Building and Environment 246 (2023) 110969

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Indoor air temperature and relative humidity measurements in Finnish schools and day-care centres

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ARTICLE INFO

Keywords:
indoor air temperature
indoor air relative humidity
moisture excess
schools
Day-care centres
Field measurements

ABSTRACT

Indoor air temperature and relative humidity measurements of schools and day-care centres in two research projects on indoor air conditions in municipal buildings with mechanical ventilation in Finland were combined for a large sample of occupied spaces with typical conditions experienced by users of the buildings. In addition to user experience, the occupied spaces represented the spaces with determining air humidity load when assessing moisture performance of envelope structures. Indoor air temperature was stable excluding extreme external conditions that caused crossings of limit values. Permanence within limit values of the Finnish Classification of Indoor Environment was inadequate leaving all buildings in the lowest classification level S3. Mechanical ventilation in municipal buildings is designed to keep pollutants at moderate level during high occupancy which results in non-existent indoor air moisture excess, which during winter leads to low indoor air relative humidity. Although dry indoor air provides safety of envelope structures, the drawback is poor performance with regards to the recommended range. Dry indoor air has negative effects on the indoor air quality experienced by the users, causing skin and eye irritation.

1. Introduction

1.1. General

Indoor air temperature (T) and relative humidity (RH) are an important part of the indoor environment. Awareness of the existing temperature and humidity levels during operational time of the building and ability to control the conditions is essential for indoor air quality (IAQ) experienced by the users.

In the climate of the Nordic countries, the impact from the annual variation of outdoor air conditions to the indoor environment is significant. In winter the outdoor air is cold and dry (with regards to absolute humidity) which creates the need for heating and temperature control of indoor air. If the indoor air is too dry (as in low relative humidity), this can cause unwanted effects such as skin and eye irritation and respiratory symptoms ([1], Ch. 9). Too high indoor air temperature can also affect indoor air thermal comfort and contribute to low indoor air relative humidity. In summer, high indoor temperature can occur due to solar and indoor thermal loads, and due to the characteristics of the building. Standard EN ISO 7730 provides a calculation method for thermal comfort [2]. Too high indoor air relative humidity can cause also unwanted effects such as microbial growth. Therefore, in many aspects, it is highly beneficial to control indoor air conditions to be within recommended limit values.

In typical cold Nordic climate, the indoor air water vapour concentration typically exceeds the outdoor air water vapour concentration, due to the moisture sources indoors that increase the humidity level compared to outdoor air. Higher indoor air humidity levels can lead to higher moisture loads into the building envelope structures by air leakages and water vapour diffusion. Building envelope structures can however be designed to withstand even high indoor air moisture loads by selecting suitable structure types and building materials. The design process needs information of the indoor air conditions as an input.

The internal humidity levels are strongly dependent on the efficiency of the buildings ventilation system and its ability to flush out the excess humidity. Ventilation systems are designed according to the building's purpose and use. The ventilation needs of municipal buildings differ greatly from residential buildings due to higher occupation rate. Higher occupation rate results in higher loads of carbon dioxide (CO_2) and other impurities which requires a more efficient ventilation system to keep the

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https://doi.org/10.1016/j.buildenv.2023.110969
Received 24 April 2023; Received in revised form 19 October 2023; Accepted 22 October 2023
Available online 30 October 2023
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indoor air quality at regulated levels. As a side effect, the indoor air humidity in municipal buildings can be flushed more strongly than what would be required only from moisture safety and humidity comfort perspectives. Short calculation example of this is given in Ch. 1.2.

1.2. Literature review

In the Nordic and Baltic countries, the indoor air temperature and humidity have been studied especially in dwellings in multiple studies. In Finland these studies have had a large role in the formulation of current national guidelines for indoor air moisture excess for all types of buildings. Because of this, they are described shortly below.

A study in Finland examined indoor air conditions of 171 single-family buildings and 49 apartments in multi-family buildings [3,4]. Continuous field measurements included two consecutive heating seasons to analyse the internal moisture excess of the buildings and to assess the applicability of design values in national standards and guideline values [5,6]. In the case of indoor air humidity, higher 10 % critical level (above 90 % cumulative distribution value) of weekly moisture excess was compared to outdoor temperature to find suitable correlations to be used as design values. During the cold period ($T_e \leq 5$ °C) the higher 10 % critical value was between 3.4 and 4.9 g/m^3 in single-family buildings and between 2.4 and 3.6 g/m^3 in apartments of multi-family buildings. During warm period ($T_e > 5$ °C) the corresponding values were 0.3–2.6 g/m^3 and 0.3–2.6 g/m^3 respectively. The ventilation rates in multi-storey apartment buildings were 0.63 h^{-1} (s d. 0.14 h^{-1}) in buildings with centralised ventilation systems, 0.55 h^{-1} (s d. 0.13 h^{-1}) in buildings with apartment-based supply-exhaust and 0.39 h^{-1} (s d. 0.22 h^{-1}) in buildings with exhaust ventilation system.

A similar study was carried out in Estonia with 237 dwelling units consisting of apartments and detached houses [7]. The higher 10 % critical level of moisture excess was higher compared to the Finnish study and ranged between 3 and 8 g/m^3. This was concluded to be consequent of the lower air change rates, being 0.32 h^{-1} on average with standard deviation of 0.23 h^{-1}.

Several studies have investigated the indoor air quality (IAQ) in schools and day-care buildings, although the number of studies has been much smaller compared to residential buildings. Table 1 shows the temperature and RH results of recent publications of indoor air quality studies that involved several schools in Europe and United States.

The study conducted in Gothenburg, Sweden investigated the effects of different ventilation strategies on indoor air quality [8] and is considered to best match the current study because of the climatic conditions and the use of mechanical ventilation. The study included a total of 23 primary school buildings divided into three groups for comparison between non-mechanical ventilation, balanced mechanical ventilation with constant air volume and balanced mechanical ventilation with variable air volume. Median temperature was 20.8 °C (iqr 1.4 °C) for full week and 21.2 °C (iqr 1.2 °C) for occupied time. Corresponding median RH values were 34 % RH (9 % RH) and 35 % RH (9 % RH). Compared to IAQ studies of schools in other regions, the schools in Sweden had lower and more stable temperature values. RH values were similar to other studies except for a study in Portugal where the measured RH values were higher.

Table 1
Temperature and RH results of some recent publications regarding the indoor air quality of school buildings.

Location and source	Buildings	Temperature results	RH results
Sweden [8]	23	Median 20.8 °C, IQR = 1.4 °C	Median 34 %, IQR = 9 %
Central Europe [9]	64	Median 22.8 °C, range 18.7–25.9 °C	Median 35 %, range 20–55 %
Europe [10]	115	Median 22 °C, IQR = 3.0 °C	Median 40 %, IQR = 14 %
Portugal [11]	25	Median 21.9 °C, IQR = 3.6 °C	Median 58 %, IQR = 18.2 %
Southwestern US [12]	70	Average 23 °C	Average 40 %
Midwestern US [13]	40	Average 22.4 °C	Average 40 %

IQR = interquartile range (range between 25 % and 75 % percentile).

Moisture management in buildings is addressed in ASHRAE Fundamentals 2017 chapter 36 ([1], Ch. 36). Results of indoor air temperature and vapour pressure difference measurements in five schools in temperate-climate region showed a large spread in average weekly indoor/outdoor vapour pressure difference. While mean values were proportional, minimum and maximum values showed a wide scale diffusion on both moisture excess and moisture deficit side compared to outdoor air.

Generally, the indoor air quality studies commonly focus on concentrations of air pollutants and if the indoor temperature and humidity values are measured in these studies, they are often in a secondary role. Also, climate, building stock, time period and ventilation arrangements vary by region and local methods of construction, which narrows down studies that are comparable to specific set of measurements. This reduces the number of studies considerably, that have especially focused on the temperature and humidity conditions of indoor air in schools and day-care centres.

Next we go through a short calculation example to describe the impact of ventilation requirements on the indoor water vapour excess.

The design values for ventilation rate depend on the intended use of the specific room and of the whole building. The HVAC designer has to determine the incoming and outgoing volumetric air flow rates (dm^3/s) per each room, while taking into account also the air flows between rooms. In residential buildings supply air is provided into living rooms, bedrooms and similar areas, whereas exhaust air is taken from kitchens, toilets and bathrooms. If we only look at a simple example of a single room with one supply and one exhaust and no ventilation air transfer between rooms, the steady-state carbon dioxide excess in room is calculated according to Eq. (1).

$$\Delta C_{CO2} = \frac{q_{CO2}}{q_{vent}} \tag{1}$$

where ΔC_{CO2} is the excess carbon dioxide concentration above outdoor air [ppm], q_{CO2} is the volumetric carbon dioxide production rate into the room [dm^3/s] and q_{vent} is the volumetric ventilation supply air flow rate [dm^3/s] [1, Ch. 16], [14].

Indoor air moisture excess $\Delta\nu$ [g/m^3] in steady-state conditions is calculated similarly to Eq. (1), by dividing the indoor moisture production rate G [g/s] with the volumetric ventilation supply air flow rate q_{vent} [m^3/s], i.e. $\Delta\nu = G/q_{vent}$ [6].

For a CO_2 production rate of 0.005 dm^3/(s,person) [14] and a minimum supply air flow rate of 6 dm^3/(s,person) [15], the CO_2 excess above outdoor air value in a occupied room in a residential building with two occupants becomes: $\Delta C_{CO2} = 1 \bullet 10^6$ (ppm/1) • (2 persons • 0.005 dm^3/(s,person))/(2 persons • 6 dm^3/(s,person)) = 833 ppm, which is only a little above the instantaneous maximum value of 800 ppm given in the Finnish National Building Code [16]. The CO_2 excess would be the same in a classroom or day-care centre group space with 20 persons. A difference however occurs when minimum ventilation rates are considered. For a 12 m^2 bedroom the air flow rate would be 12 dm^3/s/12 m^2 = 1 dm^3/(m^2,s), which is above the minimum requirement of 0.35 dm^3/(m^2,s) [17]. For a 60 m^2 classroom the ventilation rate would be 120 dm^3/s/60 m^2 = 2 dm^3/(m^2,s), which is higher than in residential building, but below the minimum requirement of 3 dm^3/(m^2, s) [15]. If we next assume that the water vapour release from a person is 50 g/h = 0.014 g/s [1, Ch. 36], we can calculate the steady-state indoor air moisture excess to be in residential building: $\Delta\nu$ = 2 persons • 0.014 g/(s,person)/(2 persons • 6 dm^3/(s,person)) = 2.3 g/m^3 and in school or day-care centre: $\Delta\nu$ = 20 persons • 0.014 g/(s,person)/(60 m^2 • 3

$dm^3/(m^2,s)) = 1.5\ g/m^3$. Based on these design values, the indoor air moisture excess should be lower in schools and day-care centres, compared to residential buildings, but the exact level and spread of values is currently not well known.

A study in Finland assessed the effect of overpressure (positive pressure) on the moisture performance of a school building [18]. According to the measurements, the moisture excess was very small even with ventilation rates half of the design value and with high occupancy. This lead to the conclusion that, contrary to common expectation, overpressure indoors did not compromise the moisture functionality of the envelope structures. On the contrary, exfiltrating dry air through joints of structures helped maintaining RH at lower levels. Also indoor air quality benefitted as overpressure prevents impurities from being sucked from envelope structures or outdoor air into indoor air. The authors noted that comparable studies of indoor air humidity of schools in cold climate are difficult to find, for which this publication helps to contribute.

Regulations and guidelines for ventilation rates in municipal buildings in Finland are presented in sources [15,19]. Carbon dioxide (CO_2) concentration is typically used as an indicator when assessing ventilation adequacy and IAQ in buildings with high occupancy. The regulations regarding the air flow rates of mechanical ventilation aim to ensure that the CO_2 concentration (and other impurities) in indoor air remains sufficiently low.

1.3. Goals of the study

A research project "COMBI – Comprehensive development of nearly zero-energy municipal service buildings" (2015–2018) [20] analysed 22 Finnish schools and day-care centres and two elderly homes from energy efficiency perspective. As part of the project there were field measurements of indoor air temperature and relative humidity conditions and air pressure differences over the building envelope in the studied buildings.

A subsequent project "Future Spaces" was conducted during 2020–2022. The project included field measurements 12 schools and day-care centres and two office buildings to study the effects of night-time shutdown of ventilation to IAQ. Some of the measured buildings were the same than in the previous COMBI project. In the Future Spaces project, the emphasis was shifted from the number of investigated buildings to the scope of measurements of an individual building by increasing the number of investigated spaces and measuring devices per building.

The purpose of this article is to present field measurement results of indoor air temperature and humidity conditions of 26 Finnish schools and day-care centres. The data collection and analysis were conducted as part of the two projects mentioned above. The main research questions of the paper are.

- What are the typical temperature and humidity conditions in Finnish schools and day-care centres?
- How high is the indoor air vapour excess in the studied buildings when examining only the operational time of the buildings?
- How well do the measurement results correspond with the current recommendations and guidelines?

The results have been reported previously nationally to the Finnish audience in the form of two papers in the Finnish Building Physics Symposium (in Finnish) [21,22] and as a part of the project summary report from the COMBI project (in Finnish) [20]. The current paper combines the data from the two projects and extends the analysis compared to the previous publications.

2. Methods and materials

2.1. Studied buildings

Field measurements in the COMBI project were conducted in 12 new and 12 renovated buildings with mechanical ventilation in Pirkanmaa and Helsinki region in Finland during 2016–2018. The 12 + 12 = 24 case buildings consisted of schools and day-care centres, but including two assisted living facilities as an exception. The new buildings were five years old on average. The retrofitted buildings were 58 years old on average and had been taken through extensive retrofitting work on average four years before the measurements. Two retrofitted buildings included a new extension wing to the original building which was handled as a new building. Taking these into account, the project included a total of 20 individual school and day-care buildings. All the buildings were mechanically ventilated. Some of the buildings had cooling in individual special zones, such as in kitchens. The studied buildings represent the most common type of new school and day-care centre buildings in Finland.

In the COMBI project, the selection of the new buildings was based on two criterions: (a) the building had a small air tightness number q_{50} and (b) the building already belongs to studies in other work packages of the project. The selection of renovated buildings was based on several criterions: (a) high air pressure difference over building envelope was discovered in a prior conditions survey, (b) inadequate IAQ has been pre-reported by users, (c) detection of exceptionally poor energy efficiency, (d) considerable effort were made to improve energy efficiency as part of the renovation and (e) the building already belongs to studies in other work packages of the project.

Future spaces project included 12 case buildings consisting of schools and day-care centres in Pirkanmaa and two office buildings, one in Tampere and one in Helsinki. 6 out of these 12 municipal buildings were previously included in COMBI project. The field measurements took place during 2021–2022 and the studied buildings included both new and old buildings without age-based grouping. The selected schools and day-care centres were all located in Pirkanmaa region to enable frequent visits to the case buildings to collect data and to assure the functionality of the measuring devices.

In Future spaces project, the selection of the buildings was based on the following criterions: (a) ventilation is not completely shut down even overnight in normal operating mode, (b) it is possible to completely shut down ventilation through automation, (c) the building has been found to have considerable underpressure at night, (d) the building has been or will soon be renovated, (e) the building was included in COMBI project and (f) the building location allows efficient site visit protocol. The case buildings were owned and managed by the research project partner cities and municipalities. Buildings with identified IAQ problems were not included in the studies due to the possibility that the night-time shutdown of ventilation included in the study might raise concerns among the users of the buildings. Therefore, the study only included buildings with adequate IAQ.

The measurement data from the two projects was combined to create a larger sample. The school and day-care buildings of the two research projects are comparable in purpose of use, ventilation and targeted indoor air conditions. Individual spaces (rooms) were assessed and those that were not in permanent use by teaching staff, day-care centre personnel or dependents were removed from the sample. Such facilities included kitchens, washing rooms and storage spaces. The remaining spaces were classrooms, activity rooms, work and restrooms for the personnel, lobbies and corridors. The service buildings and office buildings were also not included. The list of studied buildings and spaces is given in Appendix A. In the final analysis there were 104 rooms from 26 schools and day-care centres.

2.2. Measurement equipment

In the field measurements of COMBI project, temperature and relative humidity measurements in the examined spaces were carried out with two different dataloggers. Information on these is given in Table 2.

When installing the temperature and relative humidity dataloggers, the focus was on ensuring that the measurements describe the conditions in the breathing zone as well as possible. The dataloggers were placed at a height of 1–2 m from the floor line when possible. However, in some instances the equipment was installed higher so that they would not be accessible to dependents.

In the COMBI project, Rotronic CL11 dataloggers were placed in the same spaces where air pressure difference over building envelope was measured [26]. Comark N2003 dataloggers were used in the research project to increase the measurement volume and were installed in other rooms to monitor indoor air conditions of the building more comprehensively. In Future Spaces project only Rotronic CL11 was used for measuring indoor air conditions.

In the COMBI project, indoor air conditions were measured at 60 min intervals, which was intended to be a balance between measurement accuracy, storage capacity of the equipment (Comark) and the resources available for site visits. However, infrequent visits turned out problematic because outages were only noticed during visits (no remote access to data). This was a common problem with mains-powered measuring devices in day-care centres and schools as unplugged devices were noticed and restarted only during the next visit. The measurement set-up was reconsidered in the Future Spaces project by restricting the number of case buildings and selecting them from such locations, that all the case buildings could be visited for data collection and operation checking of dataloggers in less than a week. Case buildings were visited every fourth week on average to collect data and ensure the operation of the dataloggers. In the Future Spaces project the measurement interval was set to 5 min or 10 min depending on the phase of the project. If there was uncertainty of the correct time stamps in the measurement data, then that data was removed from the final analysis. The length of individual time series varied, shortest ones being of few months and the longest being close to two years.

Outdoor temperature and RH data of the case buildings was acquired from nearest observation stations of the Finnish Meteorological Institute (FMI), from the Open Data service [27]. In COMBI project, the selected observation stations (latitude, longitude) were Helsinki Kaisaniemi (60.18, 24.94), Helsinki Vuosaari satama (60.21, 25.20), Tampere Härmälä (61.47, 23.75), Tampere Tampella (61.50, 23.76), and Tampere-Pirkkala Airport (61.42, 23.62). The data was acquired in 10 min intervals and further treated in data analysis.

Table 2

Information on the equipment used in the field measurements.

Equipment	Range	Accuracy	Comments
Rotronic CL11 [23] Share of measuring devices: COMBI 63 %, Future Spaces 100 % (exclusive)	−20 °C … 60 °C; 0 % … 100 %	±0.3 °C; ±2 % RH (10 % RH … 90 % RH), otherwise ±5 % RH; Values are given for temperature range 23 °C ± 5 K.	Used as the primary measurement device for indoor air conditions. (Used in 64 % of studied spaces.) Acquired new equipment for the COMBI project. Calibrated by manufacturer before the Future Spaces project.
Comark N2003 [24] Share of measuring devices: COMBI 37 %, Future Spaces 0 % (not used)	−20 °C … 60 °C	±0.5 °C; ±3 % RH (in range 0 % … 97 %)	Formerly used in indoor air studies of dwellings [3,4,25] and reused in the COMBI project for a greater number of measurement points. Before the Comark loggers were installed, they were calibrated against a reliable reference in laboratory conditions but not adjusted. Deviation of the loggers was ±0.4 … 3.0 % RH, which fits within the ±3 % accuracy.

2.3. Data analysis

The first step when analysing the data was to create even hourly time series, such that each value would be on the hour. The field measurement data was first interpolated to a 5 min grid starting from full hour (00:00, 00:05, …), and then the average temperature and relative humidity was calculated from the values in the previous hour (block average). Similar procedure was used also for the FMI Open Data, which originally downloaded at 10 min time resolution, but started from full hour directly (00:00, 00:10, …). The hourly measurement data from Comark loggers was used either directly (if the data was from on the hour directly) or interpolated to match on-hour conditions, although also there the half-past values would have better represented the conditions in the previous hour. The impact from this lag in the Comark measurement data is however considered small.

From the hourly T/RH data the water vapour concentration values were calculated. The saturation vapour pressure was calculated according to the CIMO Guide [28] and converted to water vapour concentration using ideal gas equation. The measurements were started and finished in stages one building at a time, because at the beginning installation and at the end removal of the measurement units took their own time. The duration of indoor air temperature and relative humidity field measurements COMBI project was just over two years from July 20th’ 2016 to August 15th’ 2018. In Future Spaces project, the measurements in normal conditions began in first school building March 29th’ 2021 and ended January 10th’ 2022 as the altered ventilation phase was started. The altered ventilation phase was not included in the analysis. The total duration of these field measurements was over 34 months. The indoor air moisture excess was then calculated for each time step using Equation (2).

$$\Delta\nu = \nu_i - \nu_e \tag{2}$$

where ν_i is indoor air water vapour concentration (g/m^3) based on own measurements and ν_e (g/m^3) the outdoor air water vapour concentration based on nearest FMI weather station data. Weather station data was used instead of on-site measurements because that data is already generally available, the FMI has implemented various quality measures to it and also the Finnish moisture design years [29] are from the FMI weather stations. The data from the two projects was next combined to a collective timeline in Microsoft Excel and measurements from same rooms were concatenated.

Results from COMBI project showed that indoor air moisture excess in Finnish schools and day-care centres is nearly non-existent during heating season. To further analyse the phenomenon, data analysis focused on operational time of the building and on spaces that are being used actively. Therefore, the combined data was systematized by excluding spaces that are not in regular use by the teaching staff or the dependents and by discarding data measured during holidays. Systemization of the examined spaces allows analysis of the measured data as a mass as the results then represent more reliably the spaces occupied by staff and dependents.

Regular calendar weeks were then divided into four operating situations (OS). This was done in order to separate occupied hours from non-occupied hours as this is one key characteristic of the studied buildings. In addition, the time of absence was also separated between weekday nights and weekends due to the difference in ventilation operation. The four operating situations (OS) are described in Table 3.

In addition to operating situations, the data was also divided to thermal summer (S) and thermal winter (W) according to external air temperature. The definition of thermal summer in Finland is when average daily temperature is above 10° Celsius. The definition of thermal winter in Finland is when daily average temperature in below zero degrees Celsius.

Descriptive statistics were calculated for both thermal seasons and for each operating situation. The statistics were calculated directly from all the data points (including all measurement points) belonging to a specific subsection of the data. These statistics were.

i. The number of readings
ii. Percentage of time the values were below the required/recommended range
iii. Percentage of time the values were above the required/recommended range
iv. Percentage of time the values were within the required/recommended range
v. The 0 % percentile value (minimum)
vi. The 10 % percentile value
vii. The 50 % percentile value (median)
viii. The 90 % percentile value
ix. The 100 % percentile value (maximum), and
x. The arithmetic mean.

The required indoor air temperature range for schools and day-care centres is set in the Housing Health Decree of the Ministry of Social Affairs and Health (STMa 545/2015) [30] and instructed by Finnish National Supervisory Authority for Welfare and Health (Valvira) [31]. For existing schools and day-care centres it is given separately for (i) heating season +20 °C – +26 °C, and (ii) outside heating season +20 °C – +32 °C. As for the definition of heating season and outside of heating seasons, the data was divided into thermal summer (S) and thermal winter (W) according to external temperature as described above.

The range for relative humidity is not specified in the national regulations, but there are recommended values for it. Range for relative humidity was selected as recommended by the Finnish Society of Indoor Air Quality and Climate in Ref. [32]. The recommended range is given separately for (i) winter 20 % RH – 45 % RH, and (ii) summer 30 % RH – 60 % RH.

The internal moisture excess was compared to the recommended design values presented in the guideline RIL 107–2022 [33]. In the previous version from year 2012, schools and day-care centres belonged into humidity class 2, which had winter-time moisture excess design value of +5 g/m^3. In the updated version from 2022 schools and day-care centres were moved into humidity class 3, which has winter-time moisture excess design value of +3 g/m^3. The indoor air moisture excess design value in humidity class 3 depends on the outdoor air temperature and varies between 1 and 3 g/m^3. For the case (ii) in the list above, also the condition $\Delta\nu < 0$ g/m^3 was used for calculating the basic descriptive statistics.

Distributions of the measured indoor air temperature, relative humidity and moisture excess were visualized using density functions. For these purposes the measurement results were divided into 1 °C intervals for temperature, 1 % RH intervals for relative humidity and 0.1 g/m^3 intervals for moisture excess.

Table 3
The different operating situations (OS) used in the study. The daytime and night-times were selected shorter compared to full working days to include only times of full/no occupancy.

Operating situation	Symbol	Days of the Week	Time
Whole week	OS 0	Mon–Sun	00:00–24:00
Daytime during working days	OS 1	Mon–Fri	10:00–14:00
Night-time during working days	OS 2	Mon–Fri	23:00–04:00
Weekends	OS 3	Sat–Sun	00:00–24:00

The indoor air measurement results were also compared to the Classification of Indoor Environment 2018 (Sisäilmastoluokitus 2018) of The Building Information Foundation RTS [34]. The classification has three levels: S1, S2 and S3, which assess the indoor environment during occupied hours. In class S1, it is most likely to reach the highest share of user satisfaction. The class S3 corresponds to the minimum requirements set in the Finnish National Building Code [14].

Indoor air relative humidity was also compared to the design values presented in Annex A.1 of the standard EN ISO 13788:2012 [6]. Average hourly indoor air relative humidity values were plotted as a function of average daily average outdoor air temperature and compared to the given design values. For better readability, the values were divided into 1 °C bins. In addition, 10 % percentile, 90 % percentile and mean value of the bins were calculated.

Data analysis was done similarly in all the presented cases, because the combined and systematized data sample from the two research projects was used as material. The data analysis processes combined measurement data obtained by comparable long-term measurements performed in 104 comparable spaces in 26 comparable buildings. Therefore, the results represent the indoor air conditions experienced by the teaching staff and dependents as well as the moisture load conditions effecting the envelope structures of the buildings.

The results from the earlier COMBI project suggested that the average moisture excess in the studied schools and day-care centres was low and in many cases there were also conditions of moisture deficit in the indoor air. To prevent higher indoor air moisture loads during occupied hours being regressed towards mean when being pooled with results non-occupied hours, special emphasis in the analysis was given to the operating situation 1 (OS 1, weekdays).

The last part of this paper presents results on the impact of the night-time ventilation shutdown. The impacts are compared between two consecutive winter periods of 11 weeks each. The periods were chosen on the basis of duration and outdoor conditions. The period of normal conditions was between October 25, 2021 and January 9, 2022. The period of altered conditions was between January 10, 2022 and March 27, 2022. Mean outdoor air temperature was −2.1 °C during the normal period and −2.5 °C during the altered period. The effects from shutting down the night-time ventilation completely were evaluated by creating box plots of the conditions at each hour of the 24-h daily cycle.

3. Results and discussion

3.1. Basic statistics and comparison to national guidelines

Fig. 1 shows an example of measured indoor air conditions in a space that was included in both COMBI and Future Spaces project. The figure contains indoor air temperature, moisture excess and relative humidity results during the duration of the two research projects. Holidays were removed from the data to analyse occupied weeks only.

The hourly data of Fig. 1 presents the indoor air conditions of a typical case from the systemized sample of the spaces occupied by the faculty or dependents. Basic statistics are calculated from the combined data for all variables in different operating situations and thermal seasons. The required ranges for indoor air temperature were +20 – +26 °C during heating season and +20 – +32 °C outside heating season [31]. The basic statistics for indoor air temperature are presented in Table 4.

Indoor air temperature in overall was stable and differences between operating situations within thermal season were mostly small (<0.5 °C). The mean and median were also either the same or close to each other, which implies that the data was mostly symmetrically distributed. During working days (OS 1) indoor air was slightly warmer than during weekday nights (OS 2), which is expected as indoor temperature follows the daily variation of outdoor temperature. In addition, users of the

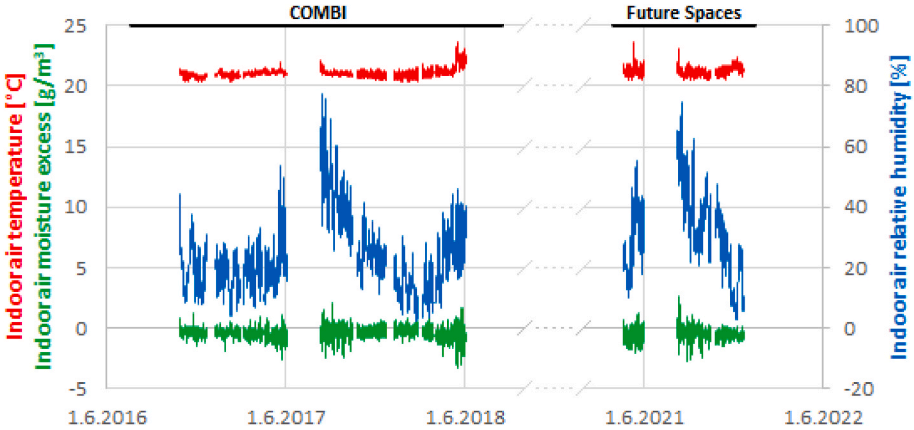

Fig. 1. Indoor air temperature (red line), moisture excess (green line) and relative humidity (blue line) measurement results from examined space 12_1 (Table A2a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Basic statistics of indoor air temperature in the measured schools and day-care centres. W = Thermal winter, S = Thermal summer. Low T (<+20 °C) and high T (>+26 °C during thermal winter and > +32 °C during thermal summer) mean the measured indoor air temperature being below or above the recommended temperature range. [NO_PRINTED_FORM].

Operating situation	Thermal season W/S	Results [no. Of data points]	Low T [% of time]	High T [% of time]	In range [% of time]	Percentile					Mean [°C]
						0 % [°C]	10 % [°C]	50 % [°C]	90 % [°C]	100 % [°C]	
OS 0 Mon-Sun 00–24	W	201,530	24	1	75	11.4	19.2	20.9	23.0	30.5	20.9
	S	160,951	7	0	93	16.8	20.2	21.5	23.7	29.1	21.7
OS 1 Mon-Fri 10–14	W	30,819	18	0	82	11.4	19.6	21.2	23.2	30.5	21.2
	S	23,904	4	0	96	16.8	20.5	21.8	23.8	29.0	22.0
OS 2 Mon-Fri 23–04	W	31,645	27	1	72	14.2	18.9	20.8	22.9	28.4	20.8
	S	24,082	8	0	92	17.5	20.1	21.4	23.5	27.0	21.6
OS 3 Sat-Sun 00–24	W	53,298	27	1	73	14.5	19.0	20.8	23.0	28.7	20.9
	S	45,649	8	0	92	17.5	20.1	21.4	23.6	28.7	21.7

buildings function as a source of heat that is in effect during occupied hours. The overall average temperature during thermal winter was 20.9 °C and during thermal summer 21.7 °C.

Larger differences in indoor air temperature can be seen, if the values at the edges of the distributions are compared. The 10 % percentile during night-time in thermal winter was 18.9 °C and the 90 % value during daytime in thermal summer was 23.8 °C. The minimum values (0 %) especially during winter likely represent single instances when the windows and/or doors have been kept open during events. The minimum temperature in within all results data was 11.4 °C and maximum 30.5 °C.

Permanence of indoor air temperature in the recommended ranges during the thermal seasons was good during summer, but the percentage values were lower for winter. Schools and day-care centres are typically not used between mid-June and beginning of August due to summer holidays of the dependents. As the primary purpose was to study conditions during occupancy hours, the holiday periods were excluded from the measurement results. This reduced the likelihood of reaching and exceeding the upper limit value 32 °C.

During thermal winter the conditions stay well under the upper limit value 26 °C, excluding individual exceptions. Maximum 90 % percentile value is at 23.2 °C during working days (OS 1). However, permanence of indoor air temperature during thermal winter is lowered by crossings below the lower 20 °C limit value in very cold outdoor temperatures. The 10 % percentile value was below 20 °C in all operating situations. Permanence in range of guideline values during thermal winter was 82 % during working days and 72 % during night-time. All of breaches of limit values were caused by low temperatures.

Next, we move onto discuss the results regarding the indoor air relative humidity. Basic statistics were calculated from the combined data for different operating situations and thermal seasons. The selected guideline ranges for indoor relative humidity were 25–45 % RH during winter and 30–60 % RH during summer [32]. The indoor air relative humidity results are presented in Table 5.

A significant difference occurred between the thermal seasons. During thermal winter, indoor air relative humidity was low in all operating situations. Both 50 % percentile (median) and mean were close to 17 % RH in all operating situations. During thermal summer, the corresponding values were approximately 43 % RH, which is still quite low value. The differences in relative humidity between operating situations was small and if the minimum and maximum value are excluded, the differences were within <4 % RH between different operating situations.

Permanence of indoor air relative humidity was fair during thermal summer as the values stayed in the recommended range approximately 80 % of the time between Mondays and Fridays (OS 1 and OS 2). However, during thermal winter, the permanence within recommended range was poor, as the indoor air relative humidity stayed below the recommended range almost constantly. The lower limit value 25 % RH was not exceeded in the 90 % percentile values in any operating situations during thermal winter.

Next, we move onto to discuss the results regarding indoor moisture excess. The basic statistics are presented in Table 6.

Overall, the moisture excess values varied around 0 g/m^3 in all operating situations in both thermal seasons. The indoor air moisture excess was below zero 55 % of the time during thermal winter and 78 % of the time during thermal summer. Mean values calculated from all measurement points and time steps were 0.0 g/m^3 during thermal winter and −0.5 g/m^3 during thermal summer. The mean and median values in different operating situation varied between −0.1 … +0.2 g/

Table 5

Summary statistics from indoor air relative humidity measurements at schools and day-care centres. The values are calculated from a single table that contained all measurement points. W = Winter, S = Summer. Low RH (<25 % RH during thermal winter and <30 % RH during thermal summer) and high RH (>45 % RH during thermal winter and >60 % RH during thermal summer) mean the measured indoor air temperature being below or above the recommended temperature range [32].

Operating situation	Thermal season W/S	Results [no. Of data points]	Low RH [% of time]	High RH [% of time]	In range [% of time]	Percentile					Mean [%]
						0 % [%]	10 % [%]	50 % [%]	90 % [%]	100 % [%]	
OS 0 Mon-Sun	W	201,530	93	0	7	2.0	9.2	17.1	24.1	71.9	17.0
00–24	S	160,951	16	6	78	12.9	27.4	43.1	57.7	81.8	42.9
OS 1 Mon-Fri	W	30,819	91	0	9	2.8	9.6	17.2	24.7	55.2	17.3
10–14	S	23,904	11	7	82	16.2	29.6	43.4	58.4	76.2	43.8
OS 2 Mon-Fri	W	31,645	92	0	8	2.3	9.3	17.6	24.3	46.8	17.2
23–04	S	24,082	12	5	83	13.9	29.2	43.1	57.0	80.1	43.2
OS 3 Sat-Sun	W	53,298	93	0	7	2.4	10.4	17.6	24.2	71.0	17.5
00–24	S	45,649	21	7	71	12.9	25.0	44.3	58.2	80.1	42.6

Table 6

Basic statistics on the indoor air moisture excess in the studied schools and day-care centres. W = Winter, S = Summer, "< 0 g/m^3" = moisture deficit compared to outdoor air, "> HC3" = moisture excess above higher than the humidity class design value [33].

Operating situation	Thermal season W/S	Results [no. Of data points]	<0 g/m^3 [% of time]	> HC3 [% of time]	In range [% of time]	Percentile					Mean [g/m^3]
						0 % [g/m^3]	10 % [g/m^3]	50 % [g/m^3]	90 % [g/m^3]	100 % [g/m^3]	
OS 0 Mon-Sun	W	201,015	55	0	100	−4.4	−0.8	−0.1	1.1	7.9	0.0
00–24	S	160,807	78	8	92	−7.7	−1.6	−0.5	0.5	5.8	−0.5
OS 1 Mon-Fri	W	30,750	46	0	100	−3.3	−0.5	0.1	0.9	4.7	0.2
10–14	S	23,840	69	12	88	−5.9	−1.1	−0.3	0.5	4.9	−0.3
OS 2 Mon-Fri	W	31,565	54	0	100	−3.8	−0.9	−0.1	1.2	4.4	0.0
23–04	S	24,074	80	2	98	−6.7	−1.8	−0.6	0.5	5.0	−0.6
OS 3 Sat-Sun	W	53,114	50	0	100	−3.8	−0.8	0.0	1.4	7.3	0.1
00–24	S	45,635	76	9	91	−6.3	−1.9	−0.6	0.8	5.8	−0.6

m^3 [29] during thermal winter and between −0.6 … -0.3 g/m^3 during thermal summer.

The moisture excess values in Table 6 behaved logically in such a way, that the winter-time values were always above the summer-time values (e.g. +0.1 g/m^3 vs −0.3 g/m^3 at 50 % percentiles at OS 1). Exceptions to this were the 100 % percentiles in OS 1–3, but these maximum values could be caused by single events, which does not represent to overall indoor air moisture excess behaviour.

The recommended design values for indoor air moisture excess in schools and day-care centres in the national guideline RIL 107–2022 is currently +3 g/m^3 during winter ($T_e \leq +5$ °C) and +1 g/m^3 during summer ($T_e \geq +15$ °C). The values in Table 6 fit into these limits, so there does not seem to be need for making the moisture excess design values stricter for schools and day-care centres.

A simple hand calculation was presented in Ch. 1.2, in which the indoor air moisture excess was 1.5 g/m^3. In Table 6, the indoor air moisture excess 90 % percentiles in winter conditions were 1.1 g/m3 (OS 0, all data), 0.9 g/m3 (OS 1, weekdays), 1.2 g/m3 (OS 2, weeknights) and 1.4 g/m3 (OS 3, weekends) for different operating situations. The mean and median values for moisture excess were close to zero or even negative. This means that the measured indoor air moisture excess was lower than what could have been expected based on a simple hand calculation. Possible reasons for this difference are essentially lower moisture production rate or higher ventilation rate compared to assumptions in the simple calculation. Lower moisture production rate could have occurred due to lower occupancy or lower moisture production per person, when compared to the used literature values. Higher total ventilation rate in (m^3/s) is currently considered unlikely compared to the values used in the example, but one reason could be that the true ventilation flows transport humidity more efficiently away from the zones. This could happen if the assumption of well-mixed air does not apply to the rooms, but the vapour concentrations should be calculated by taking the actual air flow paths into account.

3.2. Distributions of variables by operating situation and thermal season

Distribution of indoor air temperature weekly averages in different situations are shown in Fig. 2.

The indoor air temperature had triangular or normal-like distribution both during thermal winter and thermal summer. The peak of the whole week curve (OS 0) was at 20.8 °C during thermal winter and 21.3 °C during thermal summer. During thermal winter the indoor air temperature density function maximum was at about 21.3 °C for OS 1, which is about 0.5 °C higher compared to night-time and weekend conditions. During thermal summer to peak of OS 3 (weekends) was on the other hand little bit lower than that of OS 1 or OS 2 (weekdays and weekday nights).

Based on visual inspection of Fig. 2, the winter-time indoor air relative humidity distribution was close to a triangular distribution that is little skewed to the left (values between 5 % RH – 30 % RH, mean at 19 % RH). The summer-time distribution on the other hand was closer to uniform distribution or wide normal distribution, where the values were between 25 % RH and 62 % RH, and the mean being at 42 % RH.

The distribution of indoor air moisture excess weekly averages had a maximum point at −0.5 g/m^3 during both thermal winter and thermal summer on operating situation OS 0. The mean of the whole data (OS 0) was 0.0 g/m^3 for thermal winter and −0.5 g/m^3 for thermal summer. The winter-time moisture excess density functions were visibly right-skewed, but the summer-time moisture excess density functions were symmetric. For both winter and summer situations, the occupied operating situations OS 1 had density functions higher compared to non-occupied operating situations OS 2 and OS 3.

3.3. Classification of conditions at the occupied hours (OS 1)

Indoor air temperature was classified according to instruction card Classification of Indoor Environment 2018 of The Building Information Foundation RTS [34]. The results are visualized in Fig. 3. The dashed lines describe the minimum and maximum temperatures that should not

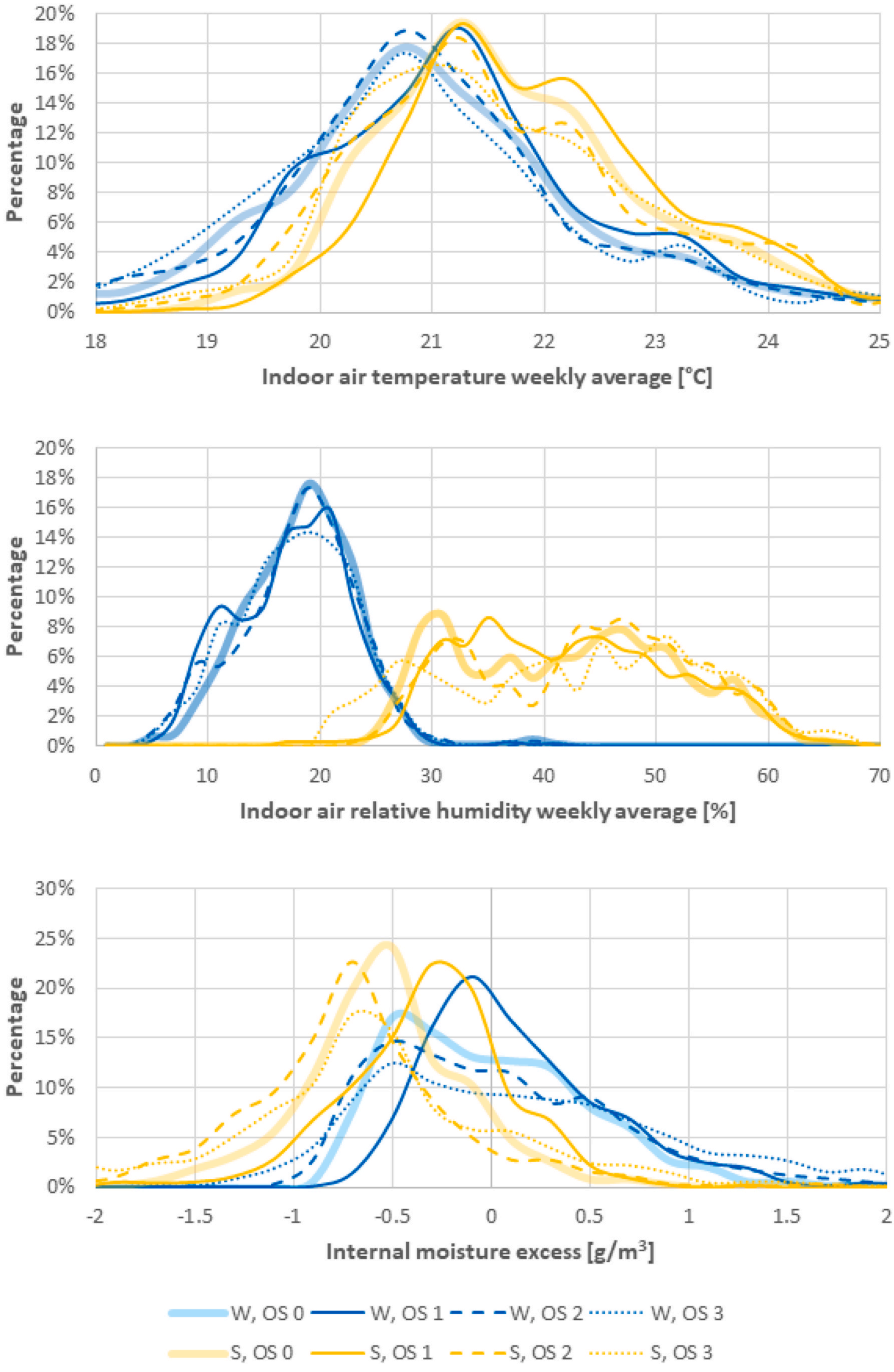

Fig. 2. Weekly averages of indoor air temperature, relative humidity and moisture excess. W = Winter, S = Summer, OS = Operating situation.

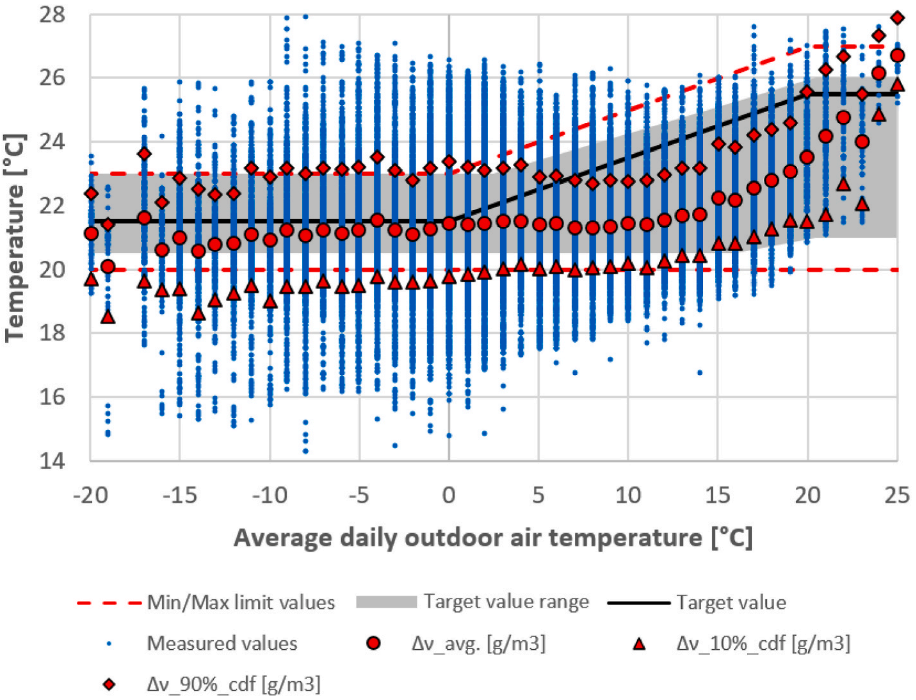

Fig. 3. Hourly indoor air temperature (blue dots) compared to operational temperature classification limits from the Classification of Indoor Environment 2018. The figure contains all the measurement points. The diamonds, dots and triangles describe the bin 90 % cdf value, mean and 10 % cdf value, respectively [34] (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

be crossed. The grey area describes the recommended range.

The visualization in Fig. 3 shows all measured data from the 104 comparable spaces. Classification of individual spaces was done according to the instruction card [34]. Deviation Limit value requirements of classification level S2 are met for the majority of the data. However, the requirement of 90 % permanence within the allowed range (grey area in Fig. 3) is not fulfilled. Therefore, the requirements of classification level S2 are not met, and all the studied buildings belong to classification level S3. During the examined data of occupied hours, 25 % of the data is below and 6 % above the allowed range. 20 case buildings have more values above and 6 buildings have more values below the allowed range.

During warm summer conditions ($T_e \geq 20$ °C) the indoor air temperature started to increase past the recommended range. If the outdoor air temperature was hot ($T_e \geq 25$ °C), then practically all measured buildings had indoor air temperature that exceeded the recommended range. It should also be noticed that the values in Fig. 3 contain only the occupied hours and the indoor air temperatures during e.g. summer holidays could be higher than what is seen in Fig. 3.

The indoor air relative humidity as a function of outdoor air temperature is shown in Fig. 4 [4].

Examination of the numeric relative humidity data shows that indoor air relative humidity stayed below the EN ISO 13788 design values (class A, normal occupancy) for the most part, as almost 99 % of the data is inside below the design values line. During thermal winter, the indoor air humidity stayed below the design values constantly. Almost 96 % of the design value exceedings are during thermal summer. For the summer conditions, the EN ISO 13788 Class B (high occupancy, 70 % RH at summer) would cover the also the summer-time values in Fig. 4. Similar discussion applies to indoor air relative humidity design values shown in EN 15026 [35].

Visual examination of Fig. 4 shows that the mean and 90 % percentiles were well below the design value curve especially below −10 °C outdoor air temperature, but there were some exceedances during warm (above +15 °C) outdoor air temperature conditions. This could imply that a descriptive curve of the indoor air conditions would start from a lower level and rise more steeply towards warmer conditions. The discontinuities in the data at temperature conditions above +20 °C are due to the non-occupancy periods of schools and day-care centres being filtered out. The variation in indoor air relative humidity decreased towards colder outdoor air temperature and increased towards warmer temperature.

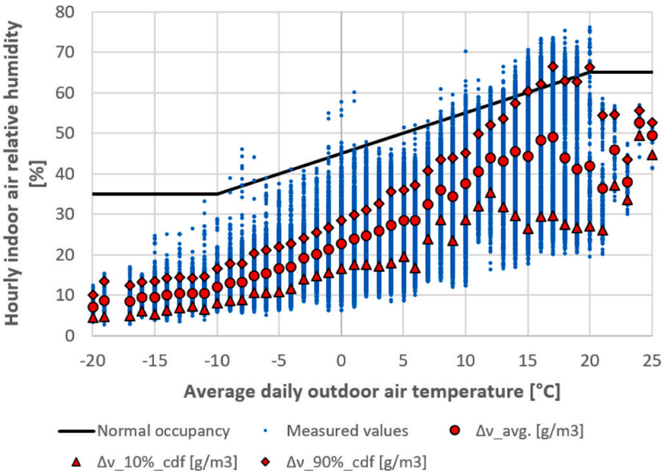

Fig. 4. Hourly indoor air relative humidity (blue dots) compared to average daily outdoor air temperature. The solid line represents the design value given in EN ISO 13788:2012. The data contains all the measurement points. The diamonds, dots and triangles describe the bin 90 % cdf value, mean and 10 % cdf value, respectively [6] (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The indoor air moisture excess as a function of outdoor air temperature is visualized in Fig. 5. Each measurement point is represented with a grey line. The 90 % percentile values for each 1 °C temperature step per outdoor air temperature is represented with a red dot.

Weekly average values (averages of individual weeks) of the

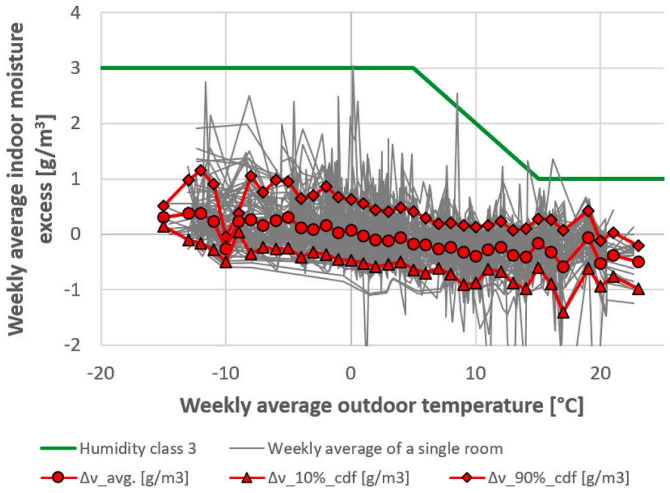

Fig. 5. Indoor air moisture excess as a function of outdoor air temperature. Each grey line represents one measurement point. The diamonds, dots and triangles describe the bin 90 % cdf value, mean and 10 % cdf value, respectively, calculated for each 1 °C outdoor air temperature bin. The solid line is the national recommendation [33] for indoor air moisture excess design value at schools and day-care centres.

occupied operating situation OS 1 data were used for both indoor air moisture excess and outdoor temperature. The use of weekly averages is justified because the envelope structures are affected by long term humidity conditions rather than momentary variation as stated in previous studies [6,25].

Visual examination of the weekly averages of occupied hours in Fig. 5 shows that even when focusing on the upper 10 % critical values, the indoor air moisture excess is within design values of the strictest humidity class. Indoor air water vapour concentration is in balance with outdoor air water vapour concentration and averages slightly in the moisture deficit side compared to external conditions. The result of the combined 26 case buildings indicate that the mechanically ventilated municipal school and day-care buildings have a sufficient air change rate in perspective of indoor air humidity as they are designed to keep carbon dioxide and other pollutants at moderate level during high occupancy.

3.4. Impacts from night-time ventilation shutdown

Fig. 6 shows a comparison between two measurement periods. Red line connects reference conditions with ventilation system run as usual. The blue line connects the altered conditions, where the mechanical ventilation system was shut down over night and restarted 2–3 h before first users arrived in the building.

Before analysing the results, it is important to notice that between the two 11-week comparison periods the average outdoor air temperatures were close to each other, but the conditions were not identical. The HVAC system of the building also adjusts the indoor air temperature, so the indoor air temperature should in any case be close to the indoor air temperature set-point values. Because of this the pre-assumption is that the indoor air temperature between the two periods would likely show some amount of differences, but not very big. Also, in Fig. 6 the temperature data is given as function of the hour of the day, but there are correlations to other factors, such as outdoor air temperature (Fig. 3).

Indoor air temperature was slightly higher during the period with altered ventilation arrangements, compared to the regular situation. On average, the mean values were 0.3 °C higher when the ventilation was shut down over night as mean values were 20.7 °C for the normal comparison period and 21.0 °C for the altered comparison period. A diurnal cycle is also visible in the results data, such that the night-time temperature was approximately 0.5 °C cooler than the daytime temperature.

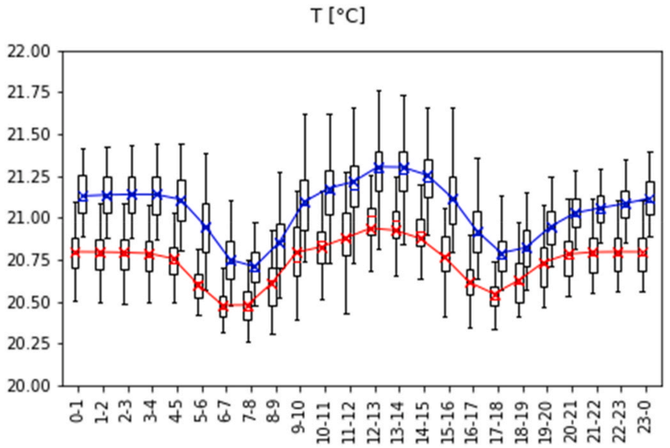

Fig. 6. Comparison between two time periods, where red line and corresponding box plots represent the time period when mechanical ventilation was run as usual. The blue line represents the time period when the mechanical ventilation system was shut down completely during night-time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Because similar temperature differences and overall diurnal behaviour is conditions of both measurement periods, the results imply that shutting down the night-time mechanical ventilation had either a small or non-existent impact on indoor air temperature.

Results for indoor air relative humidity are shown in Fig. 7.

The average indoor air relative humidity was quite stable with respect to the diurnal cycle in both time periods. On average, the mean values are 3.8 % RH lower when the ventilation was shut down over night as mean values were 21.0 % RH for the normal comparison period and 17.2 % RH for the altered comparison period. This change in relative humidity could be explained by average temperature difference, when taking also Figs. 6 and 8 into account.

The typically-run reference period contained larger variation in indoor air relative humidity when compared to the time period with altered ventilation arrangements. The average outdoor air temperature was similar between the two periods, but there could be a variation in the outdoor air temperature within the period, similar to Fig. 4, which

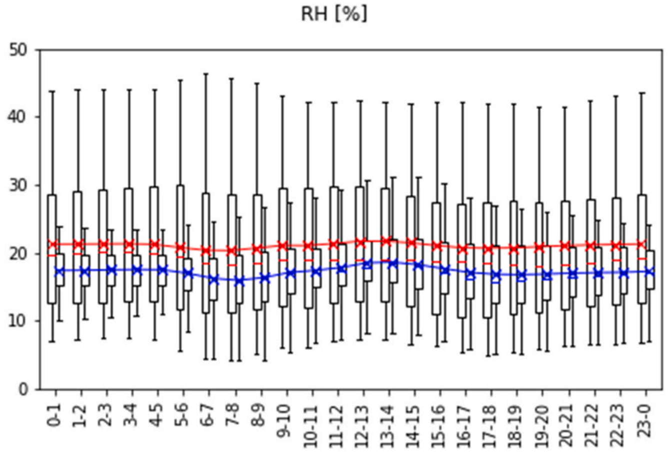

Fig. 7. Comparison between two time periods, where red line and corresponding box plots represent the time period when mechanical ventilation was run as usual. The blue line represents the time period when the mechanical ventilation system was shut down completely during night-time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

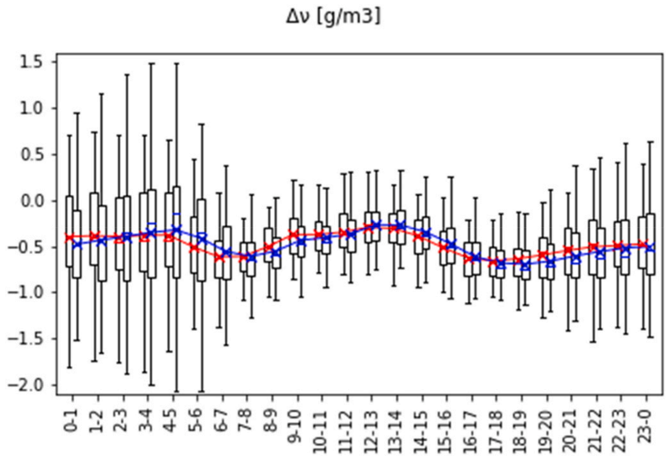

Fig. 8. Comparison between two time periods, where red line and corresponding box plots represent the time period when mechanical ventilation was run as usual. The blue line represents the time period when the mechanical ventilation system was shut down completely during night-time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

would explain the difference in variation in Fig. 7.

Results for indoor air moisture excess are shown in Fig. 8.

Overall, the indoor moisture excess was very similar between the two periods. The main reason for this was likely that the moisture excess was close to zero due to the strong daytime ventilation rates. On average, the mean values were calculated 0.01 g/m^3 lower when the ventilation was shut down over night as mean values were −0.47 g/m^3 for the normal comparison period and −0.48 g/m^3 for the altered comparison period.

Fig. 8 shows that the red (reference) and blue (altered) lines for the mean moisture excess change order within the daily cycle. In principle, the changes in ventilation rates and moisture transfer could have a relationship to the moisture buffering effects in the zones. If there was an impact from moisture capacity of building materials and furniture on the moisture excess values, then based on Fig. 8 this was small when evaluating a larger group of buildings.

4. Conclusions

This paper presented field measurement results of temperature and humidity conditions of schools and day-care centres. The data was compiled from two large research projects and included indoor air temperature, relative humidity and moisture excess from 26 Finnish schools and day-care centres with mechanical ventilation. The total number of studied spaces was 104, which were used by building personnel and the dependents. The measurement periods were divided according to thermal winter and summer and four operating situations, that describe the different occupied and non-occupied time periods within a week. The main focus of the analysis was on occupied weeks and weekday hours.

The indoor air temperature was mainly stable and stayed at moderate levels throughout the year. However, during operating hours in thermal winter, 34 % of the studied spaces had more than 10 % of the measured temperature values were below recommended range. Utilizing the limits presented in the Finnish Classification of Indoor Environment, the indoor air temperature was classified to level S3 in all buildings mainly due to values below allowed range of upper classification level S2.

When the outdoor air temperature increased above 20 °C and especially above 25 °C, the indoor air temperature increased to high levels and past the recommendations. The holiday weeks during midsummer was not included in these values, because the building users are typically not present during that time.

Indoor air relative humidity was very low during the thermal winter, which resulted in poor performance with regards to the recommended range. Dry indoor air can have a negative effect on the indoor air quality experienced by the users, causing skin and eye irritation. Dry indoor air during winter was deduced to be a consequence of effective mechanical ventilation that is designed to keep carbon dioxide and other pollutants at moderate level during high occupancy. This however at the same time leads to low indoor air indoor air moisture excess values, which again during cold outdoor air temperature conditions lead to low indoor air relative humidity.

The current national recommended indoor air moisture excess design values are 3 g/m^3 during winter and 1 g/m^3 during summer, which cover the current moisture excess values in the studied buildings. If the indoor air relative humidity according to EN ISO 13788 or EN 15026 would be assigned, then the both Class A (normal occupancy) and Class B (high occupancy) would cover the winter-time conditions, but Class B would better cover the conditions during summer.

Overall, the winter-time low relative humidity in public buildings has been recognized in the previous studies, but the constantly low values of indoor air moisture excess was somewhat surprising. The low indoor air relative humidity can negatively affect the building users, so the utilization of humidification of indoor air during winter should be investigated further. The low level of indoor air moisture excess prevents moisture problems in the building envelope from diffusion and exfiltration, so if humidification would be installed, good moisture performance of the building envelope should be ensured at the same time. The reason for the large portion of moisture deficit values should be also studied further, because it might improve the understanding on how to best control the moisture levels in the indoor air.

Funding

Research project COMBI was funded by the European Regional Development Fund [grant number A70256]; Tekes—The Finnish Funding Agency for Innovation [grant number 4676/31/2014]; and 37 companies.

Research project Future Spaces was funded by the public Finnish innovation funding agency, Business Finland, with co-innovation [grant number 33250/31/2020]; and 5 companies.

CRediT authorship contribution statement

Tuomas Raunima: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Anssi Laukkarinen:** Writing – review & editing, Software, Project administration, Methodology. **Antti Kauppinen:** Investigation. **Mihkel Kiviste:** Investigation. **Eero Tuominen:** Methodology, Investigation. **Joonas Ketko:** Visualization, Software. **Juha Vinha:** Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The contributions from Joni Pirhonen to the installation of the field measurements in COMBI project. Mikko Viitala to the disassembly of the field measurement installations in COMBI project, maintenance of the equipment and help with the installation of the field measurements in

Future Spaces project.

Appendix A

Table A1
Studied case buildings and their descriptions. Case buildings are originated from COMBI project, Future Spaces project or both. Further information on the measured buildings is given in Ch. 2.1.

Case	Area	Building Use	Construction Year	Original Project
1	Pirkanmaa	Day-care centre	1983	COMBI
2	Pirkanmaa	Day-care centre	2019	Future Spaces
3	Pirkanmaa	Day-care centre	1986	Future Spaces
4	Pirkanmaa	Day-care centre and school	2018	Future Spaces
5	Pirkanmaa	School	2018	Future Spaces
6	Pirkanmaa	Day-care centre	1980	COMBI
7	Pirkanmaa	Day-care centre and school	2014	Future Spaces
8	Pirkanmaa	Day-care centre	1904	COMBI + FS
9	Pirkanmaa	Day-care centre	2012	COMBI + FS
10	Pirkanmaa	School	1964, 1990	FS
11	Pirkanmaa	Day-care centre and school	2013	COMBI + FS
12	Pirkanmaa	Day-care centre and school	2014	COMBI + FS
13	Pirkanmaa	School	1952, 2006	COMBI + FS
14	Pirkanmaa	Day-care centre and school	2012	COMBI + FS
15	Pirkanmaa	Day-care centre	2016	COMBI
16	Pirkanmaa	School	2012	COMBI
17	Helsinki	Day-care centre and school	2015	COMBI
18	Helsinki	Day-care centre and school	2012	COMBI
19	Helsinki	Day-care centre and school	2013	COMBI
20	Helsinki	Day-care centre	1981	COMBI
21	Helsinki	Day-care centre	2013	COMBI
22	Helsinki	Day-care centre	2015	COMBI
23	Helsinki	Day-care centre	1971	COMBI
24	Helsinki	Day-care centre	1976	COMBI
25	Helsinki	School	1966	COMBI
26	Helsinki	School	1962, 1965	COMBI

Table A2a
Studied spaces and description for case buildings 1–13. Spaces are originated from COMBI project (C), Future Spaces project (F) or both (C + F).

Project	Space Id	Description	Project	Space Id	Description
C	1_1	Staff Room	F	10_1	Corridor
C	1_2	Playroom	F	10_2	School class
F	2_1	Group space	C + F	11_1	Group space
F	2_2	Group space	F	11_2	Group space
F	2_3	Hall	C + F	11_3	Consulting room
F	3_1	Group space	C + F	11_4	School class
F	3_2	Group space	F	11_5	School class
F	3_3	Group space	F	11_6	School class
F	4_1	Group space	F	11_7	School class
F	4_2	Group space	C	11_8	Office room
F	4_3	Staff Room	C	11_9	Corridor
F	4_4	School class	C	11_10	Staff room
F	5_1	Lounge	C	11_11	Hall
F	5_2	School class	C	11_12	Textile class
F	5_3	School class	C + F	12_1	Group space
C	6_2	Playroom	F	12_2	Group space
F	7_1	Group space	F	12_3	School class
F	7_2	Group space	F	12_4	School class
F	7_3	School class	C + F	13_1	School class
F	8_1	Group space	C	13_2	Staff room
C + F	8_2	Group space	F	13_3	School class
C	8_3	Office room	F	13_4	School class
F	9_1	Group space	F	13_5	School class
C + F	9_2	Group space	C + F	13_6	School class
C + F	9_3	Hall	C	13_7	Staircase

Table A2b
Studied spaces and description for case buildings 14–26. Spaces are originated from COMBI project (C), Future Spaces project (F) or both (C + F).

Project	Space Id	Description	Project	Space Id	Description
F	14_1	Group space	C	21_1	Group space
C + F	14_2	Group space	C	21_2	Group space
F	14_3	School class	C	21_3	Hall
F	14_4	School class	C	21_4	Group space
C	15_1	Group space	C	22_1	Group space
C	16_2	School class	C	22_2	Office room
C	16_3	Multi-function room	C	22_3	Office room
C	16_4	Dining room	C	22_4	Staircase
C	16_5	School class	C	22_5	Lobby
C	17_1	Hall	C	22_6	Lobby
C	17_2	School class	C	22_7	Group space
C	17_3	Gym	C	23_1	Group space
C	17_4	Corridor	C	23_2	Group space
C	18_1	School class	C	23_3	Staff room
C	18_2	Group space	C	23_4	Group space
C	18_3	Group space	C	24_1	Group space
C	18_4	Group space	C	24_2	Group space
C	18_5	Dining room	C	24_3	Group space
C	18_6	Gym	C	24_5	Lobby
C	19_2	Group space	C	25_1	School class
C	19_3	Gym	C	25_2	School class
C	19_4	Hall	C	25_3	Gym
C	20_1	Group space	C	25_4	School class
C	20_2	Hall	C	25_5	Music class
C	20_3	Corridor	C	26_1	School class
C	20_4	Corridor	C	26_2	Dining room

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