates were only measured during one day of the monitoring period, therefore no certainty can be put upon on these ventilation rates maintaining throughout the whole monitoring period.

Table 48. The air supply and air extraction rates achieved in Apartment 1 and Apartment 2 and their comparison with design values from TEK 17 (Direktoratet for byggkvalitet (TEK 17) ,2017)

Room Type	Apartment 1		Apartment 2		Design Targets	
	Supply [m^3/h]	Extract [m^3/h]	Supply [m^3/h]	Extract [m^3/h]	Supply [m^3/h]	Extract [m^3/h]
Bathroom	-	25		100	-	54
Master Bedroom	37	-	18	-	26	-
Living room Kitchen	37	-	25	21	-	36
Small Bedroom	-	-	11.5	-	26	
Total (Apartment #1)	**74**	**25**			**36 (min. 1.2 m^3/h per m^2)**	**54**
Total (Apartment #2)			**54.5**	**121**	**72(min. 1.2 m^3/h per m^2)**	**90**

5.4. Relative humidity, temperature, and indoor moisture excess

The RH and temperature of the bathroom, master bedroom, kitchen, living room, and small bedroom in each apartment measured over a period of 5-13 days were analysed and presented as boxplot graphs for each room type in Figure 24, Figure 25, Figure 26, Figure 27, Figure 28, respectively. Indoor climate data (temperature and relative humidity) were presented using boxplot graphs. The top and the bottom of the boxes stand for the 90th and 10th percentiles, respectively, and the red line close to the middle of the box represents the median value. The end of the whiskers indicates the minimum and maximum values. The mean, max, min, together with the 10th and 90th percentiles of indoors relative humidity, temperature, and internal moisture excess from the ten monitored apartments, can be observed in Table 49 and Table 50. In order to gain a better understanding, apartments which owned at least one humidifier separated from rest of the apartments and presented in Table 50 while rest of the apartments without humidifier presented in Table 49.

5.4.1. Relative Humidity Indoors

As shown in Table 49, it was found that for each room type of apartments without a humidifier, 90% of the measurement results for RH indoors were below 32% and mean values were below 23%, which is classified as “Category II” in the NS-EN 16798-1:2019 and 10% of the measurement results for RH levels indoors were even below 15%. While for apartments with humidifier, the mean RH indoors values were on the scale of 32-43%. Without making discrimination of with or without humidifiers, it was apparent that the highest RH levels are measured in the bathrooms and bedrooms of the apartments. Nakedly, RH levels in the bathroom from Apartment #1, Apartment #2B and Apartment #11 show larger interquartile ranges which contain higher values of RH than others, however the median RH value of Apartment #11 was still on the scale of 15-25%, same as all other apartments except Apartment #1 and #2B. While the highest measured RH in the bathroom were from Apartment #11, some high measured RH values in bathrooms were also observed in Apartment #1, #2B and #7. Furthermore, as shown in Figure 24, Apartments #10 and #12 had lower levels of RH peaks compared to the others.

Since Apartment #10 and #12 were the first two apartments with the largest BRAs, it was assumed that low levels of RH peaks were due to higher ventilation extract rates. When it comes to high measured levels of RH in bathrooms of Apartment #1 and #2B, it was known that both of them were using a humidifier during the monitoring period, and it must be noted that usage of humidifier has a significant effect on RH levels. Also, Apartment #1 had a lower exhaust airflow rate in the bathroom than its total supply airflow rate, which causes over pressurization and these factors might have been the reason for higher RH levels, however, even though ventilation rates for Apartment #11 were not known, the median RH in the bathroom of Apartment #11 and considering its occupancy level higher than rest of the apartments shows that possibly the reason why high levels of RH occurred was related to consecutive showering events. Also, from the logged data, it was possible to see that it took around one hour for high levels of RH to become normal back which indicates the long showering events.

Bedroom

For the apartments without a humidifier, the mean RH in master bedrooms was 22.13%, and 90% of the measured RH levels in master bedrooms were lower than 27%. The highest measured RH value of master bedrooms was observed in Apartment #1, which was one of the two apartments that own at least one humidifier which possibly was placed in the bedroom. The second highest measured RH value in master bedrooms was observed in Apartment 2, which only observed once for approximately 20 minutes around 15:20 during one monitoring day, and according to the measurements, it was possible to see an increase in RH every day around 15:20. With humidifier usage, there were no great differences in RH observed in the master bedroom of Apartment #2. Also, as shown in Table 49 and Table 50, for the apartments without a humidifier, there was no significant differences of RH observed in master bedrooms and small bedrooms while, for the apartments with humidifier, the mean RH in small bedrooms were significantly higher when compared to master bedrooms. Additionally, it was possible to see that the RH levels in the bathroom were observed in Apartment #3 were close to the ones from Apartment #2. Another apartment where outstanding RH values were observed was Apartment #11. As shown in Figure 25, the median RH in the bedroom of Apartment #11 was 21.49%, however, it was exposed to higher levels of RH up to 38% and decreased until to the level of 15% RH after some days of the measurement period while at the same time its CO_2 levels were decreasing.

Regardless of owning a humidifier, the RH levels in bedrooms were generally lower during the period between morning and evening-time. In most of the monitored apartments, during the period of low RH observations, low CO_2 levels (approximately 400 ppm) were observed while, in the night times where higher RH values were observed as well as higher CO_2 levels (over 700 ppm). And these two observations indicate low RH values were occurred due to low occupancy levels and/or the window opening events in the bedrooms during the morning until evening times. The peaks of RH levels in master bedrooms during the daytime were assumed due to short usage of bedrooms, such as kids' nap time. Furthermore, even though the RH values in the bathroom were observed in Apartment #3 were close to the ones from Apartment #2, there was so little information about Apartment #3 to comment on these results. Additionally, the reason why there was a significant difference in observed RH in small bedrooms and master bedrooms was presumed that due to the fact that the placement of the humidifier was close to the small bedroom of Apartment #2B.

Living room

The lowest mean RH value was observed in living rooms regardless of owning a humidifier. 90% of the measured RH values for the living room were below 30% for the apartments without a humidifier, while this number was 40.28% for the apartments with a humidifier. The median values of measured RH levels in living rooms of each apartment without a humidifier except Apartment 2 were below 25%. According to the data of questionnaires, Apartment #2 and #11 had the highest number of weekly cooking events comparing to the others.

Considering all of the apartments had open kitchen design where the living room includes a kitchen, it was assumed that higher RH levels observation from the living room of Apartment #2 and #11 was due to the higher numbers of weekly cooking events. However, the reason why the median RH value in the living room of Apartment #11 was below 20% even though it was exposed to high levels of RH was due to unoccupied periods of the apartment that was possible to see from its CO_2 levels decreases after some days of the monitoring period.

Kitchen

The mean RH value measured in the kitchen of the apartments without a humidifier was 21.52%, and the maximum achieved RH was 43.53%, while 90% of measured RH values were below 29.66%. The measurement results from kitchens and living rooms were closer to each other, with some minor differences which due to the placements of the sensors. The sensors measuring in the kitchen were able to measure differences in RH and temperature due to the cooking events, while the sensors placed in living rooms were away from the kitchen.

A Spearman's rank-order correlation was conducted to determine the relationship between the number of weekly cooking events and measured RH levels in the kitchen from each apartment regardless of owning a humidifier. There was a moderate positive correlation between the number of weekly cooking events and measured RH levels in the kitchen from each apartment which was statistically significant ($r_s[21111]= 0.538$, $p < .001$). Even though, in general, there was a moderate positive correlation between cooking events and measured RH levels, Apartment #5 and #8 had the same occupancy levels and reported approximately the same numbers of cooking events, as shown in Figure 26, each apartment was exposed to slightly different RH levels.

Considering the BRA of Apartment #8 was almost double size of the Apartment #5, it was assumed that ventilation rates for Apartment #8 were higher than what Apartment #5 had. This support why Apartment #5 was exposed to higher RH levels comparing to Apartment #8.

5.4.2. Temperature

The mean temperature values for the apartments, regardless of owning a humidifier, were on the scale of 21-27 °C. Temperature percentiles show that at least 10% of the measured values of each room were above 23 °C, which is higher than what NS-EN 16798-1:2019 requires and TEK 17 recommends (indoor temperature be kept below 22 °C as far as possible when there is a need for heating) (Direktoratet for byggkvalitet (TEK 17), 2017; Standard Norge, 2019)

Bedroom

As shown in and Table 50, regardless of owning a humidifier, the lowest mean temperature for each room type was observed in master bedrooms. As shown in Figure 25, while the mean temperature in the bedroom for eight of eleven apartments was in the scale of 20-23 °C, in the other three apartments (#8, #10 and #12), higher mean temperature values in the bedroom were observed. Furthermore, regardless of having a humidifier, the measured minimum temperature from small bedrooms was warmer compared to master bedrooms.

The low temperature occurring in bedrooms might have due to the window opening events and low occupancy activities in bedrooms during the daytime while, it assumed that window opening events for small bedrooms were less compared to the master bedrooms, which might explain why the minimum temperature observed in small bedrooms were warmer when compared to master bedrooms.

Bathroom

The highest mean temperature for each room type was observed in bathrooms, regardless of owning a humidifier. The highest observed RH in bathrooms was 38.995% which occurred in Apartment #20. In Figure 24, it was possible to see that higher peak values of temperature were observed in Apartment #1, #2, #5, and #20. While the observed values in the bathroom of Apartment #3 and #12 were significantly lower than other apartments. Moreover, the interquartile ranges for apartments #2A, #2B, #3, #8 and #10 were smaller compared to the others.

The small interquartile ranges show more stable temperature values were exposed to these bathrooms than the others, which might have due to the normal showering temperatures and keeping the bathroom door closed most of the time. Moreover, it was assumed that higher peak values of temperature in bathrooms of Apartment #1, #2, #5 were due to hot and long showering events while, the cause of the peaks in the bathroom of Apartment #20 was presumed to be high-temperature settings of floor heating together with the usage of a dryer according to the measurements, low RH levels were observed while temperatures were in its peaks. Furthermore, the reason for lower temperatures observations in Apartment #3 and #12 was assumed that due to the lower temperature settings of floor heating, short-cold showering, and keeping the bathroom doors open while not showering.

Kitchen

The measured mean temperature value in kitchens of the apartments without humidifier was 23.9 °C, and the maximum was 29.01, while 90% of the measured values were below 25.9 °C. The data findings also show that measured temperatures from kitchens were significantly higher ($p < 0.05$) when compared with the monitored living rooms and bedrooms regardless of owning a humidifier. As shown in Figure 26, slightly higher median temperature values were observed in Apartment #8, #10 and #11. While the lowest median temperature in kitchens was observed in Apartment #5 as 22.26 °C.

It was assumed that the low-temperature values in the kitchen of Apartment #5 were due to its small BRA, low occupancy level and low numbers of cooking activities. According to the data from the questionnaire, it was assumed that observation of high-temperature values was due to less window airing and/or higher occupancy levels that causes more cooking events.

Living Room

The mean temperature in living rooms of the apartments without a humidifier and with a humidifier was 23.74 °C and 23.87 °C, respectively. Also, the difference between measured min temperature values was not significant. However, when comparing Apartment #2A and #2B, it was obvious higher temperatures observed during the period with humidifier (#2B) when compared to #2A. Furthermore, through temperature values of Apartment #1 and #20 were the two lowest temperature values achieved in living rooms. Additionally, as shown in Figure 27, the boxplot of Apartment #12, where the highest mean temperature value was observed, was noticeable.

The observation of higher temperature values in Apartment #2B when compared to #2A, was not considered as an indicator for the hypothesis of "when humidifier was on temperature was increasing", because while the measurement period for #2A was February ($T_e < 0$), for #2B was April ($T_e > 0$). Apart from this, the reason for the through values observation in Apartment #1 and #20 might have due to more/longer window opening events compared to others. Furthermore, it was assumed that Apartment #12 was set on higher indoor temperature by households according to its median temperature value was 27.2 °C and peaks were due to its occupancy level and temperature increasements in the living room during the evening times. While for the rest of the apartments, it was assumed that high peaks of temperature in living rooms were occurring due to the increased occupancy levels and cooking events.

Outdoor and Indoor Temperature

Outdoor temperature was considered as a possible causal factor concerning indoor temperature differences. As shown in Figure 22, while indoor temperatures for Apartment #1 and Apartment #10 were increasing with increasing outdoor temperature, the rest of the monitored apartments have not shown a strong correlation to outdoor temperatures. Nevertheless, as shown in Figure 27, Apartment #20 seem to have lower temperatures (17 °C) in the living room, mostly in the morning and night-time, and higher temperature (over 20ºC) during the day. During the period of low-temperature observations, low CO_2 levels (approximately 400 ppm) were observed while, in the evening times where higher temperature values were observed as well as higher CO_2 levels (over 700 ppm). And this indicates low-temperature values were occurred due to the window opening events and low occupancy levels in the living room during the morning and night times. Once again, since no clear correlation was observed in Figure 22, it seems improbable that changes in indoor temperature were a result of outdoor temperatures. While another possible explanation for this situation could be correlated to window opening events and occupancy levels in the living room during the day.

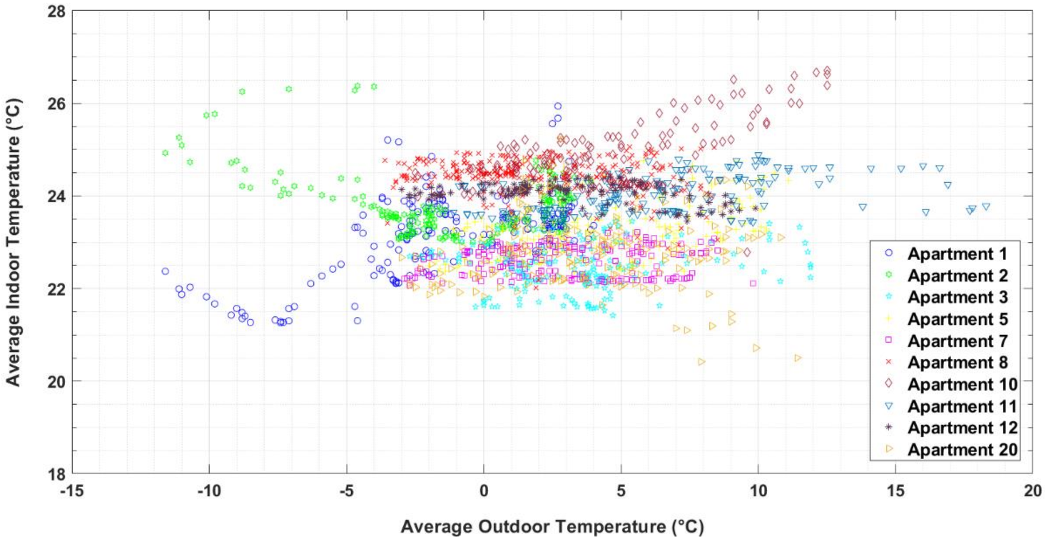


Figure 22. Corresponding values of indoor and outdoor temperatures, average values per house

5.4.3. *Absolute Humidity*

As expected by occupancy patterns, 80% of the highest hourly average absolute humidity values from bedrooms occurred between evening and night-time hours (approximately 18:00 to 03:00). While for kitchens and living rooms, hourly average absolute humidity values were at their highest, mostly during the evening hours (approximately 15:00 to 22:00), when most of the people from Norway are usually at home. Furthermore, it is important to mention that outdoor absolute humidity has a significant effect on indoor moisture loads, as shown in Figure 23, the absolute humidity outdoors was generally low during the measurement period except for Apartment #1 and #2A, which assumed as together with high indoor temperatures, it was one of the causes of the dry indoor environment.

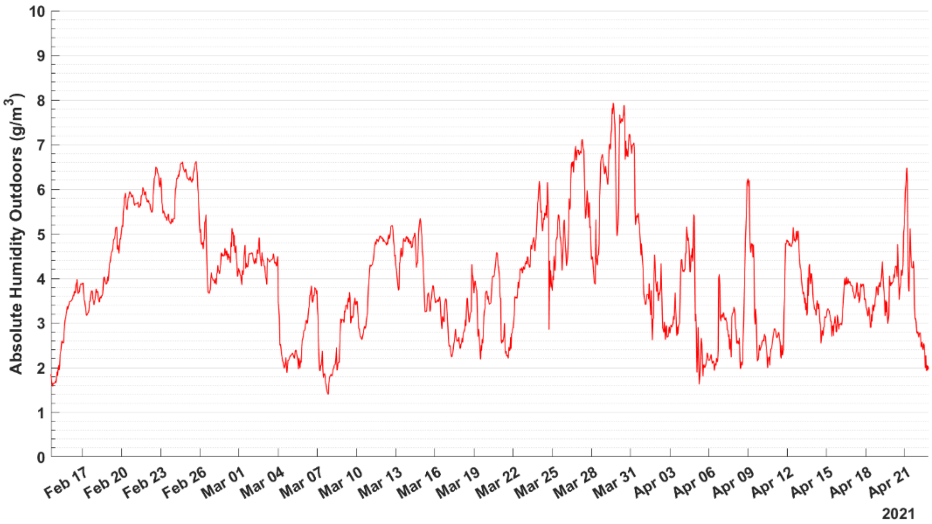


Figure 23. Absolute humidity outdoors expressed in g/m^3, during the experiment period.

5.4.4. Moisture excess

As expected, the highest estimated mean internal moisture excess was observed in bathrooms of the apartments without a humidifier and followed by kitchens, 1.3565 g/m^3 and 0.8963 g/m^3, respectively. For the apartments with humidifier, the highest mean internal moisture excess was observed in the small bedroom and followed by the bathroom, 5.4446 g/m^3 and 4.7710 g/m^3 however, higher measured values in the small bedroom were due to the positioning of the humidifier, which was placed in the corridor closer to the small bedroom considering Apartment #2B was the only apartment with a humidifier which had a small bedroom.

Bedroom

When it comes to internal moisture excess values from bedrooms, half of the highest hourly average values were observed during the night-time while the other half were observed during afternoon and evening hours (approximately 12:00 to 19:00). The reason why the peak moisture excess values were occurring could be due to kids taking a nap or/and usage of the bedroom as an office.

Kitchen

The mean estimated internal moisture excess from kitchens of the apartments without humidifier was 0.8963 g/m^3, and the maximum estimated moisture excess was 4.3303 g/m^3, while 90% of the estimated internal moisture excess values were below 1.8624 g/m^3. A Spearman's rank-order correlation was conducted to determine the relationship between the number of weekly cooking events and estimated average indoor moisture excess in the kitchen from each apartment regardless of owning a humidifier. There was a moderate positive correlation between the number of weekly cooking events and the estimated average indoor moisture excess in the kitchen from each apartment which was statistically significant (r_s[1763]= 0.415, $p < .001$). The indoor moisture excess from the kitchen was generally higher in the five apartments (#2, #7, #10, #11, #12, #20), which had more occupancy than others and claimed to do more dinner activities than the rest of the apartments. Even though Apartment #5 had closer values to these five apartments, according to the questionnaire data, fewer dinner activities were happening in Apartment #5. However, it assumed that the ventilation rate of the Apartment #5 was lower than the rest according to its smaller BRA.

Bathrooms

The mean internal moisture excess in bathrooms of apartments without humidifier was 1.3565 g/m^3, which was the highest internal moisture excess from all room types as expected, while 4.7710 g/m^3 for the apartments with a humidifier which was the second-highest internal moisture excess from all room types for apartments with a humidifier. In both cases, the maximum value has not passed beyond 9.3 g/m^3. While the median moisture excess values for seven of eleven apartments (#5, #7, #8, #10, #11, #12, #20) were on the scale of 0.8-2 g/m^3, the mean moisture excess in the bathroom of Apartment #3 was the lowest observed as 0.36 g/m^3.

It was assumed that the observed peak moisture excess values from bathrooms regardless of owning a humidifier were due to warmer temperatures together with higher RH levels which caused by showering events. While the lowest moisture excess values observed from Apartment #3 were due to its low temperature and low RH levels, which might be due to short-cold showering, keeping the bathroom door open most of the time since from the logged data, it was observed an air exchange after showers between corridor and bathroom. However, it was obvious that in most of the apartments, low median moisture excess values were observed. The observation of low median moisture excess values was possibly due to under pressurisation caused by higher ventilation extract rates compared to supply rates which takes out the moisture more than it supposed to, especially during the heating season. It must also be noted that

Apartment #1 and #2 measurements were performed during February (T_e < 0) while the measurement period for the rest measurement of the apartments was from 22nd of February – 22nd of April (T_e > 0).

Living rooms

The lowest mean indoor moisture excess observed was the bedrooms and followed by living rooms in apartments without humidifiers. The highest median internal moisture excess was observed in Apartment #2B and followed by Apartment #1. As shown in Figure 32, the negative load on moisture supply was observed in most of the monitored apartments. While Apartment #10 was noticeable compared to the other apartments with its negative loads on moisture supply. Furthermore, the highest internal moisture excess for the apartments without humidifier was observed in Apartment #12 as 1.57 g/m^3 and followed by Apartment #2A as 1.54 g/m^3.

The overheating and low RH values, higher ventilation extract rates compared to supply rates, and large BRA (90 m^2), which minimises the effect of moisture created due to cooking events to the living room environment, was presumed to be a cause for the negative load on moisture supplies in Apartment #10. While for Apartment #12, it was assumed that the overheating together with stable RH levels in the living room was the cause of higher internal moisture excess compared to the others. Furthermore, for Apartment #2A, stable indoor temperatures (approx. 24 °C) together with increasing RH levels due to occupancy and cooking events were presumed to be the cause for the highest internal moisture excess. Moreover, as might be expected, observed median internal moisture excess was higher in Apartment #2B when compared to Apartment #1 considering the monitoring periods for the apartments were in different seasons, and occupancy level in Apartment #2B was higher than Apartment #1.

Table 49. Mean, max and min values of indoor temperature, RH and internal moisture excess of the apartments without a humidifier

Room Types	***Parameters***	***N***	***Max***	***Min***	***Mean***	***SD***	***10th percentile***	***90th percentile***
Bathroom	RH [%]	19988	74.834	12.2766	21.5525	5.5523	15.6248	28.7121
	T [°C]	19988	38.9951	21.6864	25.4833	1.7580	23.2107	26.9041
	Δv [g/m^3]	1675	9.1322	-0.7973	1.3565	1.1169	0.2795	2.6012
Master Bedroom	RH [%]	20014	43.7466	12.0840	22.1259	5.7499	15.3797	31.8157
	T [°C]	20014	26.6457	16.8039	22.5247	1.8684	20.2448	26.0465
	Δv [g/m^3]	1674	2.8965	-0.8962	0.5936	0.6082	-0.1072	1.4212
Living Room	RH [%]	19838	36.6906	11.5884	20.8888	5.4840	14.3323	29.7989
	T [°C]	19838	28.6737	16.9915	23.7433	1.6050	21.8688	26.0530
	Δv [g/m^3]	1657	3.8917	-1.0590	0.6858	0.7400	-0.1129	1.7098
Kitchen	RH [%]	19080	43.5262	12.0329	21.5217	5.0695	15.4337	29.6608
	T [°C]	19080	29.0132	19.0928	23.9080	1.4580	22.2335	25.8995
	Δv [g/m^3]	1594	4.3303	-1.1912	0.8963	0.7366	0.0521	1.8624
Small Bedroom	RH [%]	17329	41.7743	12.0009	21.5530	5.6822	15.2739	29.6608
	T [°C]	17329	28.6737	20.4207	22.8545	1.2373	21.2021	24.0390
	Δv [g/m^3]	1450	2.8086	-1.0557	0.5278	0.5972	-0.1316	1.2499

Table 50. Mean, max and min values of indoor temperature, relative humidity and internal moisture excess of apartments with humidifier

Room Types	***Parameters***	***N***	***Max***	***Min***	***Mean***	***SD***	***10th percentile***	***90th percentile***
Bathroom	RH [%]	4324	65.2272	20.0890	33.0737	6.5198	25.2060	40.5488
	T [°C]	4324	34.4335	23.0755	26.2407	1.4857	24.4632	27.0131
	Δv [g/m^3]	361	9.2726	1.4598	4.7710	1.5750	2.6981	6.6714
Master Bedroom	RH [%]	4324	65.4798	23.2937	35.6966	8.3155	27.2706	49.1098
	T [°C]	4324	26.4700	18.8853	21.6454	1.2856	19.8355	23.1424
	Δv [g/m^3]	361	6.1302	0.9516	3.2627	1.2533	1.7286	5.1049
Living Room	RH [%]	4319	55.4640	19.3141	32.3769	5.8060	24.8324	40.2836
	T [°C]	4319	29.4356	17.9711	23.8707	1.3153	22.3219	24.8419
	Δv [g/m^3]	361	7.5989	0.8728	3.4940	1.3046	1.8423	5.2044
Kitchen	RH [%]	4323	58.6823	20.8724	33.1531	6.3993	25.2666	40.6463
	T [°C]	4323	27.7409	21.0970	23.5697	0.8775	22.4546	24.5445
	Δv [g/m^3]	361	6.4159	0.6141	3.5335	1.3925	1.7602	5.4875
Small Bedroom	RH [%]	2019	64.4669	24.4584	42.0024	10.0336	27.6486	55.0899
	T [°C]	2019	23.2508	22.1521	22.7875	0.2322	22.4391	23.0429
	Δv [g/m^3]	169	9.0012	1.6185	5.4446	2.1216	2.1527	7.9819

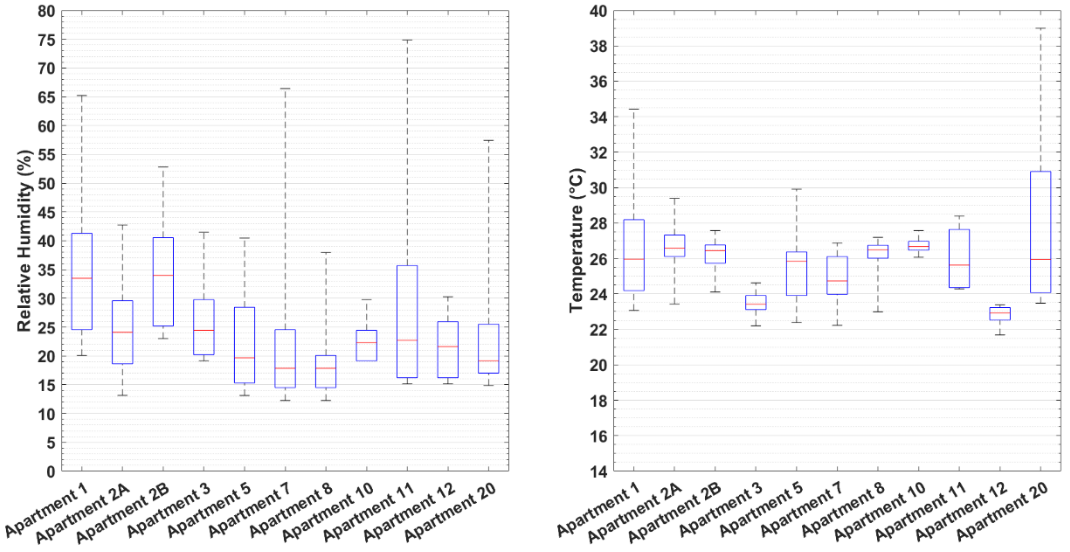


Figure 24. Measured RH and temperature values from bathroom of each tested apartment.

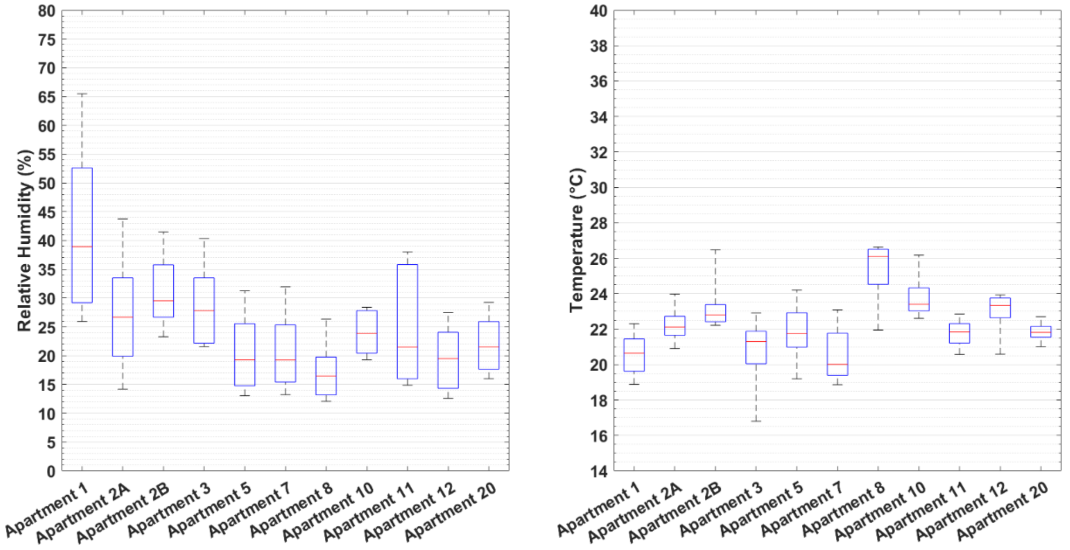


Figure 25. Measured RH and temperature values from master bedroom of each tested apartment.

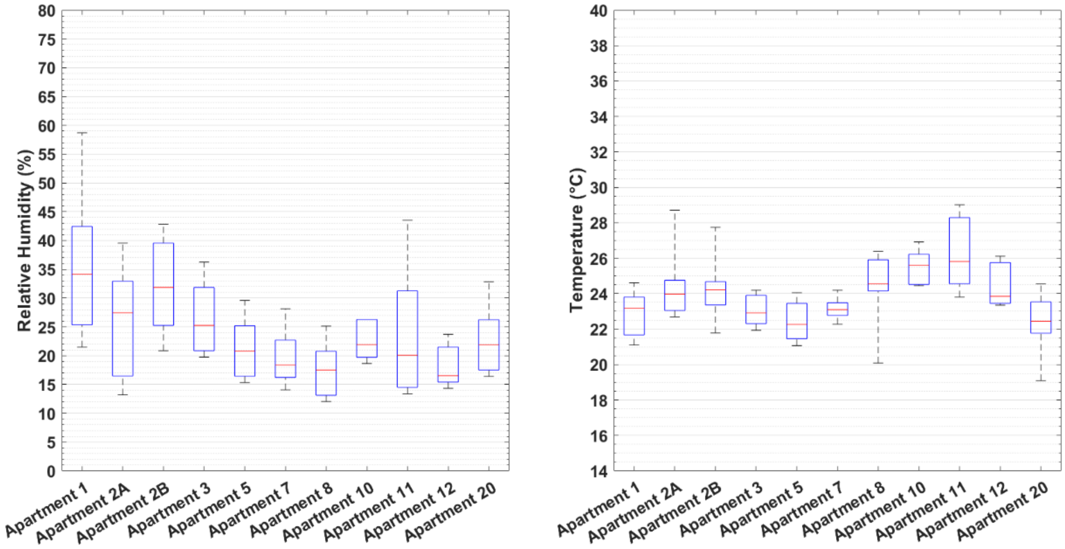


Figure 26. Measured RH and temperature values from kitchen of each tested apartment.

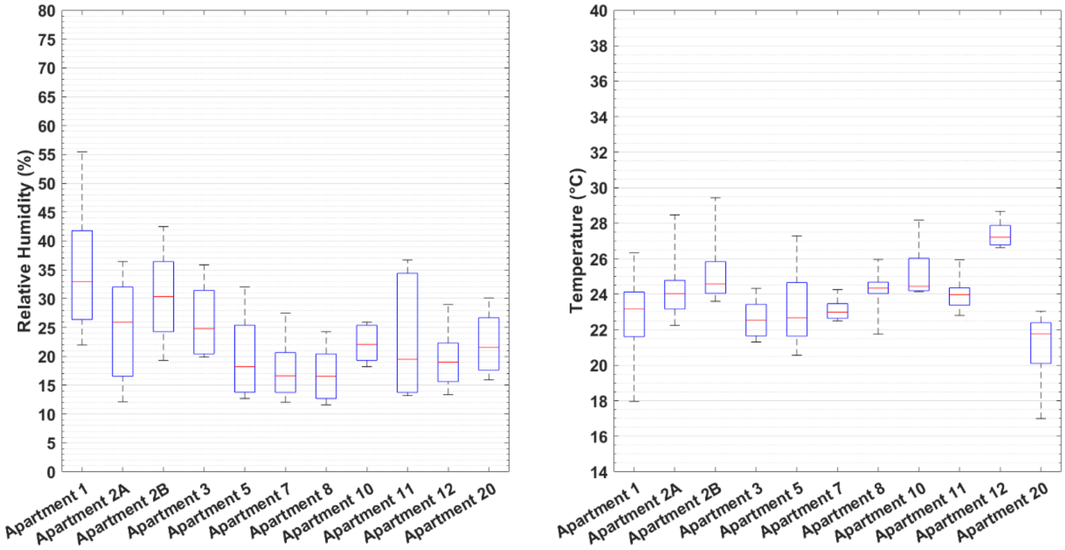


Figure 27. Measured RH and temperature values from living room of each tested apartment.

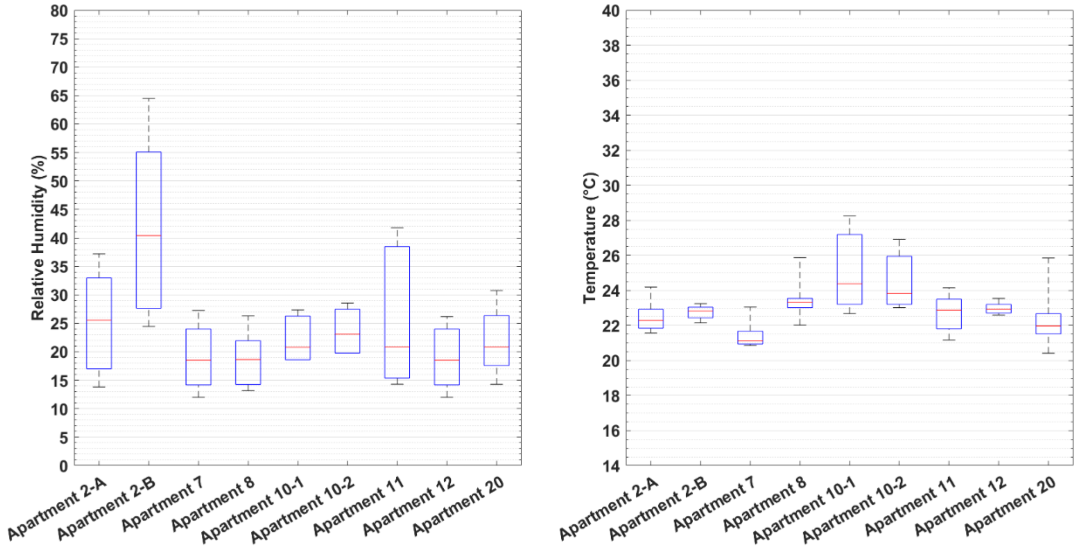


Figure 28. Measured RH and temperature values from the small bedroom of each tested apartment. (Apartment 10 had two small bedrooms and was therefore named as Apartment 10-1 and Apartment 10-2)

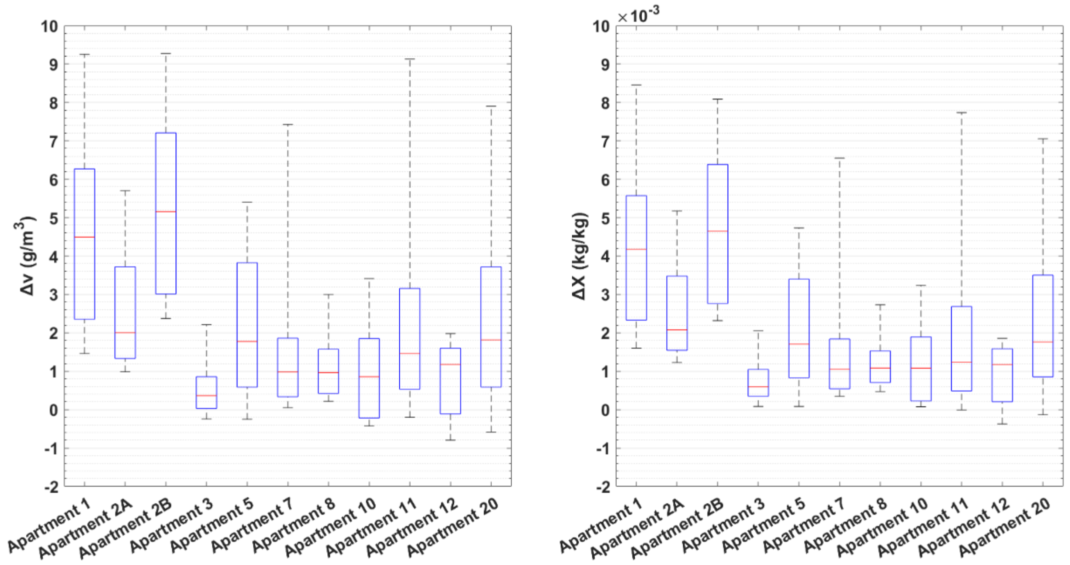


Figure 29. Moisture excess values in bathrooms of each tested apartment, on the left side, expressed in g/m^3 and on the right side expressed in kg/kg.

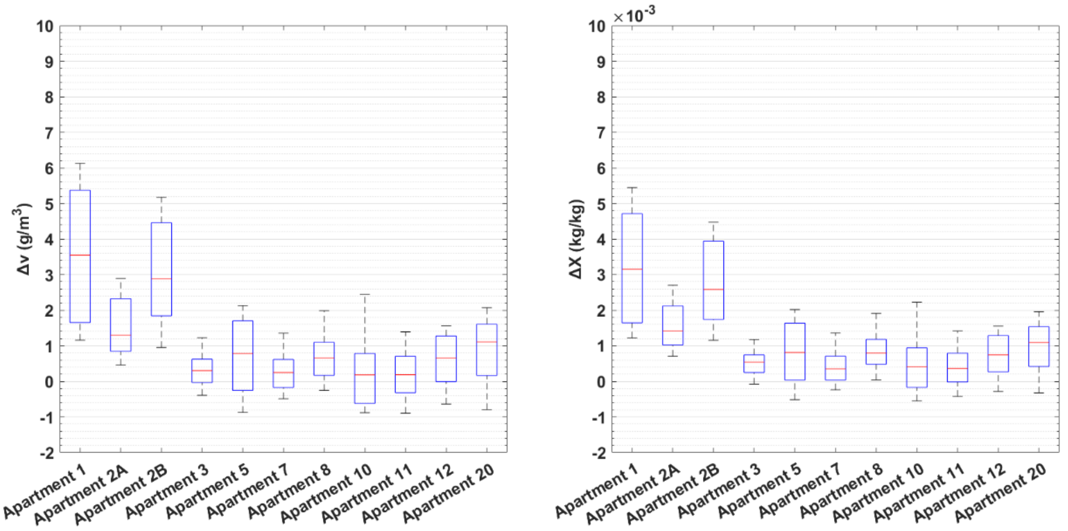


Figure 30. Moisture excess values in master bedrooms of each tested apartment, on the left side, expressed in g/m3 and on the right side expressed in kg/kg.

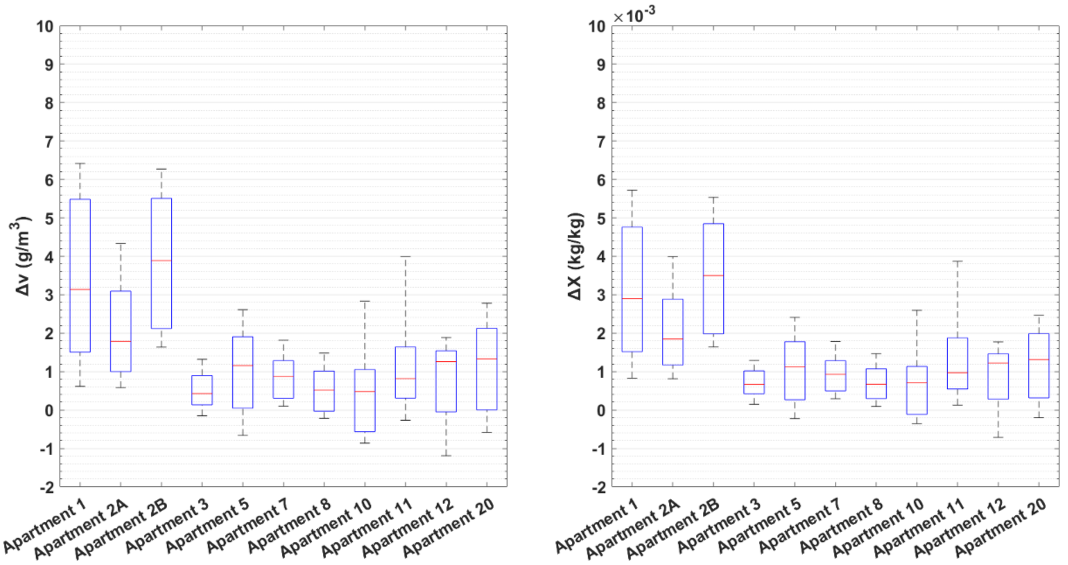


Figure 31. Moisture excess values in the kitchen of each tested apartment, on the left side, expressed in g/m3 and on the right side expressed in kg/kg.

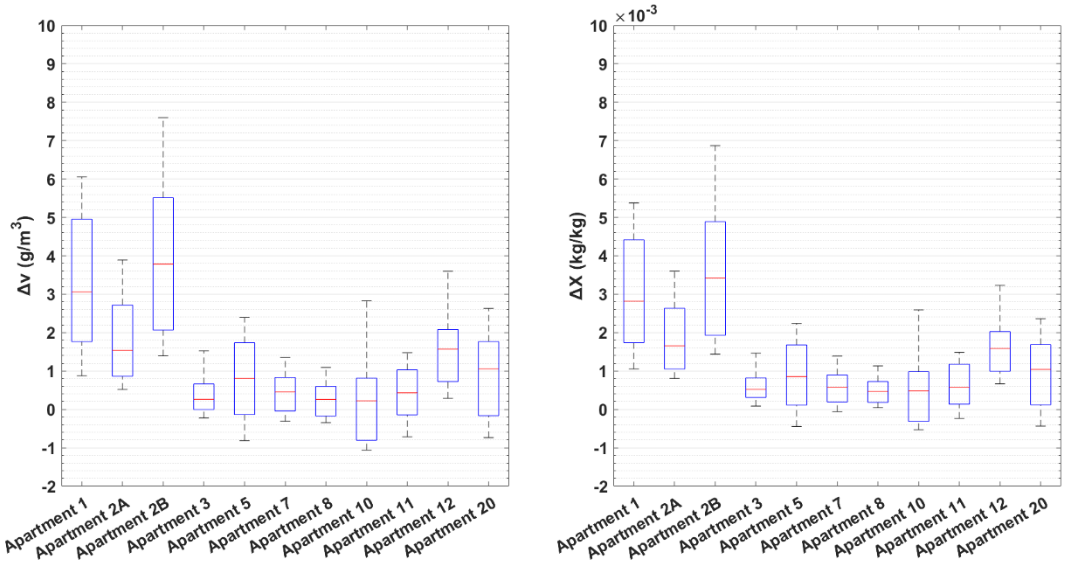


Figure 32. Moisture excess values in the living room of each tested apartment, on the left side, expressed in g/m3 and on the right side expressed in kg/kg.

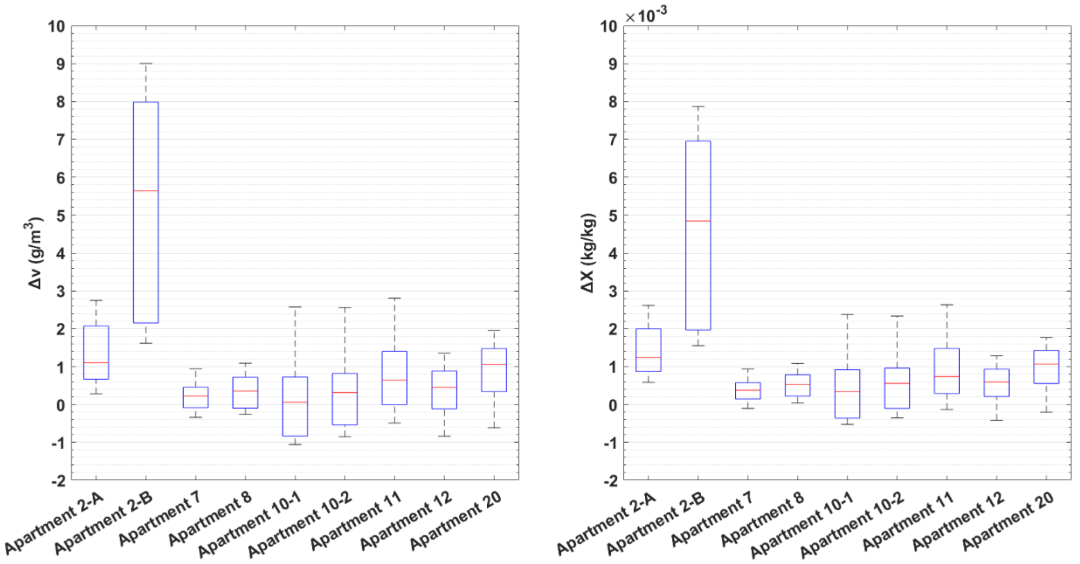


Figure 33. Moisture excess values in the small bedroom of each tested apartment, on the left side, expressed in g/m3 and on the right side expressed in kg/kg.

5.5. Moisture Production

The average moisture production rates from each apartment were estimated according to the procedure described in section 4.5. The expected moisture production from each house calculated according to the data from the questionnaire, which contained the occupants' behaviour from each apartment. It must be noted that as questionnaire answers from Apartment #3 were not received during the study period, the expected moisture production for Apartment

#3 was not calculated. The average estimated moisture production rates from each apartment listed in Table 52 together with expected moisture production from Koch et al. (1986) and Angell & Olson (1988). Moisture generation rates from different sources in order to calculate expected moisture production from each apartment were taken from the literature and are presented in Appendix C. In six of nine apartments without a humidifier, moisture production estimation was higher than expected moisture production given in literature by, e.g. Angell & Olson (1988), Koch et al. (1986). Considering the apartments with at least one humidifier, in Apartment #1, moisture production estimation was lower than expected moisture production given in the literature, while in Apartment #2B, moisture production estimation was higher. However, since there was no information regarding the usage pattern of humidifiers in the monitoring apartments, moisture production caused by humidifiers might have overestimated while calculation expected moisture production given in the literature. The average daily moisture production in tested apartments without humidifier was 9.37 kg/day/apartment (5 kg/person), while for apartments with humidifier was 35.22 kg/day/apartment (13.39 kg/person). In Table 51, the daily maximum and averages from daily averages moisture production values were compared in correlation to houses with different average moisture supply and different occupancy levels. It must be noted that the ventilation airflow rates differ according to the size of the apartment, as the same ventilation airflow rate was used in order to estimate daily average moisture production from each apartment, and this assumption might have been a cause of overestimated/underestimated daily average moisture production values. The reason why relatively low moisture production values were observed in Apartment #3 and Apartment #10 was their low moisture excess levels which might have occurred due to low occupancy, higher extract ventilation rates and/or more window opening events.

Table 51. Daily maximum (Max MP) and average from daily averages (Average MP) moisture production during the measurement period in the monitored apartments without a humidifier.

	Daily average moisture production (kg/day/house)			
	Average $\Delta v < 2$ g/m3		Average $\Delta v > 2$ g/m3	
	Average MP	Max MP	Average MP	Max MP
≤3 occupants	3.82	4.44	11.51	19.46
>3 occupants	-	-	9.56	9.64
All houses except the ones with humidifier	3.82	4.44	11.51	19.46

Table 52. Moisture production in the monitored apartments along with expected values from Angell & Olson (1988) and Koch et al. (1986)

Apartment Number	Moisture production [kg/day]	Expected moisture production from Koch et al. (1986) & Angell & Olson (1988) [kg/day]
1*	19.81	28.54
2A	19.46	8.15
2B*	50.64	32.07
3	3.20	-
5	10.5	1.81
7	6.27	2.48
8	6.69	5.05
10	4.44	3.94
11	9.64	15.16
12	9.47	13.63
20	14.63	7.84

* The measurements in Apartment 1 and Apartment 2B were conducted while both apartments were using at least one humidifier.

5.6. Indoor air quality

The CO_2 measurements have been categorised in accordance with NS 16798-2019 (Standard Norge, 2019). Outdoor CO_2 concentration was set to 416 ppm in accordance with (*CO2 i atmosfæren til nytt toppnivå – Klimavakten*, 2021). Table 53 shows the summarized CO_2 concentration of ten apartments and their rooms. After calculation, it became apparent that there were no apartments going over to CO_2 category 4 in accordance with NS 16798-2019; that’s why Table 53 does not contain a column for classification four. The CO_2 measuring equipment was placed in the living room/kitchen and the master bedroom. There were no CO_2 tests conducted for any other rooms. However, the measured rooms were the most used rooms, and thus, the rooms which were more likely to have higher CO_2 concentration. There was, in general, low CO_2 concentration in the tested rooms, which was consistent with the apartments extract air being high. The extract air was likely efficient in drawing polluted air such as CO_2 and moist air out of the apartments. On the other hand, the measured air supply was relatively low, probably causing an under pressure in the apartments in combination with the extract air of the bathroom in general.

The CO_2 levels of the living room & bathroom were in general better than the bedrooms. This was consistent with the living room and kitchen having an inlet and outlet on top of having a higher ventilation rate than the bedroom. Table 53 suggests that the bedrooms of the apartment #5, #12, and #20 had more than 80% of measured CO_2 values in classification 1, while all other bedrooms measured had 90% and above in classification 1. Table 55 shows that 10% of the households found the indoor air to be trapped and often bad, while 60% of the households felt that this was only the case sometimes. The remaining 30% had no issues with trapped and bad air.

Table 53. CO_2 concentration of rooms in each apartment. The CO_2 measurements are categorized according to NS 16798-2019, and the outdoor CO_2 concentration is set to 416.2 ppm.

Apartment	**Room**	**Class 1** Livingroom/kitchen: [CO_2] < outdoor conc. + 550[%]	**Class 1** Bedroom: [CO_2] < outdoor conc. + 380 [%]	**Class 2** Livingroom/kitchen: [CO_2] < outdoor conc. + 800 [%]	**Class 2** Bedroom: [CO_2] < outdoor conc. + 550 [%]	**Class 3** Livingroom/kitchen: [CO_2] < outdoor conc. + 1350 [%]	**Class 3** Bedroom: [CO_2] < outdoor conc. + 950 [%]
1	Bedroom	-	93.834	-	4.559	-	1.607
	Kitchen	96.876	-	2.907	-	0.217	-
2A	Bedroom	-	56.903	-	19.964	-	23.133
	Kitchen	97.561	-	1.655	-	0.784	-
2B	Bedroom	-	80.933	-	19.067	-	0
	Kitchen	100	-	0	-	0	-
3	Bedroom	-	100	-	0	-	0
	Kitchen	100	-	0	-	0	-
5	Bedroom	-	83.998	-	14.357	-	1.645
	Kitchen	100	-	0	-	0	-
7	Bedroom	-	97.286	-	2.327	-	0.388
	Kitchen	100	-	0	-	0	-
8	Bedroom	-	-	-	-	-	-
	Kitchen	100	-	0	-	0	
10	Bedroom	-	100	-	0	-	0
	Kitchen	100	-	0	-	0	-
11	Bedroom	-	100	-	0	-	0
	Kitchen	100	-	0	-	0	-
12	Bedroom	-	82.077	-	17.923	-	0
	Kitchen	100	-	0	-	0	-
20	Bedroom	-	80.987	-	19.013	-	0
	Kitchen	99.462	-	0.493	-	0.045	-

The apartment occupants had little but some issues with CO_2 related problems, such as dizziness, headaches, fatigue, difficulty concentrating. As seen in Table 54, answer “often” was only used one time for dizziness by Apartment #7. On the other hand, Apartment #2A and #2B answered sometimes on all accounts of CO_2 associated questions (both without humidification and with humidification). Apartment #12 and #13 had responded, sometimes on all questions except one. Apartment #1 had also answered sometimes on all but one question connected to CO_2. If the CO_2 levels were to be connected to the resident's survey answers, it would be more likely that it would be due to the CO_2 measurement of the bedrooms as this area had the higher concentration of it.

Apartment #7 had 97.286 % of the indoor CO_2 in class one in the bedroom and 100% in class one in the living room/kitchen, so that the survey was unlikely connected to the CO_2 level in the living room/kitchen or the bedroom of the apartment.

Apartment #2 had probably the worst experience out of the tested apartments, considering the survey. This was in line with also having the highest CO_2 concentration from field experiments out of all tested apartments when looking at the bedroom only. The bedroom of Apartment #2 had 56.903% in class one and 19.964% in class two, and 23.133% in class three, this means that class three of this apartment had 20% higher CO_2 concentration than any other apartment having CO_2 in class three, the bedroom of this apartment did not have the minimum fresh air intake given in TEK 17 requirement (Direktoratet for byggkvalitet (TEK 17), 2017). CO_2 levels dropped for apartment two during the second test with humidifier was probably due to the second test happened two months later, from April 16, 2021 to April 22, 2021. The air was a lot warmer during this period in Oslo and might have led to the balcony door opening to let fresh air in, which would, of course, lead to lower CO_2. Thus, the survey and the CO_2 level in the bedroom were most likely connected. The living room of Apartment #2 had, however, no issue regarding CO_2 levels.

Often was not used more than one time during the survey questions connected to CO_2. This was in line with the CO_2 levels being in class one for the most part. Furthermore, it was noticeable that the higher CO_2 levels of the bedroom could be partly due to the bedroom not having an outlet such as the living room has or that the inlet does not have a high enough ventilation rate. The apartment was, after all, underpressurized.

Studies have found that increasing temperature and RH decreases the perceived quality or acceptability of the air, which at times also happens concerning odours. Furthermore, the sensation of dryness with the decrease of humidity (Lind et al., 2019), and thus the results from the occupants of the field experiment, were in line with previous research. It could help to understand how so many participants could have symptoms that are associated with indoor air.

Although technically, the RH was not high in the living room and bedrooms, the temperature tended to be above the recommendations mentioned.

Table 54. Survey responses to CO_2 related problems

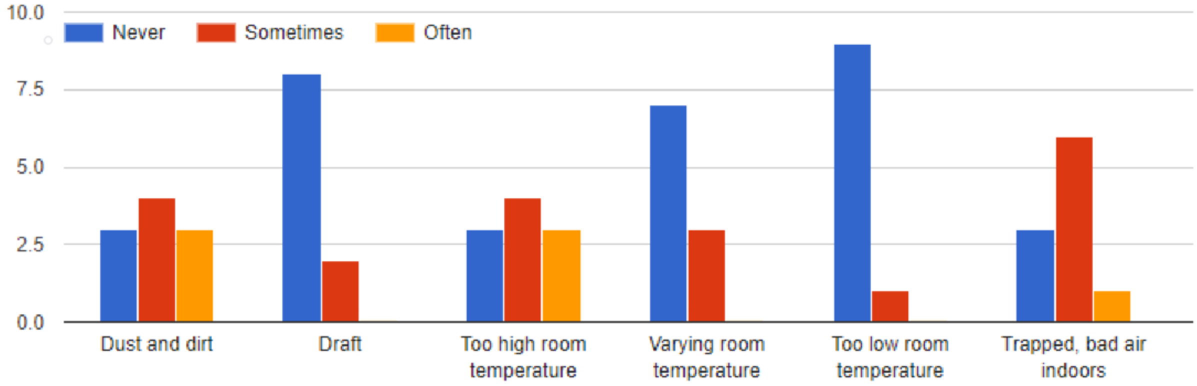
Apartment	Dizziness	Headache	Fatigue	Difficulty concentrating	Heavy in the head
11	Never	Never	Sometimes	Sometimes	Never
10	Never	Never	Never	Never	Sometimes
8	Never	Never	Never	Never	Never
12	Never	Sometimes	Sometimes	Sometimes	Sometimes
5	Never	Never	Sometimes	Sometimes	Sometimes
20	Sometimes	Sometimes	Never	Never	Never
2A	Sometimes	Sometimes	Sometimes	Sometimes	Sometimes
2B	Sometimes	Sometimes	Sometimes	Sometimes	Sometimes
1	Never	Sometimes	Sometimes	Sometimes	Sometimes
7	Often	Never	Never	Sometimes	Sometimes

The field experiment showed that the ventilation rates for the livingroom/kitchen was 25 m^3/h, the bathroom was 100 m^3/h (extract air), the master bedroom was 18 m^3/h, the small bedroom was 11 m^3/h. Notably, these numbers were not in line with the requirements of Direktoratet for byggkvalitet (TEK 17) (2017) seen in Table 11. This could explain the high CO_2 of the bedrooms since not enough fresh air was let into the bedroom. Furthermore, ventilation rates measured in monitoring apartments compared to Direktoratet for byggkvalitet (TEK 17) (2017) requirements discussed in the section 5.3.

Indoor thermal environment

From the field measurements, without considering the temperature of the bathrooms. The mean temperature was found to be above 22.53 °C in all instances without a humidifier, while it was 21.65 °C with the humidifier. As seen in Table 55, only 10% of the households felt that the air temperature sometimes was too low, and 90% of the households felt that the air temperature was never too low, which was in line with the temperatures of field measurement showed that the indoor temperature rarely being too low but rather often high. There was, however, more participants that felt the air temperature to be too warm where 30% of households expressed the air temperature to be too warm, and 40% expressed the air temperature to sometimes be too high and as NS-EN 16798-1:2019 requirement and Direktoratet for byggkvalitet (TEK 17) (2017) recommendation that indoor temperature should be kept below 22 °C as far as possible when there is a need for heating shows that the field measurement and survey to be connected. Altogether 70% of the households felt, therefore, that at times too high air temperature was an issue. When it comes to varying room temperature, as understood, the 10th and 90th percentile showed a temperature variation of about 6 °C. Sometimes 30% of the residents felt varying room temperatures. While 70% of the residents never felt any variations. The temperature variations were happening gradually, which could explain why the residents were not feeling them as variations but rather as high temperatures.

Table 55. Survey responses correlated with the thermal environment



All participant without a humidifier expressed in the survey that the indoor air was perceived as dry. All participants were expressing dry air was well in line with the relative humidity, showing a dry environment.

A lot of the participants had, at times, issues with hoarseness/dry throat. And when asked about an irritated, stuffy or runny nose, many of the participants frequently were answered often, making it the most likely issue the participants may encounter. Only Apartment #8 did not have any issues with any humidity related problem. All other apartments had encountered and answered as “yes” to at least some of the questions.

It has been deemed that the survey and the indoor RH (without humidifier) had common traits. Field measurements showed low RH, while symptoms associated with low RH were frequently experienced by most residents. They were indicating that it may be an issue for the residents of the apartments.

Table 56. Survey responses to humidity related problems

Apartment	Is the indoor air perceived as dry, humid?	Itchy burning/ irritation in the eyes	Irritated, stuffy, or runny nose	Hoarseness / dry throat	Dry or red skin on the face	Cough	Dandruff/itching of the scalp/ears	Dry, irritated/red skin on the hands
11	Dry	Never	Often	Sometimes	Sometimes	Never	Never	Sometimes
10	Dry	Never	Often	Sometimes	Never	Sometimes	Never	Sometimes
8	Dry	Never	Never	Never	Never	Never	Never	Never
12	Dry	Never	Never	Sometimes	Sometimes	Sometimes	Never	Sometimes
5	Dry	Sometimes	Never	Never	Never	Never	Sometimes	Sometimes
20	Dry	Sometimes	Often	Sometimes	Never	Sometimes	Sometimes	Often
2A	Dry	Sometimes	Often	Often	Never	Sometimes	Never	Never
2B	Humid	Never	Sometimes	Sometimes	Never	Never	Never	Never
1	Dry	Sometimes	Often	Sometimes	Often	Never	Never	Often
7	Humid	Often	Often	Often	Often	Often	Often	Never

5.7. Field result confirmation by WUFI®PLUS simulation

The result from WUFI®PLUS will be presented in four parts, as there were four scenarios for the simulations. The focus will be on relative humidity and operative temperature (resultant temperature). Both WUFI®PLUS and field measurement data for relative humidity and temperature have been implemented at one/h time step. The numerical model from field measurements should be as close as possible to the WUFI®PLUS simulations. All rooms were interconnected so that their values affect the relative humidity and temperature of other rooms.

5.7.1. Relative humidity and temperature comparison of scenario one

The WUFI®PLUS result of scenario one is seen in Figure 34 to Figure 38. The peaks of relative humidity from field experiments were reflected rather well compared to the peaks of the WUFI®PLUS simulation results. There were, however, some discrepancies to highlight. Firstly, the living room/ kitchen has some asymmetrical peaks in the living room, while the simulation of this room has more even peaks. This was partly due to the simulation having the exact same occupancy load during weekdays and another during weekends. This creates a more even graph in the WUFI®PLUS simulation showing the peaks to be gradually escalating or descaling. While the real-life scenario seen in the field experiment results were showing more asymmetrical peaks due to the room been used differently day by day. Activity indoors, as well as the amount of occupant in the room, might change depending on occupancy type and behaviour. The number of peaks was consistent with the peaks seen in the WUFI®PLUS simulation. However, the graph could have followed the field experiment more closely, but even if it did, the same graph would not have been feasible to recreate, considering different occupancy loads, weather etc. That’s why the authors wanted to replicate the maximal and minimal points of RH so that the field experiment would have been deemed feasible.

Living room/kitchen

The living room/kitchen seen in Figure 34 had a temperature in the WUFI®PLUS simulation of about 2°C lower than the field measurement and even lower from 14th to 16th of April. And the RH levels have the same max peak RH. The minimal values of RH were, however, slightly of with 2%. But more importantly, the curve shape of the simulation shows significant similarities to the field measurement and its timeframe.

The difference of 2 °C may be due to the room being on the south wall, which also was the sunniest side of the apartment; this was also the case in WUFI®PLUS. However, the room was also connected to a fair amount of cooking and was the most occupied space during the day. A small effect of the temperature deficiency might be that the simulation walls were made based on the minimum U-value requirements in TEK-17, the exterior wall assembly of the real monitored building might have been of lower U-value, which helps with heat loss (Direktoratet for byggkvalitet (TEK 17), 2017). The living room/kitchen was one of three rooms deviating from the average temperature in the field measurement than the sett temperature for the room, which was 22°C, considering this was the temperature the apartment occupants had set, it did not change. The assumption was that the deficiency in temperature was not brought forth by the apartment's thermostat. The biggest difference in the temperature results of field measurement and simulation was during 14th to 16th of April, further examination showed that the exterior temperature was the coldest during this period than any other day of measurement. This could have led to indoor heating, which could explain the high indoor temperatures.

Both the relative humidity and temperature graph from the simulation was seen as being related and comparable field measurement results.

Bathroom

The bathroom simulation had a generic setting WUFI®PLUS comes equipped with for the standard bathroom usage given for the size of the family living there. The simulation has the bathroom set to be more in use (shower) two times a day. This was reflected in the weeklong simulation with two peaks per day. The maximal and minimal values of the graph suggest that the simulation was comparable to the field measurement. The maximum was 4-5% off, while the minimum values were proximate for February 15, 2021 and February 22, 2021.

Considering the average temperature was higher in the field experiments compare to the simulation suggest that the temperature of the bathroom floor may have had a more significant impact than the 24°C agreed upon with the resident of the apartment. The bathroom was the only room with a higher set temperature than the other rooms. Bathrooms were set to 24°C as opposed to the other rooms at 22°C. Of course, the room has by far the highest extract air in the apartment, which has a part to play in both the temperature as well as the relative humidity. The two graphs have a minimal discrepancy due to different showering lengths and different showering times. The simulation could have a slightly smaller occupancy load for showering, which would result in even better similarities. And the showering load in 21st of February could have been halved to match the field measurement even better. However, the similarities between the simulation and the field measurement suggest the field measurement and the simulation having enough patterns in common to suggest that the result from the field measurement have been strengthened.

Master bedroom

The simulation graph of the master bedroom was correctly reflecting on the temperature set in WUFI®PLUS simulation. The RH levels were following the minimal values of the field measurement. And the highs of the RH graph were also following the curves except, smaller durations for some peak RH from February 15 to February 16 and February 20. Two adults and a child slept in this room.

This room was primarily used for sleeping and had, therefore, its peaks of RH during night-time when the room was occupied. The maximal values seen in Figure 36, such as the one seen on 20th of February, could be due to the entry door being less open or closed, which could explain the higher RH or that the balcony door was opened for a brief period and then closed again. The balcony door could have been opened other times as well. The temperature was following the 22 °C curves more closely on the Northside where no sun shines through the window. The values of relative humidity and temperature were well represented in both the field measurement and the simulation, providing reassurance through similarities of the results of field measurement.

Small bedroom

The usage of the small bedroom ranged between being an office or playroom. The relative humidity is affected by the latent heat source. Therefore, fewer people mean that the relative humidity being lower and vice versa. The maximal values of RH were off, while the lowest values of RH during measurement were similar. Therefore, more extensive usage of the room in the simulation could possibly have closed the difference of relative humidity on the maximal RH value, this would generate higher RH levels in WUFI®PLUS.

The relative humidity of this room was likely influenced by the relative humidity of the corridor, thus why the relative humidity graphs looking similar. Both of the rooms were of little use, but the small bedroom, on the other hand, does have an inlet, exchanging its air into the only connected room to it, namely the corridor. Its temperature and relative humidity graphs were confirming that the field experiment and WUFI®PLUS having similarities.

Corridor

The corridor had similarities with the small bedroom graph. This room had practically no occupancy, but the graph of RH was still showing considerable RH levels. The peaks of the field experiment showed RH of 39% while simulation showing 34%. The temperature of this room had both WUFI®PLUS and field measurement following each other closer after the 16th of February. The indoor temperature was higher in all rooms except the bathroom before 16th of February. After this date, the simulation and the field experiment followed each other's temperature more closely.

The corridor was the only room not containing either inlet or outlet as ventilation. Finding an occupancy load for the corridor was probably the most challenging out of all the apartment rooms. It connects all the rooms so that both relative humidity and temperature were exchanged between this room and the others. The corridor did not have any form for ventilation, which resulted in air moving from this room and into the bathroom, where the apartments extract air was the highest. Nevertheless, its maximum and minimum relative humidity and temperature were accepted as good similarities of the field measurement.

In general, the temperatures of all rooms except the bathroom were higher from February 15, 2021 to February 16, 2021. It could be because of higher temperatures or sunny skies. Resulting in more sun rays coming in through the windows.

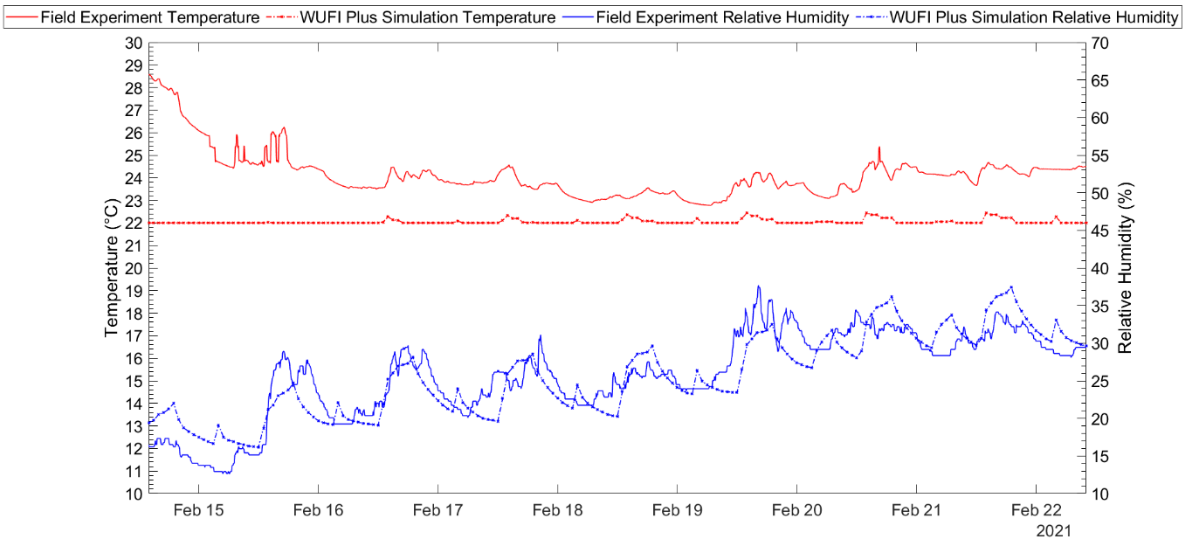


Figure 34. Relative humidity and temperature comparison for living room/ kitchen.

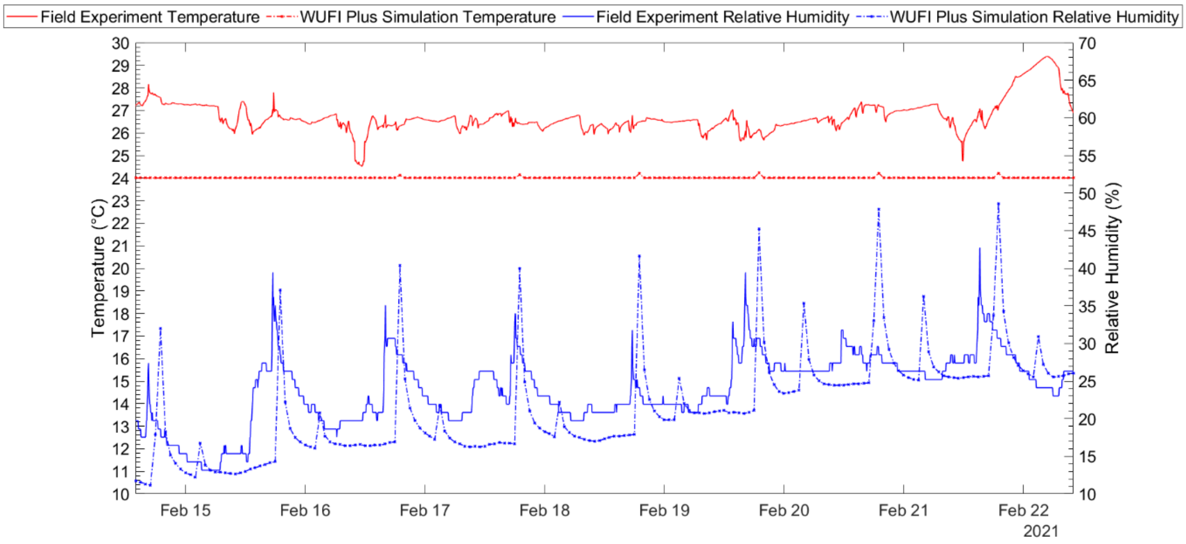


Figure 35. Relative humidity and temperature comparison for bathroom

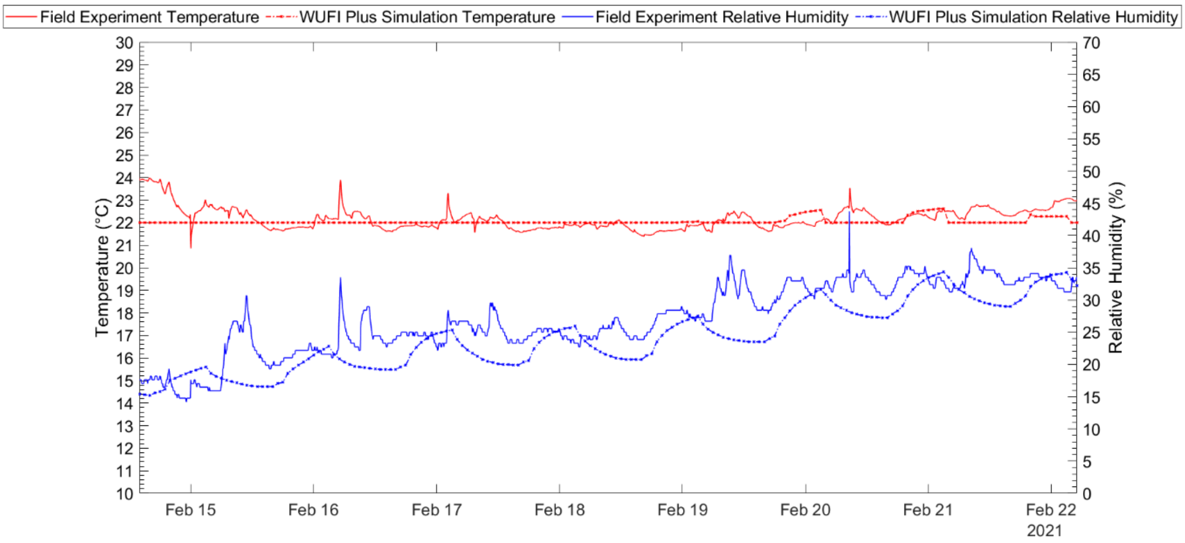


Figure 36. Relative humidity and temperature comparison for master bedroom

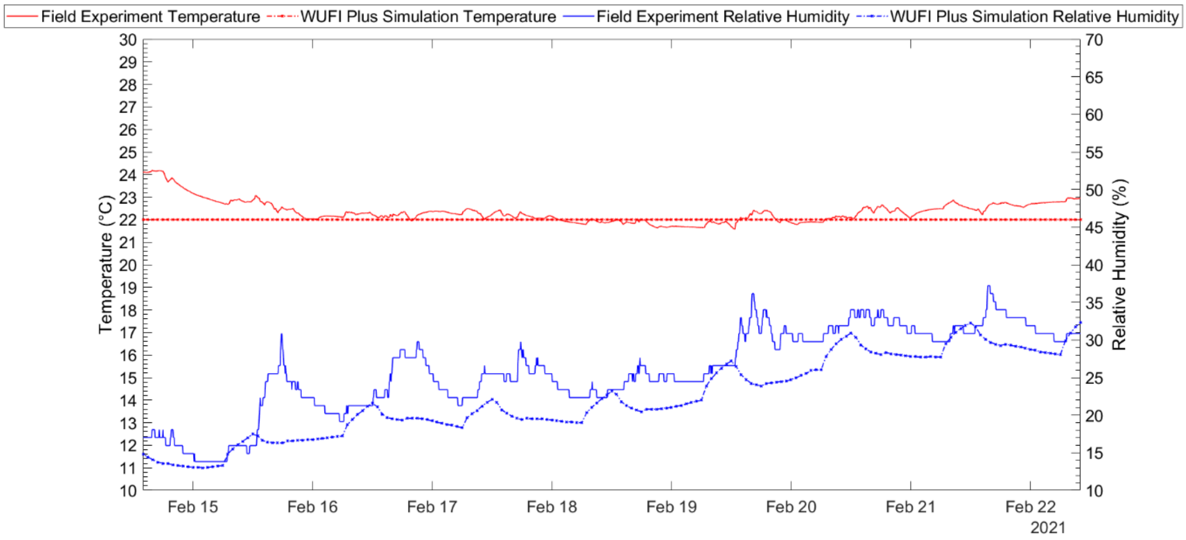


Figure 37. Relative humidity and temperature comparison for small bedroom

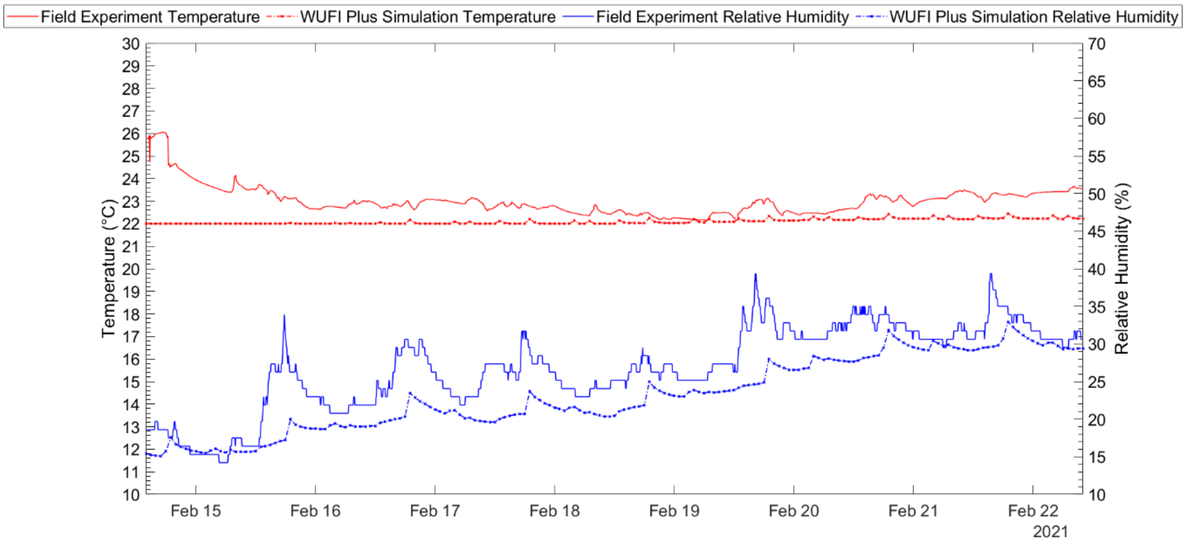


Figure 38. Relative humidity and temperature comparison for the corridor

5.7.2. Relative humidity and temperature comparison of scenario two with humidification

The scenario two simulation results of WUFI®PLUS shows the results with a humidifier. The field measurements of scenario two were also with a humidifier. The results from WUFI®PLUS will help to verify whether the use of a humidifier creates a better relative humidity indoors or not by having one more result from WUFI®PLUS, showing what the RH would be if there were no humidifier during this period. At times the humidifier in the field measurement went out of the water and might also have been turned off during the night, which makes it very hard to meet its fluctuations. The approach of meeting the maximum and minimum RH during the field measurement was therefore adopted.

The ideal relative humidity level should be between 30% and 50%. However, field measurement done with at least one humidifier, done from April 16, 2021 at 04:00 to April 22, 2021 at 19:00, showed the relative humidity in the whole apartment to be between 20% at the lowest and at 53% at the highest, with some maximal points higher than 50% is also visible in the field experiment graphs. The results without a humidifier were added to the same graph as with the humidifier to highlight the difference. This highlighted how the results changed with a humidifier compared to not using a humidifier. All results were for the same period as the field experiment done from April 16, 2021 to April 22, 2021. The authors did not try the emulate the exact RH graph from the field experiment in the WUFI®PLUS simulation. Mainly because the field measurement data would not have been possible to replicate again even if the graph of WUFI®PLUS would have been identical. Indoor RH levels change with temperature, occupancy load and their activity, cooking load, showering and more. That’s why the WUFI®PLUS simulation with a humidifier was used to replicate the maximal and minimal points of the different rooms. The corridor was the only room controlled with a humidifier and a minimum RH setting of 40% in WUFI®PLUS (identical to the field measurement). The other rooms were only interconnected and affected by the humidifier through the corridors minimal RH control.

How the humidifiers sensor works is different in WUFI®PLUS than in the field experiment. Due to the humidity sensor in WUFI®PLUS pretty much working instantly in the way that it distributes the humidity to the whole room. While the humidifier in the field experiment was set to a single point, adding humidity not too far from where it measures RH creates more fluctuation in regard to RH than in WUFI®PLUS

Living room/kitchen

Firstly. According to WUFI®PLUS, Figure 39, the living room/kitchen showed relative humidity between 20% and 30% without using a humidifier. On the other hand, the field measurement result showed 25% to 44%. The WUFI®PLUS simulation with humidifier shows the same maximum and minimum RH trends when looking at the field measurements maximal and minimal values.

The WUFI®PLUS simulation shows some differences compared to the field measurement because of the occupancy load and the duration of the loads being different for the weekdays and weekends. The field measurements, however, changes sporadically as well as hardly being the same. The big changes could be due to the humidifier being out of water or off, as well as occupancy and cooking loads varying.

Bathroom

As Figure 40 shows, the bathroom would have an RH of 15% to 45% without humidification under the same time frame. In comparison, the field measurement with a humidifier has shown results between 25% - 40% for the most part, together with some minor peaks going up to 53% RH. The WUFI®PLUS simulation has shown the same peaks occurring, thus suggesting that it was possible to gain the same minimal and maximal values during the same time period.

The simulation without a humidifier shows the RH levels to be between 15% - 20% over longer durations every day from April 16, 2021 to April 22, 2021 when there was no showering, in contrast, when the showering starts, it goes up to 45 %. The results show that relative humidity in the bathroom was higher with a humidifier. Such as the theory section implies. The field experiments and simulation with humidifier showed the same promising effects as the RH levels were elevated to improve indoor RH levels outside of the showering period. The simulation has shown proximity when comparing the minimal and maximal points of the field experiment and therefore acknowledged to be emulating the same trend.

Master bedroom

Figure 41 shows the simulation RH levels of the master bedroom to be 17% - 30% without humidification. However, the field measurements showed values of 25% - 45 %. At the same time, the simulation with a humidifier showed minimal and maximal values of RH 25% - 45%.

The field measurement tends to show that the RH levels were higher with the humidifier. This has been confirmed with the simulation, which shows the same maximal points occurring around the same time. Relative humidity of 25% to 43% was showing that a better RH could be accomplished with the humidifier. However, RH fluctuates with a higher amplitude when the humidifier is on. An ideal scenario would be if these fluctuations had a lower magnitude and been more stable. The simulation results with humidifier have been accepted as showing the result of field Measurement to be plausible. Considering that both the field experiment and the simulation with humidifier shows the same maximal and minimal values.

Small bedroom

Figure 42 shows the simulation RH levels of the small bedroom to be 15% - 30% without humidification. The field measurements showed values of 25% - 55 %, with some minor spikes up to 65%. The simulation with a humidifier also showed an RH of 25%-67%, it was slightly higher than field results. The variation of RH in the small bedroom was more extensive than in any other room of the apartment. And the maximum RH were considerably higher than the maximum RH simulation without humidification would suggest, which confirms the relative humidity of this room, undergoing the most significant change of RH.

The RH levels of the bedroom without humidification were as low as 15%, which was not sufficient. The reason that the field measurement with humidifier was showing lower values of 25% RH and peaks with RH as high as 60% was probably due to the sensor in the small bedroom being close to the humidifier in the corridor. This shows that a more even distribution of humidity in the corridor was of importance. This room has higher peaks of RH than the corridor where the humidifier was placed. This could be due to the small bedroom being in use as an office/playroom, in contrast to the corridor, which was being used to move through the different zones of the apartment. Since the humidifier in both field measurement and simulation has shown that a humidifier creates better average values of RH, a recommendation for the use of a humidifier with a more stable humidity distribution is preferable. Field measurement has been verified to be correct since the maximum and minimum values of RH were present in the simulation as well.

Corridor

The corridor with the results seen in Figure 43 had the placement of the humidifier, both in the field experiment and the WUFI®PLUS simulation with a humidifier. From there, it distributed humidity to other rooms of the apartment. RH without any humidification was found to be between 18% - 26%. Field measurement of the apartment showed the relative RH to be 25% - 50%. The RH from the WUFI®PLUS simulation with humidifier showed values from 40% to 50%.

WUFI®PLUS had a minimum humidity control of 40% RH only added to this room. This resulted in the WUFI®PLUS simulation with a humidifier to ensure that the RH keeps above 40%. This was not the case in the field measurement as the relative humidity fluctuated from 30% - 50%. It was assumed that this fluctuation was partly due to the sensor of the humidifier not being as good as the sensor of WUFI®PLUS. WUFI®PLUS has its humidifier added to the whole zone rather than a single point as the field experiment. The sensor of the humidifier in the field experiment would most likely control the RH easier if the humidity were distributed more evenly throughout the room. Another reason could be that the humidifier was at times off or empty for water. This room has lower maximal RH in the field measurement compared to the small bedroom. Even though the humidifier was located in the corridor. It was most likely to do with the corridor being less in use than any other room of the apartment. The maximal RH peaks have been confirmed by the simulation with a humidifier. However, the minimal RH for the reasons mentioned were not.

Results from WUFI®PLUS clearly showed that the indoor relative humidity for all rooms, not being at the ideal level without the use of a humidifier.

The WUFI®PLUS simulation confirms that a higher relative humidity was accomplished in all rooms by using a humidifier in the corridor only, set to 40% minimal relative humidity. The whole apartment showed a higher relative humidity average level during the simulation of the field experiment when a humidifier was utilised. However, bigger fluctuations of RH were present in all rooms when using a humidifier, except for the bathroom due to the highest extract of air at 100m^3/h and because of the presence of high RH fluctuation, which already was present due to showering. Preferably keeping the RH level balanced would be better. This could be accomplished with a better humidifier system that works with the HVAC system, supplying a more even distribution of humidity to all rooms instead of a single point as the corridor.

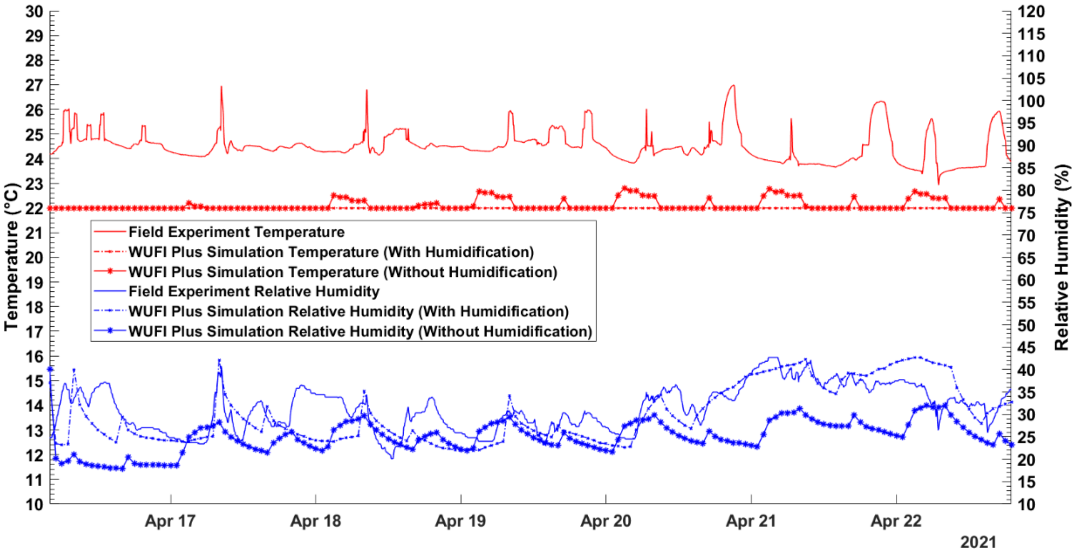


Figure 39. Relative humidity and temperature in living room/kitchen for the period of with humidification comparison

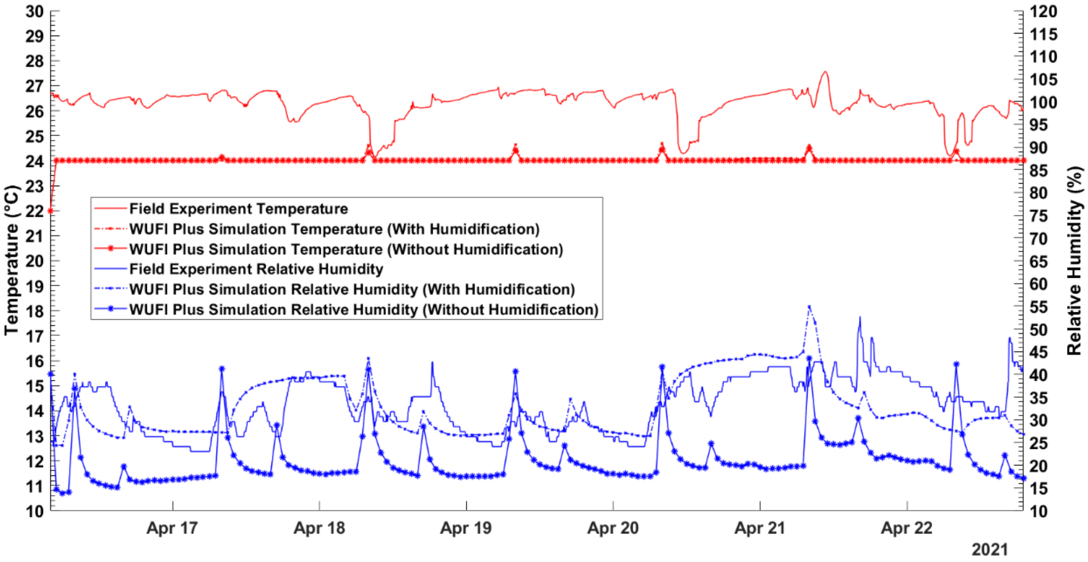


Figure 40. Relative humidity and temperature in bathroom for the period of with humidification comparison

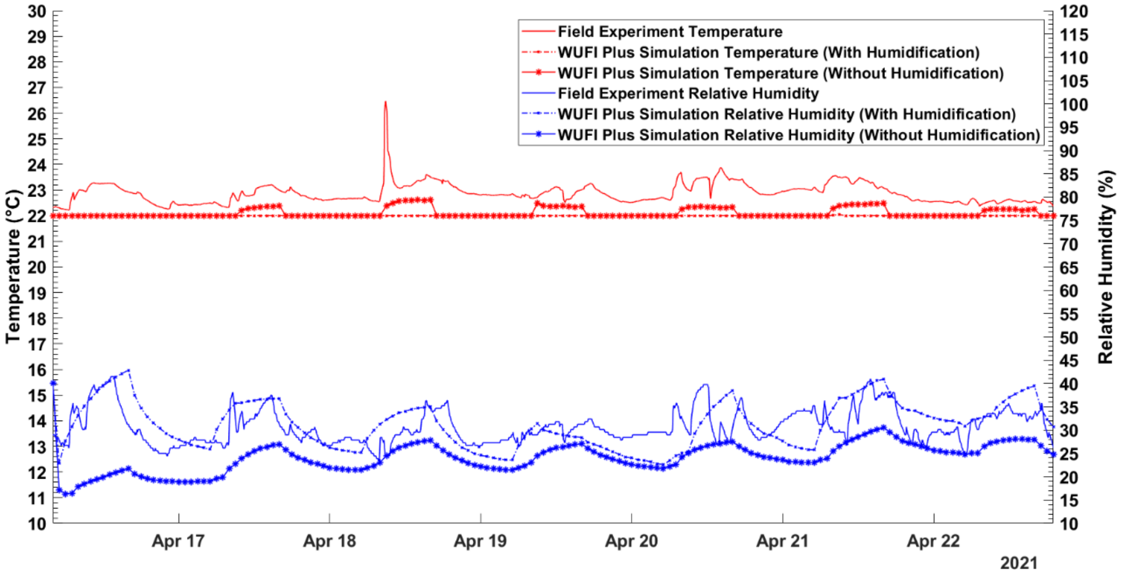


Figure 41. Relative humidity and temperature in master bedroom for the period of with humidification comparison

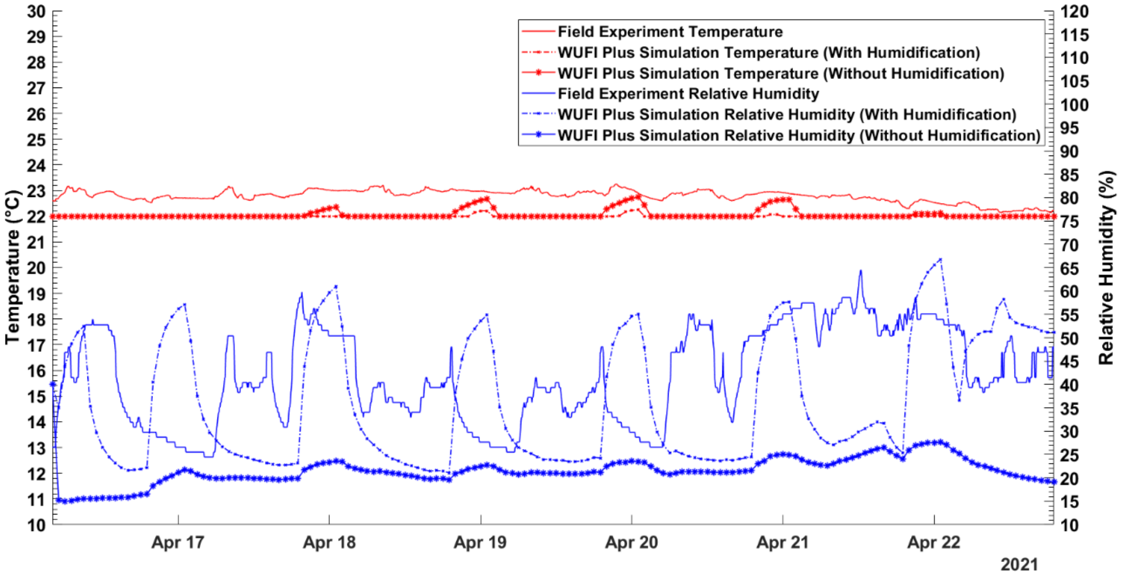


Figure 42. Relative humidity and temperature in small bedroom for the period of with humidification comparison

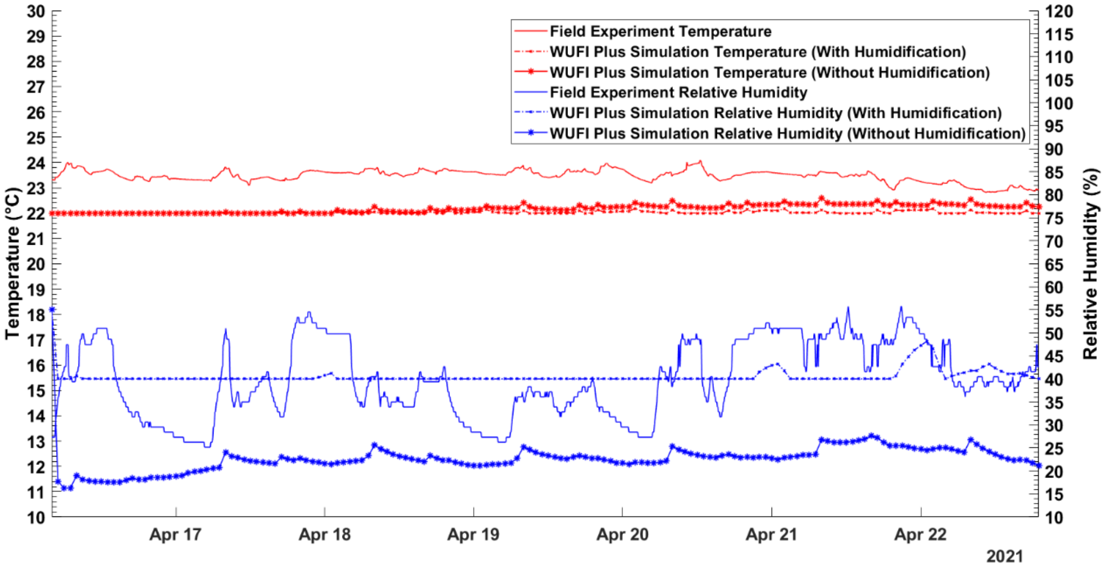


Figure 43. Relative humidity and temperature in corridor for the period of with humidification comparison

5.7.3. Scenario three whole year calculation with and without humidifier

Scenario three was done to find the comparison of an entire year, with and without a humidifier. The humidifier's location was in the corridor.

Living room/kitchen

Without humidifier

The results in Figure 44 from the living room show that the RH levels were too low during the wintertime. The living room was infrequent use. Having acceptable RH levels in this room was therefore essential.

The ideal RH level was between 30% and 50%, and The living room has RH levels lower than 30% for significant parts of the year and as low as 15% during the winter season and summer values of RH were showing numbers as high as 60%. The Temperature without a humidifier went as high as 27 °C while the temperature with a humidifier never went above 24 °C.

With humidifier

The RH levels were at higher average during wintertime when the humidifier was added to the simulation, the RH levels in the summertime had peaks of RH up to 20% higher with a humidifier where RH was as high as 85%.

The graphs suggest that the average relative humidity level was higher when the humidifier was active from December to the end of April. There was no need for a humidifier from the start of May to the end of November, as this duration already has RH above 50%. RH was nevertheless changed more during the day when the humidifier was added. By not using a humidifier the RH values were found to range from 15% to 35% during January and February. Up to 60% during June and July. The reason for the operative temperature being lower with the humidifier might be due to the cooling effect of moisture. Of course, sweating can be a problem with too much moisture, which can cause the opposite effect, making it feel warmer. But it seems that it was not an issue here as the temperatures were close to 22 °C.

Bathroom

Without humidifier

As seen in Figure 45, the bathroom had RH values from aproximately10% to 55% during significant periods of the winter months. The summer period, however, showed the RH levels to be as high as 70% to 80% RH

With humidifier

The bathroom with humidifier had RH values from 20% to 60% during periods of the winter months. The summer period showed the RH levels to be up to 90%, with highest value were observed in August.

The bathroom had already high amplitudes of RH due to showering. It did also have low values of RH during its winter months. The use of humidification was created a lower amplitude of RH in the days of the wintertime. Probably due to showering where the spikes already were gone high up. When humidification was added to the bathroom, the lower values of RH were removed. This made the difference when showering in the wintertime. The amplitudes of the showering event became smaller because the RH started at a higher level before the showering event started. The upper levels of RH were nevertheless kept at the same level with and without humidification during the wintertime which results in humidification only being advisable in the wintertime period.

Master bedroom

Without humidifier

As seen in Figure 46, the scale of observed RH during December to the start of May spans was about 18% to 42%. While the peak RH observed in August when it only went approximately

65 % RH. The temperature was between 22 °C and 24 °C, except for the summer period, where higher temperatures of about 27 °C occurred during the day.

With humidifier

RH during the period of December and the start of May was observed as approximately 15% to 55%. However, the highest RH values were observed in the summer period were about 80%, with a small amount of higher temperatures compared to without humidification during all non-winter months.

The RH levels observed in master bedroom was significantly low as 15%, especially in the January and February months. Humidification during December to end of April could potentially create a better indoor RH environment. Temperatures were also marginally higher on average during the summer months when a humidifier was in use. No humidifier was, however, found to be necessary for the summer months.

Small bedroom

Without humidifier

Figure 47 shows the RH and temperature comparison of both with and without humidification for the period of 01.01.2021 - 01.01.2022. Similarities were found in the results between this room and the master bedroom. RH levels during December to the start of May were observed as approximately 13% to 40%. While the highest RH was observed in August as approximately 63%. The temperature was between 22 °C and 24 °C, except for June and July, where higher temperatures of about 26 °C occurred during the day.

With humidifier

The RH levels for the humidification were observed as in the scale of 15% to 75% during the period of December to the start of May. The summer months had significant RH values maxing at 90% during the summer months also in September. Larger temperature variations compared to without a humidifier were also present.

The small bedroom was the room that was the most affected by the RH variations in scenario two. The summer months clearly indicate that there was no need for a humidifier. The maximum RH values were higher in the small bedroom even though the humidifiers’ location was in the corridor. This could be due to the small bedroom being more occupied compared to the corridor. The difference from day-to-day RH was quite higher when the humidifier was active.

Corridor

Without humidifier

As seen in Figure 48, the corridor had a very similar fluctuations as the small bedroom since both the sensors of these rooms were closer to the humidifier. RH was at the scale of 15% to 35% in January to the end of March before RH went higher, having its peak approximately 65% during the August. The operative temperature was staying under 24 °C, only going higher in the summer months of June and July at around 26 °C while it was going lower after middle of August.

With humidifier

The corridor had the lowest RH value at 40%, which also was set as minimum RH value in the simulation. The highest peak RH at approximately 85%, was during the summer months. The values observed in Figure 48, shows that the minimum RH control settings worked.

The minimum RH control was assigned to this room (with a humidifier). This was apparent when looking at the minimum RH as 40%. The temperature operative temperatures were below 24 °C except for the summer months, when it was observed between 23 – 25 °C.

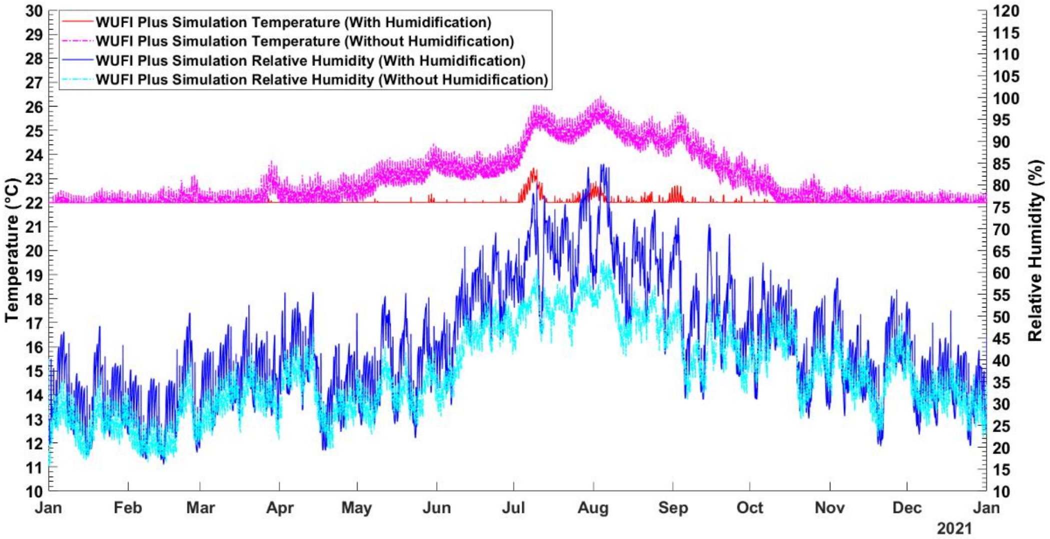


Figure 44. Whole year comparison with and without humidification of living room/kitchen

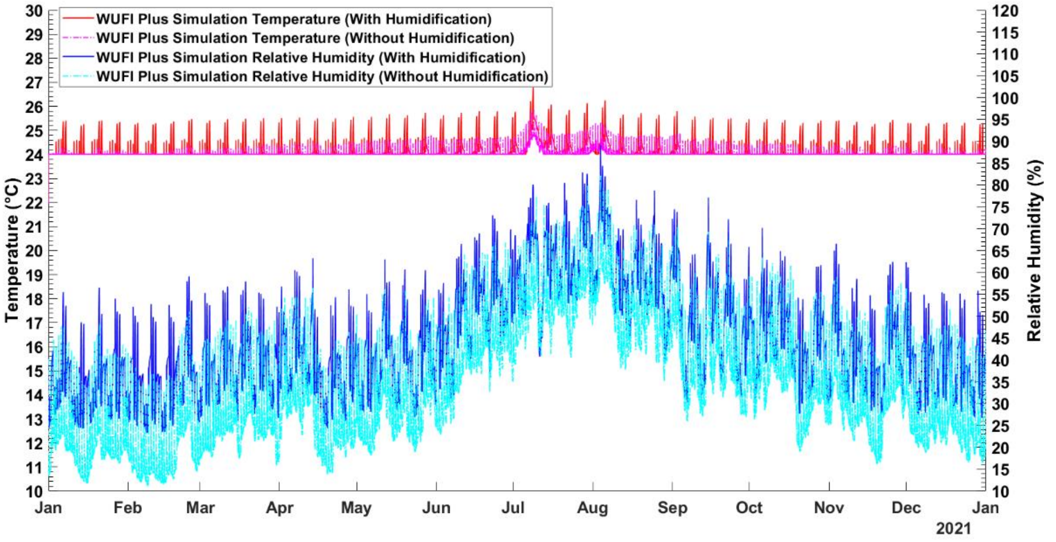


Figure 45. Whole year comparison with and without humidification of bathroom

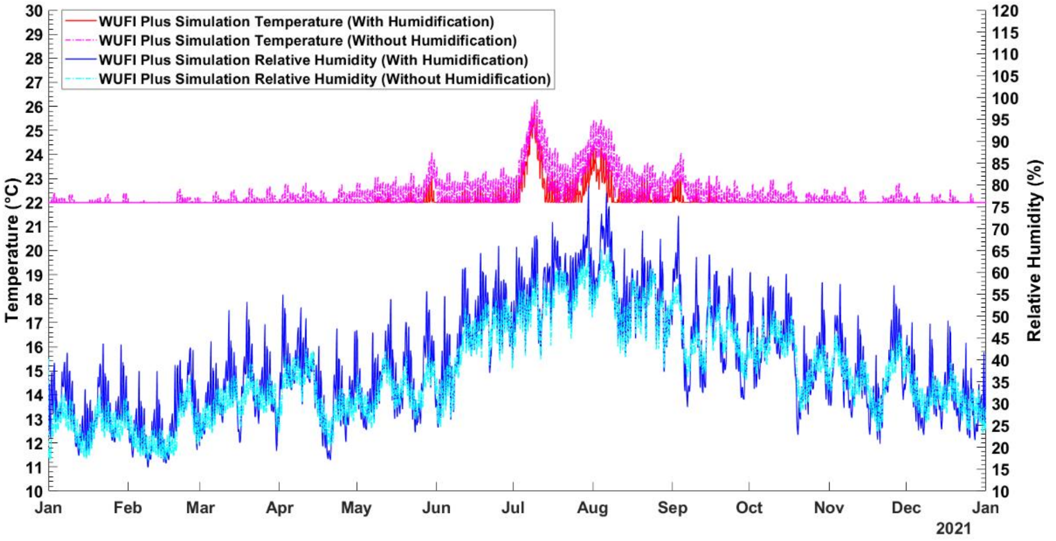


Figure 46. Whole year comparison with and without humidification of master bedroom

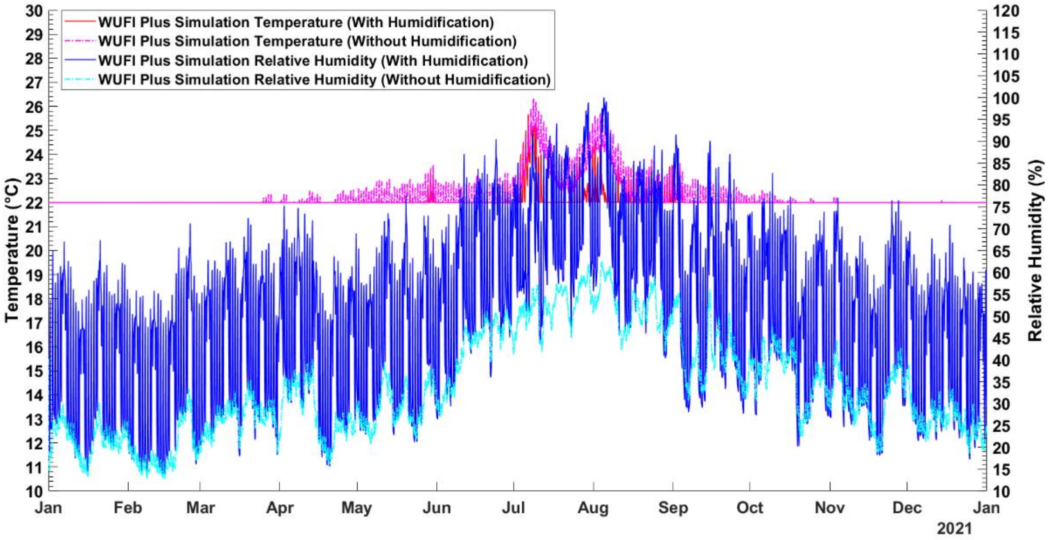


Figure 47. Whole year comparison with and without humidification of small bedroom

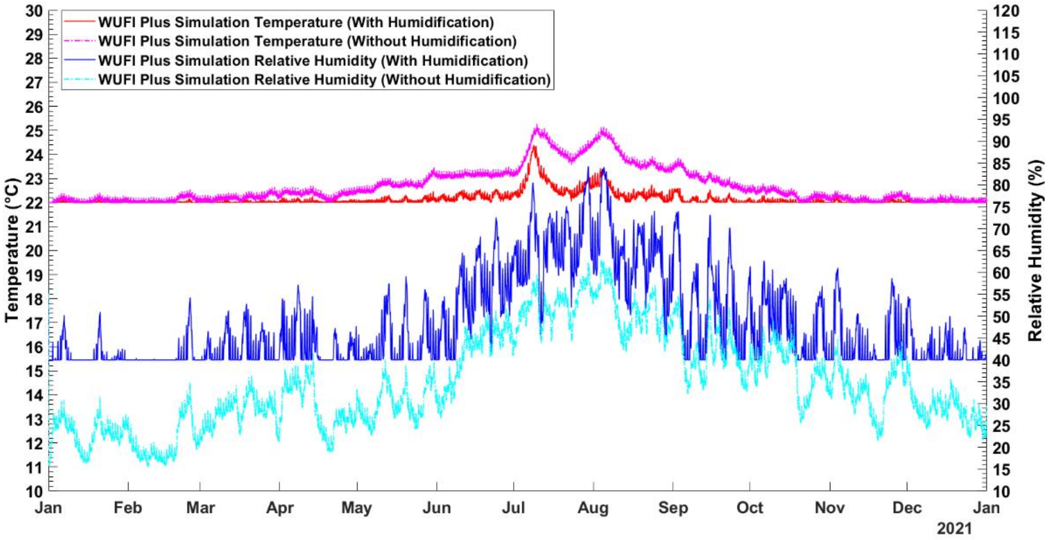


Figure 48. Whole year comparison with and without humidification of corridor

6. Conclusion

The indoor climate conditions and indoor air quality in 11 apartments from modern Norwegian residential buildings were evaluated according to following parameters; outdoor air supply/extract, temperature, RH, CO_2 concentration, indoor moisture excess, and moisture production. The study showed that measured ventilation rates were either lower or higher than what Norwegian building regulations (Direktoratet for byggkvalitet (TEK 17), 2017) require. Generally, all mean internal moisture supply values were lower compared to the other studies in literature (Bagge et al., 2014; Geving et al., 2008; Geving & Holme, 2012; Ilomets et al., 2017; Kalamees et al., 2006). In general, high ventilation extract rates, low air supply together with low outdoor absolute humidity were presumed as the causes for why most of the apartments exposed to lower indoor moisture supply.

Moisture supply depends on the type of room; bathroom and kitchen had the highest values and followed by living rooms. Even though the highest mean moisture supply measured in bathrooms, it was still significantly low compared to other studies, as mentioned above. Differences in moisture supply in modern Norwegian occupied residential buildings cannot be explained with only one particular parameter relating to occupant behaviour: Ventilation behaviours, social status, age, occupancy levels, cooking activities, showering events or indoor drying of clothes. However, the study showed that there was significant correlation between cooking events vs both RH and internal moisture excess values from kitchen. Therefore, it was assumed that higher numbers of internal moisture excess in kitchen and living rooms (due to the open kitchen design) were due to cooking events and occupancy levels.

The measurement period of indoor RH and temperature is also significant for evaluating moisture conditions. It was observed that except for Apartment #1 and #2, outdoor absolute humidity levels were low while the monitoring most of the apartments which causes low moisture levels indoors when it is combined with high indoor temperatures.

Moreover, indoor temperature measurements are crucial when evaluating indoor climate, as it was observed very often higher than 20 °C, which normally assumed for simulating moisture conditions.

The estimated moisture production in most of the apartments was considerably higher than expected values from literature, however, the measured RH in the monitored apartments was generally not high. It was suggested that in order to achieve reliable moisture production rates, correctly measured ventilation rates and detailed information on moisture sources from each monitoring apartment were crucial. It must be noted that in this study concluded moisture production rates were estimated according to the ventilation rates measured in only one sample apartment.

According to the data of questionnaires, most of the participants claimed that perceived air was dry. Considerable amount of participants, claimed to have symptoms that correlated with low RH and high indoor temperatures by many studies in the literature (Reinikainen & Jaakkola, 2003; Sato et al., 2003; Wolkoff & Kjærgaard, 2007). Moreover, 70% of the participants claimed that indoor temperatures were too high, while 60% of the participants claimed the feeling of bad, trapped air indoors which also observed from field measurement data compared to ISO 17772-1:2017 and TEK 17 (Direktoratet for byggkvalitet (TEK 17), 2017; International Organization for Standardization, 2017). Additionally, monitored CO_2 concentration from apartments were generally low and in Category 1 according to NS 16798-2019 which higher ventilation extract rates was presumed to be a cause (Standard Norge, 2019).

Furthermore, it was found that occupancy levels and patterns, ventilation rate, age status, showering events and loads had a significant impact on the WUFI®PLUS simulations. And when it comes to the humidifier being turned on and off on top of going empty for water, it made the RH change more dramatically in the humidifier scenario. Humidification should be kept for the winter month in general, although it could potentially be used in early spring or late fall. The WUFI®PLUS simulations were able to replicate the maximum and minimum relative humidity of the field measurements to verify the possibility of achieving the relative humidity values mentioned. The relative humidity of simulation in WUFI®PLUS showed that it was for the most part low which is in line with the field measurements as well as occupants mentioning that they perceive the air as dry. The simulations also showed the room temperatures to be higher than the set temperature which is not only in line with the field experiments but also in line with occupant questionaries.

7. Future recommendations

The research conducted in this thesis has led to some valuable outcomes and conclusions on identifying of the indoor environment of modern Norwegian residential buildings in connection with moisture-related parameters. This study has merely started to touch the useful findings related to indoor environment of modern Norwegian residential buildings in relation to moisture-related parameters, while there are several aspects left to study. It is highly recommended to continue conducting field measurements of modern Norwegian residential buildings until there is more reliable data achieved in order to repurpose for revealing a ventilation of urban residential buildings which can handle moisture-related problems, microbial growth, and overheating while lowering relative humidity related problems.

There are some recommendations for further research as following:

- Using more detailed questionnaire for the households in order to gain better understanding of occupant behaviours when estimating moisture production, additionally, asking for the exact time of cooking and showering events to be diarised by occupants.
- Measuring ventilation rates during the monitoring period for each monitoring apartments.
- Increasing the number of sample size with conducting more field measurements in modern Norwegian residential buildings
- Constructing the same research in rest of the Scandinavian countries.
- Constructing the same research for the other seasons of the year.
- Working on the computer simulation model in order to create validation for further usage.

8. References

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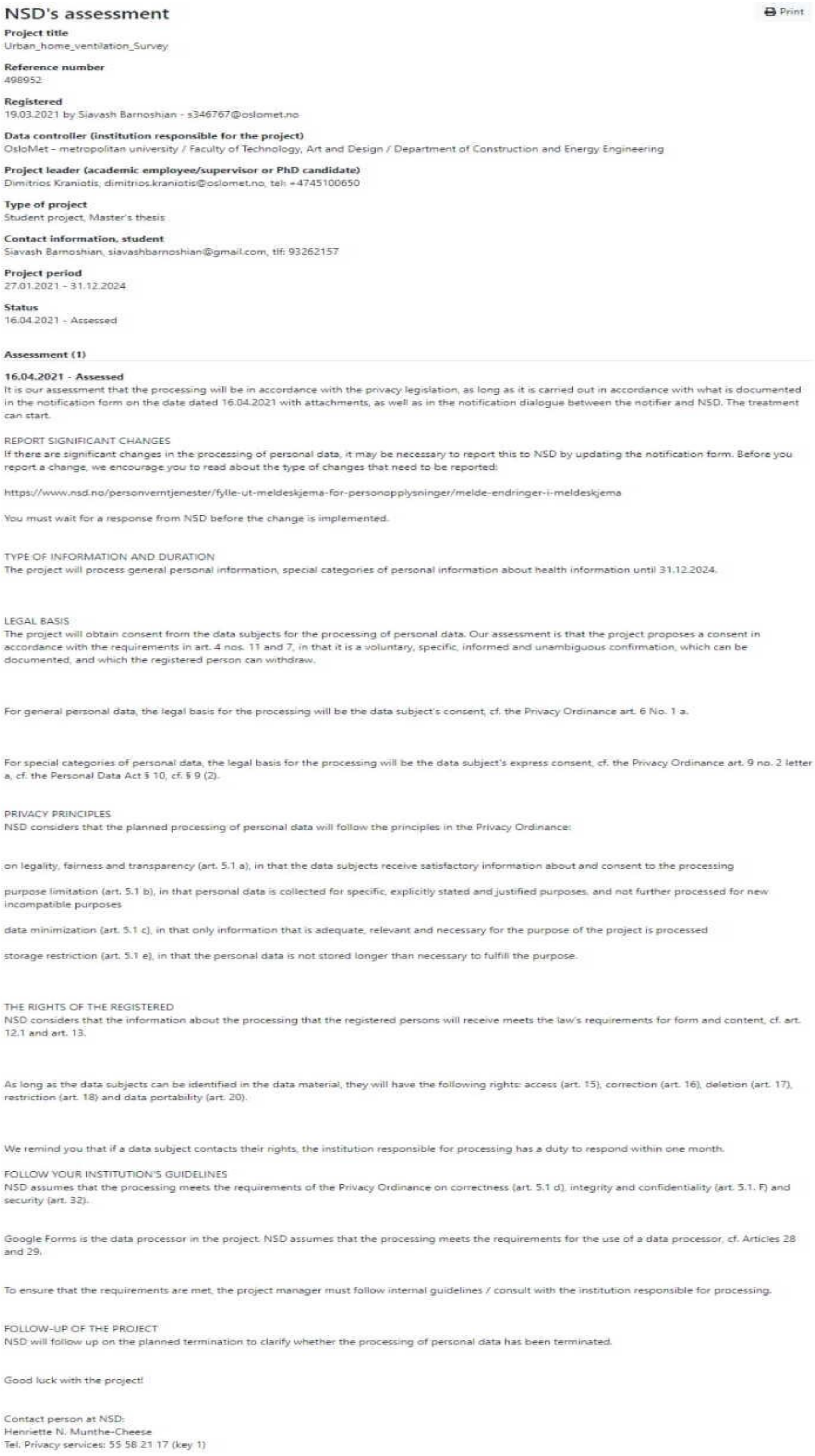
9. Appendices

Appendix A.

NSD approval for the questionnaires



NSD's assessment

Project title
Urban_home_ventilation_Survey

Reference number
498952

Registered
19.03.2021 by Siavash Barnoshian - s346767@oslomet.no

Data controller (institution responsible for the project)
OsloMet – metropolitan university / Faculty of Technology, Art and Design / Department of Construction and Energy Engineering

Project leader (academic employee/supervisor or PhD candidate)
Dimitrios Kraniotis, dimitrios.kraniotis@oslomet.no, tel: +4745100650

Type of project
Student project, Master's thesis

Contact information, student
Siavash Barnoshian, siavashbarnoshian@gmail.com, tlf: 93262157

Project period
27.01.2021 - 31.12.2024

Status
16.04.2021 - Assessed

Assessment (1)

16.04.2021 - Assessed
It is our assessment that the processing will be in accordance with the privacy legislation, as long as it is carried out in accordance with what is documented in the notification form on the date dated 16.04.2021 with attachments, as well as in the notification dialogue between the notifier and NSD. The treatment can start.

REPORT SIGNIFICANT CHANGES
If there are significant changes in the processing of personal data, it may be necessary to report this to NSD by updating the notification form. Before you report a change, we encourage you to read about the type of changes that need to be reported:

https://www.nsd.no/personverntjenester/fylle-ut-meldeskjema-for-personopplysninger/melde-endringer-i-meldeskjema

You must wait for a response from NSD before the change is implemented.

TYPE OF INFORMATION AND DURATION
The project will process general personal information, special categories of personal information about health information until 31.12.2024.

LEGAL BASIS
The project will obtain consent from the data subjects for the processing of personal data. Our assessment is that the project proposes a consent in accordance with the requirements in art. 4 nos. 11 and 7, in that it is a voluntary, specific, informed and unambiguous confirmation, which can be documented, and which the registered person can withdraw.

For general personal data, the legal basis for the processing will be the data subject's consent, cf. the Privacy Ordinance art. 6 No. 1 a.

For special categories of personal data, the legal basis for the processing will be the data subject's express consent, cf. the Privacy Ordinance art. 9 no. 2 letter a, cf. the Personal Data Act § 10, cf. § 9 (2).

PRIVACY PRINCIPLES
NSD considers that the planned processing of personal data will follow the principles in the Privacy Ordinance:

on legality, fairness and transparency (art. 5.1 a), in that the data subjects receive satisfactory information about and consent to the processing

purpose limitation (art. 5.1 b), in that personal data is collected for specific, explicitly stated and justified purposes, and not further processed for new incompatible purposes

data minimization (art. 5.1 c), in that only information that is adequate, relevant and necessary for the purpose of the project is processed

storage restriction (art. 5.1 e), in that the personal data is not stored longer than necessary to fulfill the purpose.

THE RIGHTS OF THE REGISTERED
NSD considers that the information about the processing that the registered persons will receive meets the law's requirements for form and content, cf. art. 12.1 and art. 13.

As long as the data subjects can be identified in the data material, they will have the following rights: access (art. 15), correction (art. 16), deletion (art. 17), restriction (art. 18) and data portability (art. 20).

We remind you that if a data subject contacts their rights, the institution responsible for processing has a duty to respond within one month.

FOLLOW YOUR INSTITUTION'S GUIDELINES
NSD assumes that the processing meets the requirements of the Privacy Ordinance on correctness (art. 5.1 d), integrity and confidentiality (art. 5.1. F) and security (art. 32).

Google Forms is the data processor in the project. NSD assumes that the processing meets the requirements for the use of a data processor, cf. Articles 28 and 29.

To ensure that the requirements are met, the project manager must follow internal guidelines / consult with the institution responsible for processing.

FOLLOW-UP OF THE PROJECT
NSD will follow up on the planned termination to clarify whether the processing of personal data has been terminated.

Good luck with the project!

Contact person at NSD:
Henriette N. Munthe-Cheese
Tel. Privacy services: 55 58 21 17 (key 1)

Appendix B.

The calculated per cent error constants used for calibration of sensors

The calculated per cent error constants used for interpolation or extrapolation for each sensor. While (#) means extrapolation, (*) means interpolation.

Sensor Codes	Constant Values if,					
	Temperature (°C)			Relative Humidity (%)		
	<25 °C (#)	≥25 °C (*)	≥28 °C (*)	<40 (*)	≥40 (*)	≥55 (*)
N32	0.006961019	0.028837082	0.044414212	0.116056649	0.207910891	0.056488621
N36	0.015960727	0.014545836	0.039608192	0.146580197	0.201025555	0.066071946
N37	0.012695291	0.019252534	0.033448363	0.136276563	0.207662131	0.072418246
N40	0.004571213	0.02813737	0.046734148	0.1036613	0.171840613	0.046837582
N41	0.010733567	0.02982121	0.046647996	0.093899962	0.185771203	0.043185748
N52	0.010184855	0.032709411	0.043252193	0.063409435	0.17212491	0.036812488
N56	0.00906535	0.025514707	0.042333244	0.102406948	0.185500636	0.04504044
N61	0.00878535	0.026333974	0.03433962	0.090992474	0.17724227	0.036378679
N63	0.010206731	0.020279449	0.035595996	0.081814497	0.169281933	0.023581777
N71	0.008702364	0.03318008	0.046580306	0.098548218	0.194300136	0.043327455
N77	0.006544036	0.021273645	0.043421419	0.095914207	0.173262101	0.037246297
N98	0.004373702	0.026291186	0.051623243	0.099322928	0.180085248	0.033096005

Appendix C.

Moisture production rates used in this study

Moisture production rates found from literature and moisture production rates used in this study.

Activity	Used in this study [kg/d]	Moisture Production rates found from literature [kg/d]	
		Angel (1988)	***Koch (1986)***
People	0.9	1.25	0.9
Cooking (family of four)	0.9		0.9
Breakfast		0.17 – 0.27	
Lunch		0.25 – 0.32	
Dinner		0.58 – 0.75	
Diswashing (family of four)	0.4	0.10 – 0.32	0.4
House plants(~ 5 st.)	0.4	0.41 – 0.45	0.1
Shower (once)	0.4	0.25	0.4
Drying clothes (load)	1.8	2.2 – 2.9	1.8
Floor Mopping	0.15/m^2	0.15/m^2	
Humidifier	23.616	23.616	

Appendix D.

Simplified version of a Moller diagram

Simplified version of a Mollier diagram created by ASHRAE (ASHRAE Psychrometric Chart #1 (SI), 1992).