Parametric simulation to optimize moisture removal from urban apartment blocks

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Abstract. This study utilizes building energy simulation software, to explore indoor humidity management in urban apartments. A novel approach is employed to generate moisture load profiles, calibrated against real-world data. Findings suggest that current TEK-17 airflow regulations may not adequately address varying apartment sizes and usage scenarios, potentially leading to suboptimal indoor relative humidity levels. This research advocates for a more nuanced ventilation strategy, emphasizing tailored solutions based on apartment characteristics. Such insights could inform future building codes, enhancing indoor air quality and energy efficiency in residential buildings in cold climates.

1 Background

This study was conducted as a part of the project Healthy Energy-Efficient Urban Home Ventilation which aims at providing guidelines for mechanical ventilation in the urban residential context. Of special interest is therefore ventilation in apartments of different sizes.

In Norway, mechanical balanced ventilation with efficient heat recovery is regarded as mandatory in residential housing projects to comply with indoor air quality (IAQ) and energy efficiency regulations in the building code (TEK-17). Mechanical balanced ventilation has been the standard system choice for housing units for the last decades, as the requirements in the building code limits the viable options for system design. Indoor air must not flow from rooms of lower IAQ requirements to rooms of higher IAQ requirements. In practical terms for apartments, this means that supplied air by the mechanical ventilation must be supplied to occupied spaces like bedrooms and living rooms, while being removed from unoccupied spaces like the kitchen and bathrooms. Additionally, outdoor air of unsatisfactory quality shall be purified before being supplied into the buildings which means that air handling units (AHU) with efficient air filtering is necessary. Residential housing can fulfil the energy requirements either by complying with pre accepted solutions or fulfilling allowed energy budgets as outlined in the Norwegian building code TEK17 [1]. TEK-17 governs the choice of the base airflow rates in housing units, which is set to 36 m^3/h for per kitchen, WC or laundry room and 54 m^3/h for the bathroom. Furthermore, bathrooms, kitchens and laundry rooms must also have the possibility for forced airflow rates for extraction of 108 m^3/h, 108 m^3/h and 72 m^3/h, respectively.

Often the case, different sized apartments can have the same airflow rate for their mechanical ventilation systems. For example, a small-sized student apartment may have the same airflow rate as a medium to large-sized apartment if they both only have one kitchen and one bathroom. This can however result in vastly different air changes per hour (ACH caused by the mechanical ventilation and thus influence IAQ parameters such carbon dioxide (CO_2) levels, relative humidity (RH), temperature as well as energy use for space heating and mechanical ventilation. The role of the ACH in mitigating undesired levels for IAQ parameters can also lead to conflicting objectives. While a higher ACH can be beneficial for reducing pollutant concentrations, it may concurrently lead to increased energy use and excessive low RH in colder climates. Prior studies on the impact of the ACH on IAQ and energy use have focused on single-family dwellings, while few have studied apartments [2]. With the evolution of the building code, residential buildings in Norway have become very energy efficient with well insulated and air-tight building envelopes [3]. The mechanical ventilation system therefore plays a crucial role in the resulting ACH of buildings while also making the indoor environment susceptible to dry conditions during cold weather which can result in health issues for the occupants [4] .

Building energy simulations (BES) software can be a powerful tool for analysing resulting IAQ and energy use in buildings upon variations of multiple parameters. IDA Indoor Energy and Climate (IDA-ICE) can predict energy consumption of HVAC technologies as well as thermal climate, CO_2 concentrations and indoor RH. It is however important to realize the limitations of the approach, as only rough estimates are given as the equations are solved at a central node and at the boundaries of a zone, which is usually a room in the

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simulation model [5]. A room can be divided into finer zones, but at the cost of computational power. However, if the analysis of very local and momentary effects are the goal of the study, other methods and tools will be more suiting. The power of the BES for studying IAQ lies in the computational efficiency, enabling the possibility to vary a vast number of variables which would otherwise be difficult to study. The build-up and decay of IAQ variables over time in rooms has a well understood mathematical relation with the ACH [2].

Using BES to simulate indoor RH has most commonly been studied with specialized humidity models to account for moisture buffering effects of building materials [6]. However, specialized models can compromise the utility for studying a multitude of effects simultaneously as one may need a tool that can accurately account for effects that may require features such as e.g. detailed HVAC modelling, advanced heat and energy balance, dynamic thermal material properties, ray tracing, window airing and occupancy behaviour models. IDA-ICE is a powerful tool with a comprehensive tool-box of building physics models while retaining effective simulation times with complex models [7]. Although it lacks a model for moisture buffering effects of materials, it can account for other effects in the moisture balance such as moisture production and supplied, removed and recovered moisture through mechanical ventilation. While moisture buffering in hygroscopic building materials is well agreed on as a physical phenomenon, it's impact on the indoor RH in real buildings and lack of consistent lab results remains a controversial topic [8]. Under the assumption that moisture buffering acts as a short-term dampening effect of momentary peaks in indoor RH and that mechanical ventilation airflow rates and outdoor climate are more important for the long-term indoor RH levels, a novel approach of this study is to include indoor RH as a parameter of study in parametric simulations of ventilation airflow rates with IDA-ICE.

2 Methods

The methods used in this study are summarized as follows:

- IDA-ICE modelling of three typical apartment layouts of different sizes, collected from building developers.
- IDA-ICE modelling of two AHUs with plate heat exchanger for no moisture recovery and rotary heat exchanger for some moisture recovery
- Creating usage profiles based on questionnaires.
- Creating moisture production profiles
- IDA-ICE modelling of a student apartment for validation of showering profiles, indoor RH and CO_2 levels
- Parametric runs for the three apartments, combining AHUs, user and moisture profiles with varying amounts of airflow rates.

2.1 Modelling apartments and AHUs

Three apartment layouts were chosen based on a desired diversity of floor area and ventilation setup of supply and extract air overflow and can be seen in Figure 1. All apartments are designed by TEK-17 standard and have external solar shading. Table 1 summarizes the most important details of the apartments. Due to the same number of bathrooms and kitchens, apartments 1 and 2 have the same airflow rate for the baseline case of TEK-17, but vastly different ACH due to the differences in room volume. However, a max user load scenario would naturally be lower in the smaller apartment. Apartment 2 and 3 has approximately the same total ACH even though they are different in size. However, the living room of apartment 3 will have a locally lower ACH than any room in apartment 2 due to the apartment layout that realistically would need balancing of air in the living room to suffice good air circulation. Figure 1 shows where supply and extraction vents are placed in each apartment.

Two AHUs were modelled with different heat exchanger configurations. The goal was to model a plate heat exchanger with no moisture recovery to serve as a worst-case scenario when combined with low moisture production indoors, and a typical rotary heat exchanger that can recover some moisture when extract air condensates on the rotor blades. This would serve as a worst-case scenario with heavy moisture production indoors.

For the plate heat exchanger model, a simple air to air plate heat exchanger called "HXSIMCTR" in IDA-ICE was used. This has no moisture transfer between the air streams. The temperature efficiency was set to 80% and the frost protection mode to 1°C. For the rotary heat exchanger, the simplified model called "Enthalpy Wheel" was used. The real physics of moisture recovery in the heat exchanger is indeed complex and will depend on many variables. A general model that is viable for all cases might not be possible to achieve. The simplified model was developed based on FprEN 16798-5-1:2016 specification and is only intended to give a rough estimate of the effects of moisture recovery by mechanical ventilation, as it resembles no specific product or configuration. The model is capable of estimating moisture recovery through condensation, as well as via hygroscopic and sorption wheels. However, the default setting of condensation was used, as relying heavily on moisture recovery for the results introduces a significant degree of uncertainty. The model estimates a humidity efficiency that changes as a linear function of condensation potential, the difference of the humidity ratio of warm air with humidity ratio of saturated cold air. The frost protection mode was set to -10°C and the temperature efficiency was adjusted to be approximately 80%. Preliminary testing showed the humidity efficiency to often approach 30% when condensation took place over the rotor.

Table 1. Specifications of the modelled apartments.

Apartment no.	1	2	3
Floor area (m^2)	30	47.5	71
Room volume (m^3)	73	112.5	166.5
Supply vents	1	2	3
Extract vents	1	2	3
Bedrooms	1	2	2
Living rooms	1	1	1
Bathrooms	1	1	1
WC	0	0	1
Max occupancy	2	4	4
Base airflow rate (TEK-17, m^3/h)	90	90	144
ACH at base rate (total, h^{-1})	1.23	0.80	0.86

Fig. 1. The 3 apartments that were modelled and investigated in this study. Apt 1: 30 m^2, Apt 2: 47.5 m^2, Apt 3: 71 m^2. The blue dots indicate the placement of supply vents, while the red dots indicate extract vents.

2.2 User scenarios use and moisture loads

The methodology of creating input data for the moisture profiles is described in detail by Holøs et al [9]. For the moisture production from showering, IDA-ICE was used as a method. Three user load profiles were established based on a combination of user surveys from the project, and the authors' own experience from the typical lifestyles of the Norwegian culture. The easy load scenario is representative for when an apartment is only occupied by one person, regardless of apartment size, and there are no moisture producing events. This scenario represents a risk for dry conditions indoors. The normal scenario is a more typical day where an apartment might be unoccupied during working hours, and there are a couple of showers and preparation of a hot meal when occupied. The heavy load scenario is representative for days when the apartments are occupied 24h and multiple moisture events are occurring throughout the day, which can be realistic on occasions for families living together. This scenario represents a risk for excessive moisture buildup indoors.

Table 2. Moisture loads for the simulations.

Moisture loads	Moisture production	Duration
Showering	19.92 g/min	10 min
Hot meal	Heavy load scenario : 33 g/min Normal load scenario: 22 g/min	20 min
Drying of clothes on rack	3.5 g/min	4 h

2.3 Parametric simulations

2.3.1 Climate data and simulation settings

Three climate data files from Oslo, Norway were considered for the simulations. The ASHRAE file is from the ASHRAE IWEC2 databse and is a TMY for Fornebu, Oslo which is a coastal area outside of the city center. Most of data in the file stems from the 1990's. The Tek-Sjekk file contains data for Blindern, Oslo which is close to the city center of Oslo. The file was created by OsloMet University, and used for an in-house developed BES software. The ERA5 file is a TMY also for Oslo, Blindern which was created by Wu. et al in 2022 and stems from the ERA5 database [10]. The climate file contains metrological data for the period 2006-2020.

Figure 2 displays the full year outdoor dry-bulb temperature for all 3 climate files. Generally, these files align quite well with each other. Conducting a thorough analysis of climate data is a complex and time-consuming task. It is desired to have a dataset with multiple climate parameters that fits both the average trends while still containing the natural variations of day-to-day shifting weather. The rare and absolute extreme weather periods was not prioritized to include, as the focus of this study is more on general assessments of typical and current conditions. The selection of climate the climate file involved a manual inspection of the files, comparing them with Oslo's new temperature norm from 1991-2020 and recent trends in outdoor dew-point temperatures. The ERA5 file was selected due to its satisfactory data quality and its basis on more recent meteorological data.

Table 3. User scenarios for the simulations.

User scenarios	Kitchen / living room	Bathroom	Bedrooms
1: Easy load	For A01, A02 & A03: 1 person (20:00 – 23:00)	For A01, A02 & A03: No events	For A01, A02 & A03: 1 person in main bedroom (23:00 – 06:00)
2: Normal load	For A01, A02 & A03: 2 persons (06:00 – 08:00, 16:00 – 23:00)	For A01, A02 & A03: 2 showers (06:30, 22:00)	For A01, A02 & A03: 2 persons in main bedroom (23:00 – 06:00)
3: Heavy load	For A02 & A03: 4 persons (06:00 – 08:00, 16:00-23:00) 2 persons (08:00 – 16:00) 1 hot meal (17:00-17:20) Dry clothes on rack (18:00 – 22:00) For A01: 2 persons (06:00 – 23:00) 1 hot meal (17:00-17:20) Dry clothes on rack (18:00 – 22:00)	For A02 & A03: 6 showers (06:30, 07:00, 16:30, 17:00, 22:00, 22:30) For A01: 4 showers (07:00, 17:00, 22:00, 22:30)	For A02 & A03: 2 persons in main bedrom (23:00 – 06:00) 2 persons in sec. Bedroom (23:00 – 06:00) For A01: 2 persons in main bedroom (23:00 – 06:00)

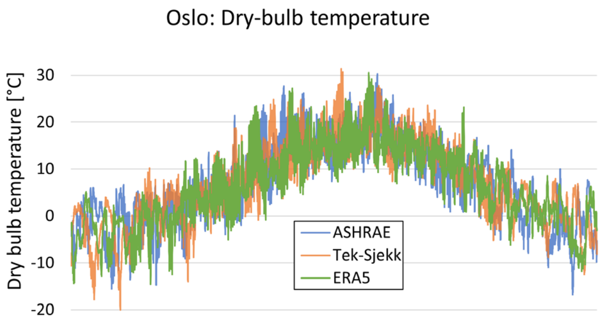

Fig. 2. Weather data for simulations.

2.3.2 Parametric run setup

The simulation was run for a full year with dynamic timesteps with a maximum step size of 15minutes. Most often when rapid changes of variables occur, IDA-ICE solves the differential equations at very fine timesteps.

For the parametric run of airflow rates, the two AHU models were combined with all user load scenarios for every single airflow rate, which is shown in Table 4. For the baseline case that follows current TEK-17 regulations, forced ventilation according to the regulations were applied when showering and preparation of hot meals took place.

Table 4. Parametric simulation set-up.

Simulation case	Ventilation principle	Airflow rate (m^3/h)
Baseline (TEK-17)	VAV	A01: 90 A02: 90 A03: 144
Parametric run	CAV	26, 40, 54, 78, 90, 144, 180, 250

An important strategy for the simulations is that every usage scenarios are repeated every single day throughout the year, where a realistic use of buildings would of course entail variations from day to day. The choice of strategy was based on a preliminary observation where it was apparent that the outdoor weather affects the indoor conditions by a great deal. By repeating the usage scenarios every day, we can capture problematic combinations of outdoor weather and different user load scenarios.

2.4 Calibration of moisture production from showers and comparison of IAQ against measured data

For the moisture events of showering, finding typical occupant behaviour is explained by Holøs et al [9]. However, the moisture production varied greatly in reviewed literature and posed an uncertainty. Field measurements from student apartments in Ås, Norway logged the indoor temperature, RH and CO_2 levels at multiple points for a couple of weeks [11]. Although the measurement setup was not strictly intended for calibration of simulation models, the showering events showed clear and consistent enough spikes for the indoor RH levels in the bathroom and extraction air that a calibration of the moisture load was attempted. As a first attempt, the moisture load was modelled as a constant emission of dry vapor for the estimated duration of the showers based on when the absolute moisture content of the air started to drop. It was assumed that this would drop immediately after the showers ended due to the extraction vent in the room and overflow of drier air into the bathroom.

Furthermore, by modelling the apartments realistically and simulating the measurement period with a climate file created based on measurements from a nearby weather station, it was tempting to investigate how simulated indoor RH levels would compare to the measurements. The building envelope of the apartment was based on known energy efficiency of the building. The mechanical ventilation airflow rates were also measured on-site and used as input. As the apartment was used by students during the measurements without perfect knowledge of ground truth in occupant behaviour, it was expected to be difficult to hit exact agreements with measurements. However, as especially indoor RH is not commonly studied with IDA-ICE in the literature, it would be interesting to see if the model comes close with a best guess of occupant behaviour based on the trajectory of measured IAQ parameters. Figure 3 shows a photo of the student apartment and 3D view of the IDA-ICE model.

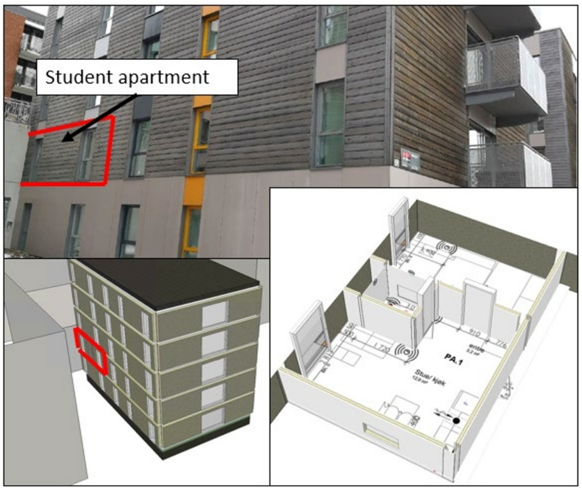

Fig. 3. The student apartment that was modelled in IDA-ICE.

3 Results and discussion

3.1 Calibration of moisture production for showering

Figure 4 shows the measurement data for RH in the bathroom, where the occurrence of showering events is clear with high spikes in RH. As the RH is dependent on indoor temperature as well as moisture content of the air, the water vapor content (v) was calculated when calibrating the moisture load. Figure 5 shows every showering event lined up after each other. The starting point of v for each event was aligned in post processing of the data, as the simulations could have a slight mismatch in the simulated water vapor content of the apartment. The moisture load was modelled as a constant emission of dry water vapor as long as the shower duration lasted, and various load strengths were simulated. Best fit was found for a moisture production of 0.33 g/sec with a R^2 of 0.86, CV_{RMSE} of 11.9 and NMBE of 1.66.

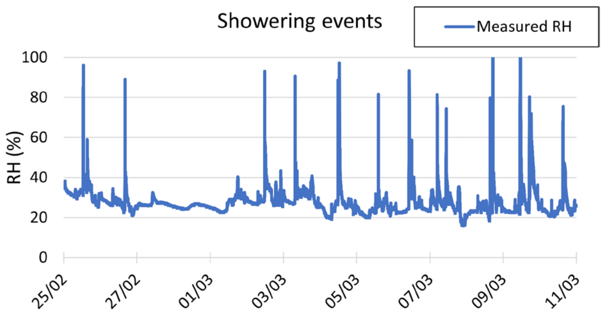

Fig. 4. Measured RH in the bathroom

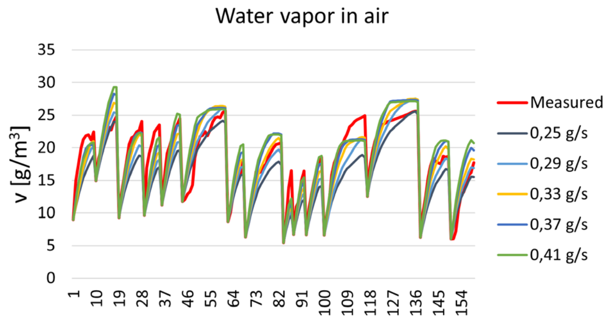

Fig. 5. Calibration of moisture loads in IDA-ICE.

Figure 6 shows the time series comparison between simulations and measurements from the bathroom for a selection of showering events. As one would expect from field measurements, some stochasticity is present but the simulations line up very well with many of the events. Figure 6a, h and f, almost perfect alignment of the water vapor content of the bathrooms. Moreover, in figure 6g, sudden drops can be seen in the measured curve after the showering when the moisture content steadily decays in the room. This is likely caused by the occupants opening the bathroom door which was not simulated. Interestingly, the moisture content seems to rise again shortly after and resume a good match with the simulations, maybe due to the door being closed again. For the remaining plots in Figure 6, a tendency is to underestimate the short-term peaks during simulations. This might be due to mismatch in the air temperatures, where condensation could be starting earlier in the simulations than in the measurements. Overall, the results show that the simulations give an adequate representation of how moisture load affect the IAQ. For the main results of this study, we are mostly interested in the longer effects and how the moisture content of the indoor air decays as a function of the mechanical ventilation. Moisture buffering effects or moisture production by evaporation of water pools does not seem to matter in bathrooms as of these results, as they would likely lead to a slower increase in moisture content when showering, and a higher moisture content after showering.

Table 5. Abbreviations used in Figure 9-13.

Abbreviation	Meaning
Lett	Easy load
Norm	Normal load
Tung	Heavy load
Mot	Plate h.x.
Rot	Rotary h.x.
L01	Apartment 1 (small)
L02	Apartment 2 (medium)
L03	Apartment 3 (large)
TEK-17	Baseline case with forced kitchen and bathroom ventilation

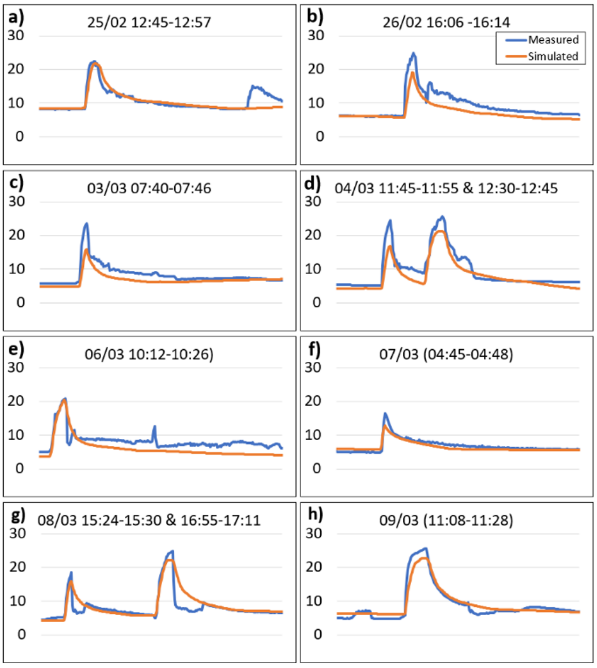

Fig. 6. Time series comparison between simulations and measurements. The titles of the subplots indicate the date and shower duration. The value on the Y-axis is water vapor content, v in g/m^3.

3.2 Comparison of indoor RH

Figures 7 and 8 show the simulated vs measured indoor RH in the living room and in the bedroom of the student apartment. Although real occupancy behaviour is not known in detail, a best guess of occupancy profiles was created in IDA-ICE which naturally would cause many hit-and-miss occurrences. Overall, the general trend of the indoor RH seems to fit well with the measurements. Sudden spikes in the measurements are probably related to moisture production events that have not been accounted for in the simulations. The most pronounced spikes seem to sometimes relate to the showering events in figure 3, which may be due to opening of the bathroom door after showering which was not simulated. However, as the general RH level and trend in development over time is captured well, the simulations show that indoor air moisture can be satisfactory simulated for the aim of this study. The goal with the main results is to uncover problematic ventilation solutions that lead to excessive high or low indoor RH over longer periods of time. In that regard, moisture buffering effects does not seem to matter much either for the general levels in indoor RH. The student apartment was in fact built with excessive use of massive wood for the improvement of IAQ, but the measurements seem to have rapid spikes in the RH levels in the same manner as the simulations, although they do not occur simultaneously. The result show that using IDA-ICE can be a promising method to also study indoor RH which is not commonly done in literature. Using IDA-ICE for this purpose must of course fit the limitations of the software, but it can be a viable tool for overall rough estimations with the possibilities to create moisture production load profiles.

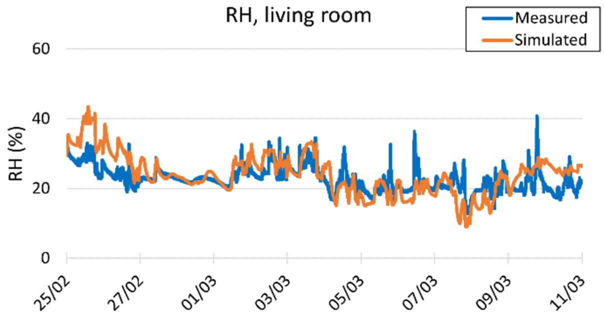

Fig. 7. Comparison of indoor RH in the living room.

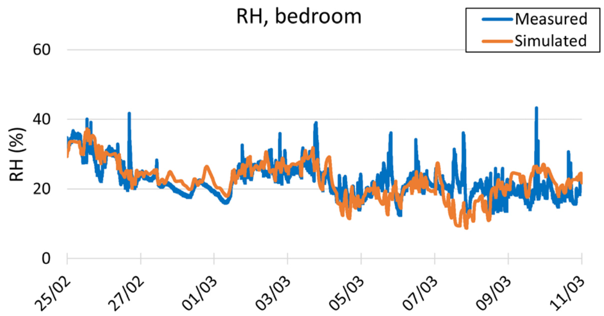

Fig. 8. Comparison of indoor RH in the bedroom.

3.3 Parametric simulations of airflow rates

The focus of this paper is the results related to moisture removal from the simulated apartments. Other results from the parametric simulations for energy use, thermal comfort and CO_2 is discussed in our assessment paper (Thunshelle et al, submitted).

A total of 54 simulations were conducted. All airflow rates and the baseline case were combined with the AHU and user load combinations that are shown in Table 6. The combination of easy load with plate heat exchanger represents a risk for dry conditions. The opposite is the case for rotary heat exchanger and heavy load. The plate and heat exchanger are compared towards each other for the normal load scenario.

Table 6. Combinations of AHU configuration and user load cases that was simulated with the varying airflow rates.

Load	Plate h.x	Rotary h.x
Easy	X	
Normal	X	X
Heavy		X

The criteria in Table 7 were considered during the analysis of the results.

Table 7. Moisture indicators for problematic IAQ.

Risk / unwanted effect	Indicator	Suggested recommendation
Surface mould, construction damage in bathrooms	RH after shower	< 80% within 5 minutes
Eye and airway health effects	% Occupied time with RH < 20%	> 20 % RH more than 95 % of occupied hours
Thermal comfort living room	% Occupied time with RH > 70%	Undetermined

3.3.1 Risk of high humidity in bathrooms

Figure 9 show the longest continuous period with excessive high RH levels in the bathrooms. Note that the x-axis shows the total airflow rates in the apartments. In relation to apartment layout and number of extract vents, the airflow rate in the bathroom alone can be lower. The small apartment (01) has only one extract vent, so the extract rate in the bathroom is the same as the total extract rate.

Figure 9 show that for high airflow rates (> 144 m^3/h), there are no problems with the duration of high RH levels. At very low airflow rates (< 44 m^3/h), the duration periods for the heavy load case starts to shoot for all apartments. This indicates a serious risk of unwanted effects with total airflow rates lower than this. Figure 10 shows a snippet of the lower end of graph. With lower airflow rates than approximately 90 m^3/h, the residuals start to spread, also indicating an area of risk where a ventilation designer should pay attention to factors such as e.g. apartment layout, how long of duration that can be accepted and the risk of continuous heavy load scenarios of multiple days.

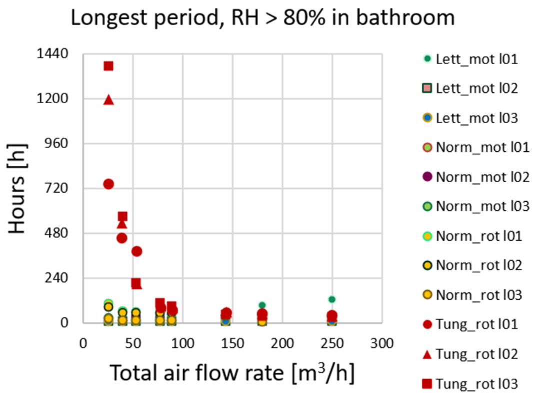

Fig. 9. The longest continuous duration of high humidity in the bathrooms.

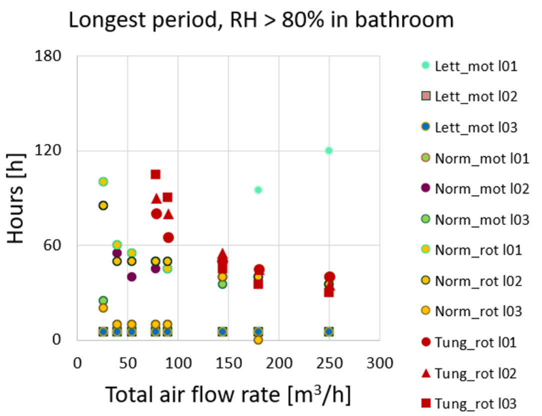

Fig. 10. A section of the lower range of the Y-axis in Fig. 9.

3.3.2 Risk of high humidity in occupied spaces

Figure 11 shows that the humidity for the heavy load cases increased rapidly for total airflows lower than approx. 54 m^3/h. Figure 12 shows that the spread between residuals is starting at airflow rates below approximately 144 m^3/h. The largest apartment shows no risk of too high humidity levels at any air flow rates. This is likely due to the apartment layout causing the living room to have locally low ACH due to the vent placements.

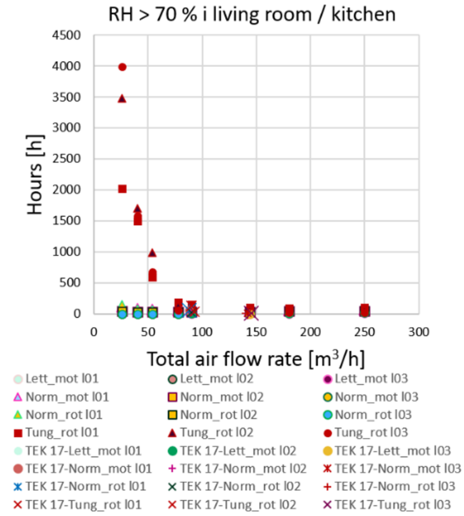

Fig. 11. Total duration of high humidity in the living rooms during occupancy.

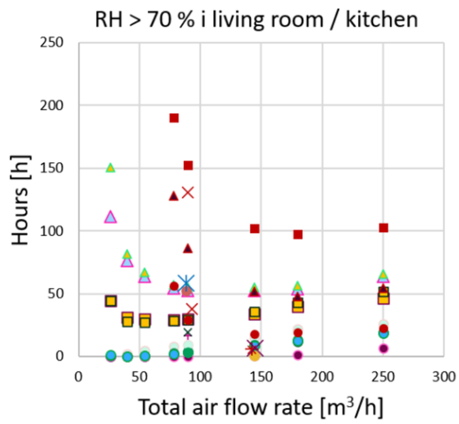

Fig. 12. A section of the lower range of the Y-axis in Fig. 11.

3.3.3 Risk of low humidity in bedrooms

Figure 13 shows that the easy load scenarios pose the greatest risk of low humidity, while the heavy load scenario pose the lowest risk. When the room is unoccupied, the conditions will be even dryer. Very low humidity may be damaging to wooden parquet floors. Furthermore, the smallest apartment (01) has the highest risk which is due to the ACH being relatively higher compared to the larger apartments for the same total airflow rate. Similarly, the largest apartment shows the lowest risk as the ACH is the lowest, indicating that when choosing the total airflow rate, considering the resulting ACH can have an impact. Moreover, the moisture recovery of the rotary heat exchanger (yellow lines) has an impact on limiting the risk for dry conditions compared to the plate heat exchanger with no moisture recovery (green lines). Overall, very low airflow rates are needed to really reduce the durations for dry conditions in easy load conditions. A noticeable decrease can be seen for air flow rates lower than 54

m^3/h. On the other hand, at these airflow rates the risk for excessive high humidity started to occur in heavy load conditions, as shown in Figure 11.

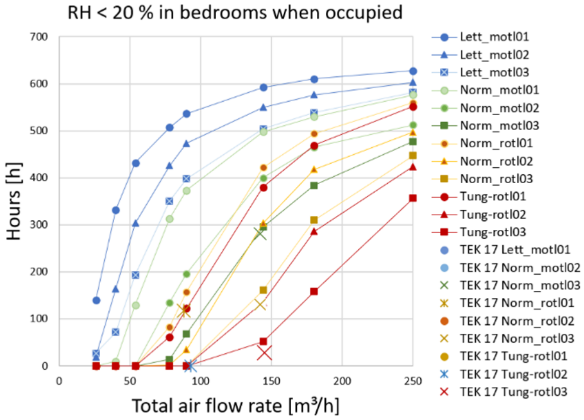

Fig. 13. Total duration of low humidity conditions in bedrooms when occupied.

4 Conclusion

This study utilizes a commonly adapted BES software in Norway, IDA-ICE, as an approach to investigate indoor air humidity in urban apartments. Moisture load profiles were created based on literature review and a calibration campaign with IDA-ICE against field measurements from a student apartment. Our findings indicate that the lack of moisture buffering material models in IDA-ICE might not be crucial when estimating the impact of ACH on indoor RH. Comparisons of simulated indoor RH with field measurements from a real apartment agree well, suggesting that using indoor RH as an indicator with IDA-ICE can be a viable approach for consultants and designers when assessing mechanical ventilation systems in apartments. Moreover, parametric simulations of airflow rates with mechanical ventilation were carried out for a combination of different apartment types, moisture recovery in AHUs and user profile scenarios. While the current TEK-17 regulations are airflow rate orientated, our results show that high airflow rates increase the risk for low indoor air humidity. Lower airflow rates might be beneficial to consider in some cases, especially for smaller apartments as the resulting ACH can be quite different between apartment sizes. A more nuanced approach for determining airflow rates can be considered in building code and practices, for example by emphasizing apartment size and layout in the integration of ventilation solutions in urban housing design.

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