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Indoor hygrothermal loads for the deterministic and stochastic design of the building envelope for dwellings in cold climates

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Abstract

In this study, several years of field measurements of indoor hygrothermal loads in 237 dwelling units are analysed. Moisture excess is calculated from hourly values of temperature, and relative humidity measured both indoors and outdoors. Air change rate and moisture production in bedrooms are calculated on the basis of carbon dioxide measurements. It is found that indoor temperature profiles differ depending on whether a building has central heating, a stove or combined heating system. The determined average moisture excess value, 2.8 g/m^3 with a standard deviation of 1.6 g/m^3 for cold periods, can be used in stochastic calculations. Critical values for moisture excess at the 90th percentile, ranging from 3–8 g/m^3, depending upon occupancy rates, can be used in the deterministic analysis. Averages and weekly maxima of moisture excess in the study are reported at different percentiles. Considerable deviations from the EN ISO 13788 standard are discovered, concerning the breaking point depending on outdoor temperature and moisture excess during the summer. The average and critical moisture production in bedroom is presented and insufficient ventilation determined based on measurements. During the heating period, the air change rate is relatively stable while moisture production levels increase along with the dropping outdoor

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temperature. Two indoor temperatures and three humidity models with different levels of detail and influencing factors are proposed. Temperature and humidity loads derived using the proposed models can be used to determine the indoor hygrothermal boundary conditions for the building envelope of dwellings in cold climates.

Keywords

Indoor hygrothermal load, moisture excess, moisture production, ventilation air change, stochastic, deterministic, occupancy

Introduction

Problem statement

According to the European Construction Products Regulation (CPR, 2011), health and safety aspects which are connected to the use of a building during its entire life cycle must be taken into account when assessing the performance of that building. Moisture-related problems in buildings (such as with dampness) increase the risk of there being adverse health effects, such as respiratory problems, asthma and allergies both in adults and children (Bornehag et al., 2004). According to meta-analyses (Fisk et al., 2007), approximately 30%–50% of the increases in a variety of respiratory and asthma-related health problems are linked to building dampness and mould. Dampness is defined as a range of moisture problems in buildings, including high relative humidity (RH), condensation, water ponding and other signs of excess moisture or microbial growth (IOM, 2004). In order to be able to prevent dampness-related problems, possible moisture sources should be taken into account in the design phase. As the hygrothermal performance of the building envelope and its surface depend upon boundary conditions, a proper evaluation of hygrothermal loads is crucial. In terms of indoor moisture load and the risk of moisture damage occurring, two room types can be found in a dwelling unit, these being the bathroom and all other rooms. The moisture load in bathrooms is higher in general but, however, it also has waterproofing or a moisture barrier on the interior surface of the building envelope. As moisture loads in bedrooms have so far been subject to less study until now, these were chosen as the object of this study.

When assessing indoor hygrothermal loads on the building envelope, it is important to consider indoor temperature and humidity conditions and their dependence on the outdoor climate. Indoor humidity levels are dependent upon the rate of moisture production (caused primarily by indoor human activities), the air change rate and moisture exchange with hygroscopic materials inside the building. Recorded air change rates in 500 bedrooms in Denmark (Bekö et al., 2010) showed that occupant behaviour is a stronger predictor of the ventilation rate than it is of building characteristics. Kalamees et al. (2006) compared moisture production values as calculated from the average air change rate and moisture excess levels, with values which had been predicted on the basis of questionnaire results. Only 45% of the predictions were correct (with an accuracy of ±75%). As the designer cannot rely on knowledge of the future behaviour of the occupants or the building's occupancy, the only recourse is to use moisture levels, determined in dwellings which are already in use. In order to acquire reliable data, what is needed are large-scale, long-term and widespread indoor climate measurements from dwellings with different characteristics. Moisture excess levels ($\Delta\nu$), represented as the difference between indoor and outdoor air vapour content by volume (the potential for vapour diffusion), is a good indicator of the indoor humidity load.

Literature review

Indoor boundary conditions in cold climates have been measured in many countries and these involve various circumstances. Rousseau et al. (2007) studied indoor temperature and humidity conditions in the cold climate of Canada, but a higher temperature load and RH levels did not translate into a more frequent occurrence of moisture-related problems, and more in-depth studies are required in this area. Arena et al. (2010) measured the monthly average temperature, RH levels and the humidity ratio in sixty homes in different climate zones in the United States. In addition to bathrooms, moisture-related problems were most often detected around windows. However, due to the small sample size being taken, they were unable to show a strong correlation between the characteristics of houses and indoor humidity levels. Covering the period up to 2006, a solid literature review concerning moisture excess levels and moisture production is given in Kalamees et al. (2006). From there on, an overview of the relevant literature concerning indoor temperature and humidity levels with the numerical results available is given in Table 1.

Some studies have concentrated on indoor temperature and thermal comfort but not on humidity levels. The Literature concerning temperature levels is reviewed and generalised by Peeters et al. (2009), who claim that bedrooms which are used only for sleeping in winter are colder when set against bedrooms which are used for other activities besides sleeping. In the former type, bedrooms used only for sleeping, comfortable indoor air temperatures are predominantly between + 15°C and + 17°C but may drop as low as + 12°C. Lower temperature limit + 16°C for bedrooms and + 18°C for all other rooms of a dwelling is proposed.

In deterministic hygrothermal calculations, critical climatic loads and material parameters ensure that the design solution is within the margins of safety. The International Energy Agency (IEA) EBC Annex 24 (Sanders, 1996) has recommended applying a 10% critical level. This means that hygrothermal loads which are higher than their normative value should not appear in more than 10% of cases. Cornick and Kumaran (2008) compared empirical indoor climate models (ASHRAE 160P, 2009; EN ISO 13788, 2012; Jones, 1993) against data collected from 25 houses (Rousseau et al., 2007) and found that, relative to the data measured, all of the models generally overestimated RH levels. Therefore, when taking a deterministic approach to hygrothermal design, in-depth studies of indoor loads and their influences are essential. An effect of moisture buffering with a literature

Table 1. Average indoor boundary conditions during cold periods as shown in various studies since 2006.

	t (°C)	RH (%)	Moisture excess, $\Delta\nu$ (g/m^3)	Household moisture production, G (kg/day)	Comments (country or region)
Kalamees et al. (2006)	21–23		1.8	5.9	Bedrooms and living rooms (Finland), occupancy 43 m^2/person
Janssens and Vandepitte (2006)	15–20		2.2		Bedrooms (Belgium)
	20–21		2.3		Living rooms
	18–20		2.8		Bath rooms Both t and $\Delta\nu$ dependent on outdoor temperature
Zhang et al. (2007)	16–22	42–43	2.8–6.1		(Japan)
Glass and Tenwolde (2009)				3–15	
Becker and Paciuk (2009)	20	40			(Israel)
Peeters et al. (2009)	15–20				Bedrooms (Belgium)
	20–21				Living rooms
Francisco and Rose (2010)			2.8		Rooms above ground (Rhode Island, USA), playroom
			3.2		Bedroom
Geving and Holme (2011)	17	43	1.8		Bedrooms, (Norway)
	22	35	1.6		living rooms: >50 m^2/person
	22	35	2.2		Living rooms: <50 m^2/person
Tariku and Simpson (2014)	17–21		2.3–4.5		Bedrooms (Canada)
	17–24		2.4–4.9		All other rooms
Bagge et al. (2014)			1.8		Central exhaust ventilation (northern Sweden), occupancy 71 m^2/person

RH: relative humidity.

review concerning constant versus cyclic moisture production is discussed in Labat and Woloszyn (2016). In addition, an advantage of using the stochastic approach over the deterministic one is something that is emphasised. Glass and Tenwolde (2009) concluded in their review paper that design moisture production rates are currently based on a rather limited data set, and more data are needed concerning the relationship between the number of occupants and indoor moisture production levels.

Uncertainties are widespread in terms of climatic loads and material parameters. The currently available deterministic methodologies for measuring hygrothermal performance are insufficient for the accurate assessment of variations in energy use, functional performance and life-cycle costs. Therefore, a research project was launched by the IEA on the 'Reliability of Energy Efficient Building Retrofitting – A Probability Assessment of Performance and Cost' (IEA EBC Annex 55, 2012). For stochastic hygrothermal simulations, load variations are important input parameters. A probabilistic assessment would require the incorporation into existing hygrothermal modelling both of correct critical values and average values with deviations. Pallin (2013) and Tariku et al. (2011) took the first steps towards this goal. Bishara et al. (2014) developed and validated a tool based on the simplified energy and moisture balance of a building to calculate indoor temperature and RH levels. IEA Annex 41 has shown that it is also possible to use a whole building indoor climate and energy simulation for hygrothermal modelling (Woloszyn and Rode, 2008). Because these simulation programmes use moisture production levels and air change values as input parameters, indoor hygrothermal loads must also be reported using these parameters.

This study contributes to this approach by providing comprehensive measurements for indoor hygrothermal loads in the case of 237 dwelling units across a range of building types. Factors were studied in depth where they affected moisture excess levels, moisture production levels and the air change rate. Three different indoor hygrothermal boundary condition models have been proposed, each with a different granularity, including a deterministic, stochastic and whole building heat, air and moisture (HAM) approach.

Methods

The buildings studied

The process of recording measurements was conducted in Estonia (24°E, 59°N; in north-eastern Europe), using apartments and detached houses of various occupancies, sizes, ages, structures and types of heating and ventilation (see Table 2). All 237 dwellings consisted of an entry hall, living room, kitchen, sanitary rooms, bedrooms and non-living spaces, such as a corridor or storage area. The kitchen area was typically enclosed in a separate room but may also have been integrated into the living room in newer apartments. One-, two- and three-bedroom apartments predominated. All of the apartments and detached houses were privately owned.

The structures of the external walls in apartment buildings typically consisted of one of three different materials (concrete 39%, brick 34%, log 25% or a combination of any of the three 2%), while walls in detached houses typically consisted of one of two different materials (log 48%, or timber frame 52%). The interior surface of the external wall was covered with plaster in the case of concrete or brick

Table 2. The main characteristics of the 237 dwellings being studied.

	Apartment building, 76% (180 apartments)	Detached house, 24% (57 houses)
Net surface area, average ± SD (min–max)	$63 \pm 28\,m^2$ ($31–299\,m^2$)	$122 \pm 49\,m^2$ ($34–300\,m^2$)
Occupancy: average ± SD (min–max)	$27 \pm 15\,m^2$/person ($9–85\,m^2$/person)	$45 \pm 22\,m^2$/person ($16–103\,m^2$/person)
Building age	<20 years: 35% 20–40 years: 16% 40–70 years: 24% >70 years: 24%	<20 years: 58% 20–40 years: 3% 40–70 years: 4% >70 years: 35%

SD: standard deviation.

apartment buildings and then painted or covered with wallpaper as an interior finishing. Buildings involving wooden structures may have wood or gypsum on the interior and may also be covered with paint or wallpaper.

Natural passive stack ventilation systems (51% in apartments and 55% in houses) and mechanical systems (49% in apartments and 45% in houses) were both represented in the dwellings being studied. Apartments typically used central heating with hydronic radiators (77%), while houses used a variety of heating systems (a stove or fireplace 33%, electrical radiators 20%, hydronic radiators 23% or combined 23%). The requirement for a ventilation air change rate according to the old Soviet SNiP was $n = 1\,h^{-1}$ for bedrooms and living rooms (Mikola et al., 2013). That gives us about $n = 0.5\,h^{-1}$ for the whole dwelling, conforming well with other Nordic countries from that era (Dimitroulopoulou, 2012).

Measurements

Small data loggers (Hobo U12-011) were used to measure indoor temperatures and RH levels with a 1-h step over the course of 1 year in a room used for sleeping – the master bedroom and/or living room. Data for the exterior climate were measured near the buildings or was taken from the nearest weather station.

Indoor carbon dioxide (CO_2) levels were measured in 88 apartments in order to be able to evaluate the air change rate in bedrooms at 10-min intervals over a period of 2–3 weeks in winter and summer. The air change rate was evaluated on the basis of CO_2 measurements and its estimated emissions from inhabitants (known as the CO_2 tracer gas method) in bedrooms during the night (≈20:00–08:00), as reported by Cui et al. (2015) (equation (1))

$$C = C_0 + \left(C_e + \frac{m}{\dot{V}} - C_0\right) \cdot \left(1 - e^{-\frac{\dot{V}}{V}\tau}\right) \tag{1}$$

where m is the CO_2 production (g/h), $\dot{V}$ is the air flow rate (m^3/h), V is the room's total volume (m^3), C_e is CO_2 in the exterior air (g/m^3), C is CO_2 indoors after measurements have been taken (g/m^3), C_0 is CO_2 indoors before the measurements are taken (g/m^3) and τ is time (h).

The calculations are based on average night-time human CO_2 emissions (adults: 13 L/h and children: 6.5 L/h), since CO_2 emissions are relatively stable during the night. Average CO_2 emissions for adults while sleeping, at 13 L/h, coincides well with the average figure of 14 L/h (which is valid for a metabolic rate (MET) of 0.8), as given in (EN 15251, 2007). This is supported by a figure of 15 L/h (which included children), found to be representative of Sweden (Bagge et al., 2014). We also checked on the reliability of the approach by calculating the CO_2 production levels according to an equation proposed by Tajima et al. (2014). This takes the MET (MET = 0.7 as used in the calculations) and body surface area into account and resulted in 16 L/h as an average for both sexes. The CO_2 tracer gas method which should be suitable for that application is proven by Mikola et al. (2017).Mechanical exhaust ventilation airflows were measured in the kitchen, toilet and bathroom with an anemometer (SwemaFlow 233). Supply air flow rates were measured with an Alnor/TSI AXD610 Digital Differential Micromanometer. The air leakage rate for the building envelope was measured using the fan pressurisation method (EN 13829, 2000).

Survey data were collected for each dwelling, including building characteristics, the building materials used, the type of building service system and its use, the habits of the building's occupants, typical complaints and health concerns related to indoor air quality. The questionnaire contained questions about moisture production and the air change rate in the dwelling.

An assessment of indoor hygrothermal loads

The value for indoor moisture excess levels, $\Delta\nu$ (g/m^3) (the difference in absolute humidity levels by volume between indoor air ν_i and outdoor air ν_e, also known as moisture supply or vapour excess) was calculated on the basis of the results of indoor and outdoor temperature measurements, along with RH measurements, using equation (2)

$$\Delta\nu = \nu_i - \nu_e (\mathrm{g/m^3}) \tag{2}$$

Moisture production (moisture source) G (g/h) in bedrooms was calculated on the basis of the measured indoor moisture excess and air change rate indoors, $\dot{V}$ (m^3/h) (determined from CO_2 decay measurements taken from the very same night-time period), using equation (3)

$$G = (\nu_i - \nu_e) \cdot \dot{V} (\mathrm{g/h}) \tag{3}$$

The temperature, RH levels and moisture excess levels were expressed in relation to the outdoor air temperature t_e with a 1°C step as a daily average. The values for moisture excess levels have been reported in this article as a weekly average over the entire year, since a week is a complete living cycle and represents the indoor climate more accurately than, for example, a month. Data in this article have been reported in two ways: first, for the purposes of deterministic modelling, based on weekly maximums, where critical loads must be taken into account; and second, based on all measurements, where the average and standard deviation (SD) are presented for the purposes of stochastic modelling. The second approach also includes data for those periods in which the dwelling was not being used and there was no humidity load, and on the calculation of moisture flow through the building envelope.

Statistical analysis

The statistical significance of parameters which may have been affecting the indoor humidity load was investigated using a student's *t*-test. The values for moisture excess levels were first separated into two arrays according to the median value. Next, other values were tested in order to achieve the smallest possible p value in order to be able to evaluate the strength of the correlation between those arrays which are under comparison. The significance level was set at 5%, that is, $p < 0.05$.

The distribution of data was analysed using the statistical distribution fitting software, EasyFit, and Pearson's chi-squared test in MS Excel in order to detect whether or not it follows the Gaussian, that is, normal distribution.

Two ranges of outdoor air temperature ($t_e \leqslant +10°C$; $t_e > +10°C$) were used for the indoor air temperature, and three ranges of outdoor air temperature ($t_e \leqslant +5°C$; $+5 < t_e < +20°C$; $t_e > +20°C$) were used for moisture excess levels.

The key parameters which affect moisture excess levels (X, Y, Z, etc.) were determined using regression analysis, based on measurements taken from 88 dwellings (A, B, C, etc. are linear regression coefficients). The moisture excess levels can be expressed in terms of these parameters and their respective regression coefficients, as in equation (4)

$$\Delta \nu = A \cdot X + B \cdot Y + C \cdot Z ... (\mathrm{g/m^3}) \tag{4}$$

Results

Temperature

The effect of the exterior, outdoor temperature on the indoor temperature was dependent upon the type of heating used in the dwelling. Central heating ensured a relatively stable indoor temperature level during the heating period ($t_e \leqslant +10°C$) (see Figure 1, left). It was also found that the indoor temperature tended, on

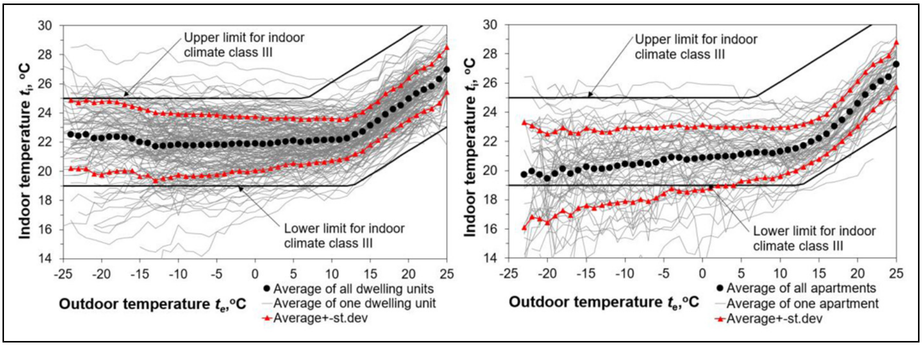

Figure 1. Indoor air temperature for 190 rooms with central heating (left) and 66 rooms using a stove or combined heating system (right). Total number of rooms 256 exceeds the number or studied dwelling units 237 because two rooms were measured in 19 dwelling units.

average, to be between 1°C and 2°C higher in dwellings which were built after 2000. Clearly, without central heating during the cold period (i.e. when a stove or combined heating is used) (see Figure 1, right), the indoor temperature depends upon outdoor temperature thanks to cyclic heating, insufficient heating capacity and large building envelope heat losses. As expected, the indoor temperature started to approximate the outdoor temperature during the warm period ($t_e > +10$°C–15°C), irrespective of the heating system in use. When the daily average outdoor temperature exceeded approximately + 10°C, the indoor temperature exceeded + 21°C– + 22°C, and the summer period began. According to indoor climate class III (EN 15251, 2007) (shown as straight bold lines in Figure 1), this is acceptable for older dwellings in which temperatures between + 19°C and + 25°C should be maintained. As can be seen, many dwellings are under-heated or over-heated during the heating period. Indoor temperatures during the warm period ($t_e > +10$°C) also match up to the ASHRAE 55 (2004) standard, which proposes temperatures of + 21°C at t_e + 10°C up to approximately + 26°C at t_e + 25°C for an average indoor operative temperature.

Moisture excess levels

The average moisture excess levels in the 237 dwellings was calculated to be + 2.8 g/m^3 (SD = ±1.6 g/m^3) during the cold period ($t_e \leqslant +5$°C), + 1.4 g/m^3 (±1.4) during the intermediate period ($+5 < t_e < +20$°C) and + 0.3 g/m^3 (±0.9) during the warm period ($t_e > +20$°C). The small dots in Figure 2 (left) show the relation between hourly indoor moisture excess levels and daily outdoor temperature in one dwelling over a 1-year period. The round dotted line shows average indoor moisture excess levels, while the square dotted line shows weekly maximum indoor moisture excess levels. The thin lines in Figure 2 (right) show the average

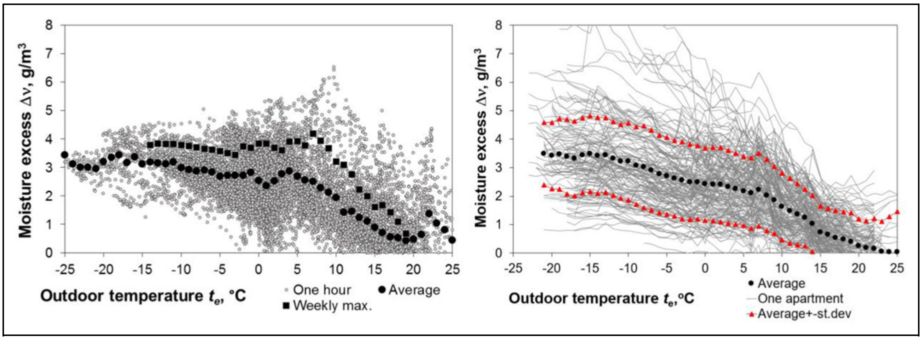

Figure 2. Hourly data for moisture excess levels for one dwelling (left) and weekly data for all 237 dwellings units (right).

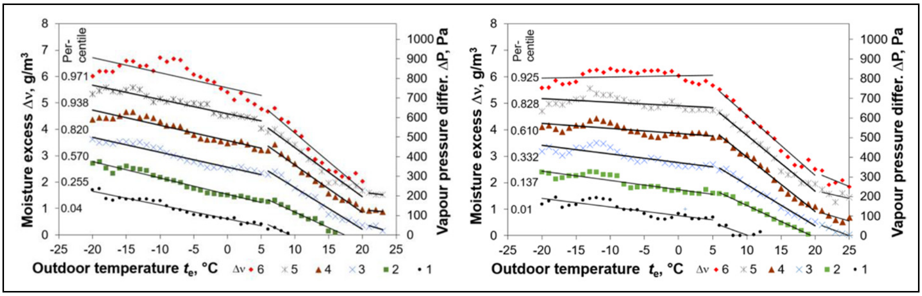

Figure 3. Moisture excess levels based on the full data set (left) and for the weekly maximums for 237 dwelling units (right). The column of values beside the rounded moisture excess values on the primary *y*-axis shows the corresponding percentiles. The straight lines are linear trend lines for moisture excess levels during cold, intermediate and warm periods.

moisture excess levels for each dwelling. The round dotted line shows the average, while the lines with triangles show the average ± SD for all dwellings.

Using the full data set in Figure 3 (left) and the weekly maximums in Figure 3 (right) curves were calculated with their corresponding percentiles to show the distribution of moisture excess levels over the whole data set. Trend lines (straight lines) for moisture excess levels based on the full data set and weekly maximums during the cold period ($t_e \leq +5°C$) are shown as rounded moisture excess values which range from one to 6 g/m^3.

The dependence of moisture excess levels on the outdoor temperature is clearly visible in Figure 3. On the basis of these curves, a change in moisture excess levels was observed of 1 g/m^3 during the cold period ($t_e \leq +5°C$) and 0.5 g/m^3 during the warm period ($t_e > +20°C$). The average moisture excess levels $\Delta\nu$ were 2.8 g/m^3 (±1.6) during the cold period and 0.3 g/m^3 (±0.9) during the warm period. The

90th percentile for weekly maximums (Figure 3, right) was $5.7\,\mathrm{g/m^3}$ during the cold period and $2.0\,\mathrm{g/m^3}$ during the warm period. The higher moisture excess levels during the cold period could have been due to a difference in air change performance and/or moisture production.

Moisture excess levels for the full data set (Figure 3, left) tend to decrease at outdoor temperatures of around 0°C mainly because the full data set also includes data which was collected when the apartments were unoccupied (when there was no moisture production). Another reason for higher measured moisture excess levels during very cold periods in Figure 3 (left) is vapour desorption from surrounding surfaces, something which is driven by the low indoor RH levels. An important outcome of the analysis is the determination of the level of moisture excess levels during the intermediate and warm periods, and the ascertaining of its dependence on the cold period's value. At low moisture loads ($\Delta\nu \approx 2\,\mathrm{g/m^3}$ during winter), the moisture excess levels were around $0\,\mathrm{g/m^3}$ in summer but with considerable fluctuation. Moisture excess levels had a positive value in summer under high moisture loads.

Air change rate and moisture production

The average air change rate during winter in a bedroom (n) was $0.6\mathrm{h}^{-1}$ (see Figure 4, left), which is remarkably below the requirement at the time of construction where $n = 1\mathrm{h}^{-1}$ as well as for the indoor climate class III (EN 15251, 2007) requirement of $0.86\,\mathrm{h}^{-1}$, that is, $0.6\,\mathrm{l/(s\,m^2)}$ with a room height of 2.5 m. In each dwelling, air change measurements were carried out on different days which may serve to amplify the large deviation shown in Figure 4 (left). Each point in Figure 4 (right) shows the measurement during one night at the corresponding average outdoor temperature. The thin lines represent linear trend lines for these results in one dwelling, while the thick line represents the average for all dwellings. During the

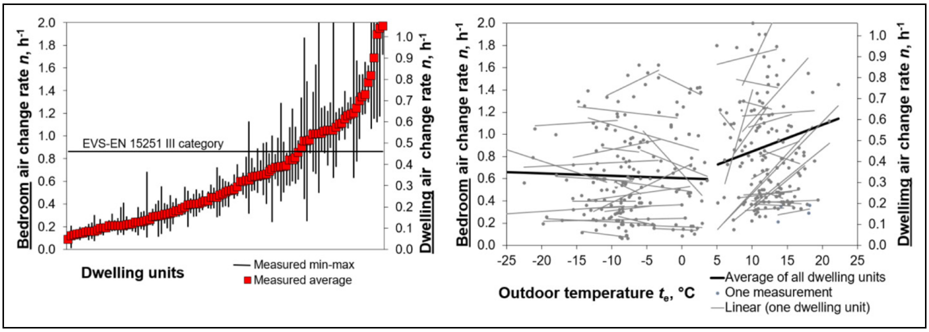

Figure 4. The average air change rate (shown in bold dots) and variability (the vertical lines) during winter in bedrooms at night (left) and the dependence of the air change rate upon the outdoor temperature (right).

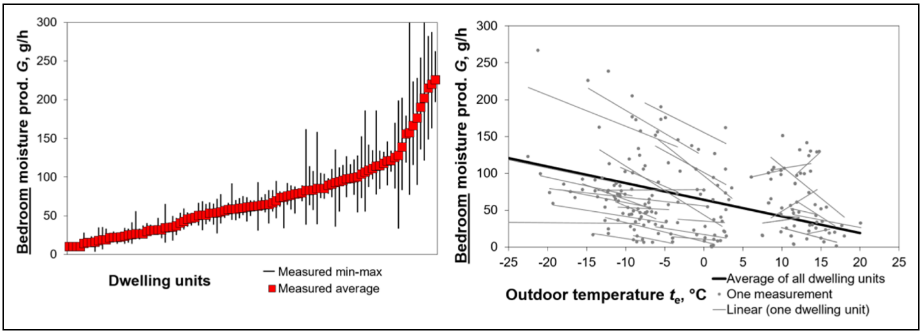

Figure 5. The average moisture production level (dots) and variability (vertical lines) during winter in bedrooms at night (left) and the dependence of moisture production levels on the outdoor temperature (right).

winter period, the air change rate did not change remarkably (see Figure 4, right). The bedroom air change rate was $0.2\,h^{-1}$ with the whole dwelling unit producing a figure of $0.1\,h^{-1}$ at the 10th percentile.

Average moisture production (G) in master bedrooms was found to be 72 ± 50 g/h (1.7 ± 1.2 kg/day) during the winter period (see Figure 5), with higher values on colder days. The assumption of constant moisture production within a period of 24 h is based on a finding which showed that the buffering-corrected values which were measured for moisture excess levels in bedrooms were not significantly different between day and night. Moisture production levels at the 90th percentile based on the full data set were at 121 g/h and 2.9 kg/day. The unexpectedly low average moisture production in some dwellings could have been due to the bedrooms being temporarily unoccupied or to a moisture buffering effect. Overall, moisture production across the entire dwelling was naturally greater since not all moisture sources were located in the bedroom.

The analysis of moisture production dynamics within the period of a week showed small fluctuations: moisture production was somewhat higher on Fridays and Saturdays, but the difference was statistically insignificant.

Factors affecting indoor humidity load

Data from the 237 dwellings were used to study those factors which may be affecting moisture excess levels (moisture production: Table 3, air change: Table 4) during the cold period ($t_e \leqslant +5°C$). Occupancy was the most significant factor ($p = 4.1 \times 10^{-11}$) when it came to affecting moisture excess levels (see Figure 6, left). Since occupancy affected the values for other factors, those subgroups with restricted occupancy (<27; >27 m^2/person) were investigated separately.

A secondary moisture production parameter which significantly influenced moisture excess levels was that of cooking ($p < 0.05$). The type of ventilation being

Table 3. Factors influencing moisture excess levels and production during the cold period ($t_e \leqslant +5°C$).

Factor studied	No. of dwellings	All occupancy		Restricted occupancy				Restricted occupancy			
		Average	90th percentile	Average		90th percentile		Average		90th percentile	
				$O < 27$	$O > 27$	$O < 27$	$O > 27$	$O < 27$	$O > 27$	$O < 27$	$O > 27$
		Moisture excess, $\Delta\nu$ (g/m^3)						Moisture production, G (g/h)			
Occupancy, O											
$\leqslant$27 m^2/person	121	**3.28**	**6.08**	N/A				N/A			
$>$27 m^2/person	116	**2.16**	**4.17**	N/A				N/A			
Cooking											
$\leqslant$Once per day	102	**2.52**	5.66	3.12	2.03	6.63	4.42	85	52	232	153
$\geqslant$Twice a day	70	**2.95**	5.55	3.40	2.26	5.67	3.74	76	61	221	161
Laundry drying											
Yes	76	2.68	6.04	3.46	2.07	6.86	4.10	62	42	143	121
No	43	2.27	5.49	2.94	1.77	6.42	4.36	65	33	186	98
Shower use											
$\leqslant$Once per day	81	2.55	5.88	3.27	2.07	6.46	4.13	84	51	269	177
$\geqslant$Three times a day	48	2.98	5.65	3.34	2.21	5.67	4.22	93	69	225	157

Bold value indicates statistically significant differences, that is, $p < 0.05$.

Table 4. Factors influencing moisture excess levels and air change during the cold period ($t_e \leqslant +5°C$).

Factor studied	No. of dwellings	All occupancy		Restricted occupancy				Restricted occupancy			
		Average	90th percentile	Average		90th percentile		Average		10th percentile	
				$O<27$	$O>27$	$O<27$	$O>27$	$O<27$	$O>27$	$O<27$	$O>27$
		Moisture excess, $\Delta\nu$ (g/m^3)						Air change rate, n (h^{-1})			
Air change, n											
$<0.3\,h^{-1}$	25	**3.50**	**7.19**	**4.34**	2.54	**7.73**	**4.25**	N/A			
$>0.6\,h^{-1}$	49	**2.48**	**4.95**	**2.90**	1.91	**5.06**	**3.49**	N/A			
Ventilation type											
Passive stack	63	3.13	**6.47**	3.41	**3.23**	7.11	4.96	**0.50**	**0.26**	**0.10**	**0.15**
Mechanical	61	2.78	**5.34**	3.16	**2.28**	5.47	4.60	**0.87**	**0.84**	**0.50**	**0.22**
Ventilation stack height											
$\leqslant 1$ m	31	**3.81**	**7.28**	**4.20**	**2.98**	**8.24**	**5.55**	**0.47**	0.58	**0.20**	0.24
>4 m	79	**2.50**	**4.91**	**2.71**	**2.08**	**5.41**	**3.72**	**0.71**	0.68	**0.14**	0.20
Window airing											
$\leqslant 2$ times/day	91	**2.62**	5.31	3.10	2.18	5.78	4.16	0.65	0.60	0.14	0.24
$\geqslant 3$ times/day	80	**3.09**	6.05	3.47	2.37	6.38	5.45	0.61	0.70	0.20	0.17
Age of windows											
$\leqslant 10$ years	92	**3.40**	**6.02**	3.02	2.16	6.39	5.42	0.59	0.39	0.13	0.15
>10 years	48	**2.70**	**5.42**	3.33	2.42	5.46	4.28	0.64	0.68	0.20	0.28
Air leakage rate, q_{50}											
$\leqslant 4\,m^3/(h\,m^2)$	82	2.79	6.34	3.69	2.09	7.77	4.27	0.57	0.62	0.18	0.21
$>4\,m^3/(h\,m^2)$	91	2.55	4.89	3.08	2.03	5.38	3.64	0.71	0.63	0.20	0.20

Bold value indicates statistically significant difference, that is, $p < 0.05$.

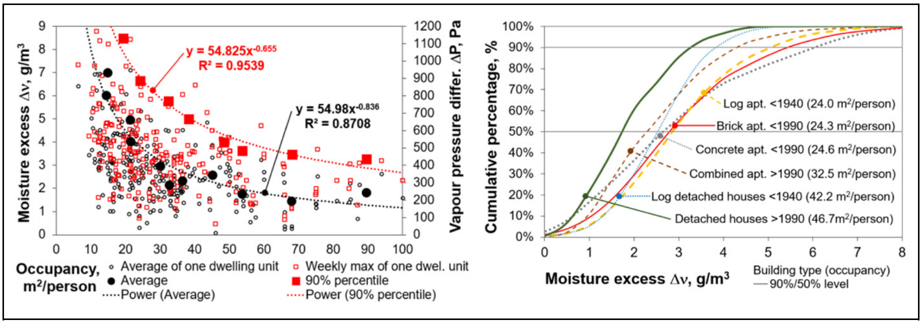

Figure 6. The dependence of moisture excess levels on occupancy (left) and cumulative distributions of moisture excess levels according to building typology during the cold period ($t_e \leqslant +5°C$) (right) based on all measurements.
Apt: apartments.

used also significantly influenced the ventilation air change rate: in dwellings with mechanical ventilation, the air change rate was higher. The height of the natural ventilation stack and the age of windows also had a significant impact upon indoor moisture excess levels. The effect of window opening was contrary to that expected: in rooms with higher moisture excess levels, the windows had been opened in order to ventilate the room.

The dependency of moisture excess levels on occupancy is shown in Figure 6 (left). The data can be sorted by moisture excess levels or by occupancy. Equations (5) and (6) are both a combination of two trend lines (with the data sorted by moisture excess levels and occupancy) using the data point to provide higher moisture excess levels.

A 90% moisture excess level depending on occupancy O, m^2/person

$$\Delta\nu = 54.825 \cdot O^{-0.655} (\mathrm{g/m^3}) \tag{5}$$

Average moisture excess level depending on occupancy O, m^2/person

$$\Delta\nu = 54.98 \cdot O^{-0.836} (\mathrm{g/m^3}) \tag{6}$$

It turns out that the 90% critical level is approximately 1.5 g/m^3 higher than the average in the case of low occupancy levels, but the difference increases with higher occupancy levels. Moisture excess distributions for different building typologies are shown graphically in Figure 6 (right) where a large deviation can be seen with values between 0 and 8 g/m^3. Some building types (Figure 6, right) have steeper slopes, especially in the case of old (pre-1940) detached houses and also in the case of apartment buildings which were constructed using wood. It appears that detached houses show significantly lower moisture excess levels ($p = 3.2 \times 10^{-6}$) – due to lower occupancy levels this was at 45 m^2/person on average – and apartments have higher moisture excess levels – with an occupancy of 27 m^2/person on average.

Old (pre-1990) concrete apartment buildings exhibited the highest moisture excess levels at the 90th percentile, reaching $\sim 6\,g/m^3$. This was due mainly to poor ventilation (with the average for a bedroom being $n = 0.35\,h^{-1}$) and high occupancy levels ($25\,m^2$/person). Ventilation stacks in concrete apartment buildings were composed of multiple vertical stack elements which were neither airtight nor exactly aligned, as revealed during the assessment of the technical condition of these buildings.

Indoor hygrothermal models

Temperature model

Model description. The indoor temperature model is based on the average indoor temperature. Since there was an indoor temperature turning point at which the outdoor temperature was around $+10°C$ to $15°C$, the model is for the heating period ($t_e \leqslant +10°C$) and for the summer period ($t_e > +10°C$). Since the heating system strongly affected the indoor temperature during the heating period (see Figure 1), two different temperature models have been proposed for the indoor air temperature. The average indoor temperature curve in dwellings with central heating (Figure 7, left) was stable at $+22°C$ during the heating period ($t_e \leqslant +10°C$) and rose up to $+27°C$ (at $t_e + 25°C$) during the summer. In the case of a stove heating system (Figure 7, right), average indoor temperature rose linearly from about $+19°C$ (at $t_e = -25°C$) to $+21°C$ (at $t_e = +10°C$) during the heating period, reaching $+27°C$ during the summer as well (equation (7))

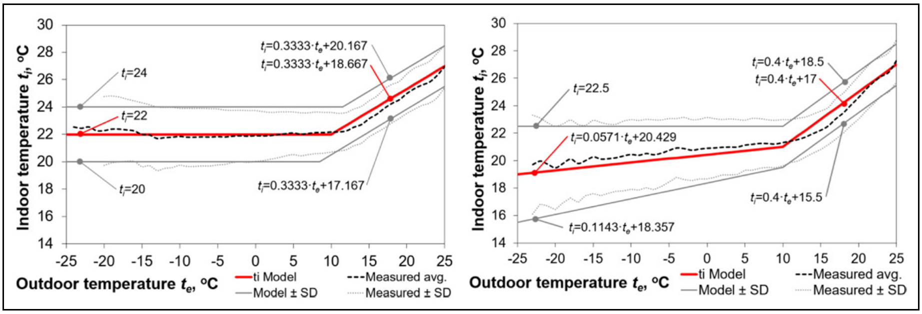

Figure 7. Indoor temperature models for dwellings with central heating (left) and stove heating (right), dependent upon the daily average outdoor temperature. Lines representing the measured results for each dwelling unit have been omitted for the sake of clarity.

$$
\begin{aligned}
t_{i,\,central\ heating} &= \begin{cases} t_e \leqslant +10^\circ\mathrm{C} \Rightarrow t_i = 22^\circ\mathrm{C} \\ t_e > +10^\circ\mathrm{C} \Rightarrow t_i = 0.3333 \cdot t_e + 18.667^\circ\mathrm{C} \end{cases} \\
t_{i,\,stove\ heating} &= \begin{cases} t_e \leqslant +10^\circ\mathrm{C} \Rightarrow t_i = 0.0571 \cdot t_e + 20.429^\circ\mathrm{C} \\ t_e > +10^\circ\mathrm{C} \Rightarrow t_i = 0.4 \cdot t_e + 17^\circ\mathrm{C} \end{cases}
\end{aligned} \tag{7}
$$

The same heating-system-dependent indoor temperature model can be used for all indoor hygrothermal models. The variability of the indoor climate for the stochastic approach can be generated using the SD values at corresponding outdoor temperatures. Normal distribution of temperatures in order to use the average and SD was ascertained via Pearson's chi-squared test, which resulted in a p value of $0.33 > 0.05$. If one has a reliable indoor temperature profile which is valid for certain buildings in a certain climate, then this should always be preferred over the models proposed in this study.

The variation demonstrates possible differences in the behaviour of occupants, on the one hand, and differences in the performance of the heating system, on the other. The SD used in the stochastic approach has a larger value (±2°C for central heating and ±3.5°C for stove heating) for low outdoor temperatures and a smaller value (±1.5°C for both heating systems) for higher outdoor temperatures ($t_e \geqslant +10$°C). It is possible to generate three types of indoor temperature data for stochastic simulations:

T1: Variation of t_i between dwellings. The same average indoor temperature equations are used for the whole year, and one dwelling is described by a single line, for example, the t_i in Figure 1. One line of the model consists of two straight parts with a breaking point at $t_e = +10$°C. The random variation is shown using SD = 1.8°C for different dwellings. Each subsequent simulation is handled using a different average temperature. This describes the situation when the variation falls between different dwellings with different temperatures.
T2: Variation of t_i within one dwelling. The random variation is expressed using SD for each hour – SD = 0.7°C in the case of central heating and SD = 1.4°C in the case of stove heating. This shows a larger variation for the indoor temperature over the course of one year, and each dwelling is described using an hourly batch of data, for example, Figure 8 (right).
T3: A combination of methods T1 and T2. This shows a variation in the average temperature between dwellings and a variation of indoor temperatures at the same outdoor temperature range within a dwelling.

Validation of the indoor temperature models. The indoor temperature data sets were generated on the basis of outdoor temperatures during the measurement period. Calculated values and measured data sets were compared for model validation. Figure 8 (left) shows a comparison of model T1 with the date gained through measurements in Estonian and Finnish dwellings which had central heating. The model T1 is can be considered to be representative by having $R^2 > 0.8$ for average

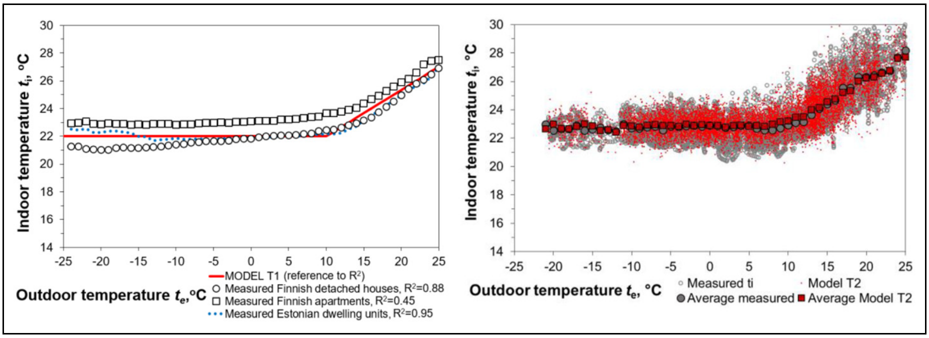

Figure 8. Indoor temperature model T1 and measured average of different dwelling groups with central heating (left) and a comparison of the measured hourly data against calculated values within one dwelling unit using model T2 (right).

measured indoor temperatures in Finnish detached houses and for Estonian dwelling units but not for Finnish apartment buildings. Hence, representative indoor temperature $t_i = 23°\text{C}$ for cold period was used in validation in case of these dwelling units.

Figure 8 (right) shows a comparison of model T2 against the measured hourly data for one dwelling. Square dots represent the average indoor temperature which was calculated using the outdoor temperature and the measured data set. The average and distribution of measured and calculated temperatures are in good agreement.

The indoor M1 humidity model based on moisture excess levels

Model description. It is possible to calculate indoor air humidity by volume (or by water vapour pressure) by adding moisture excess levels (or vapour pressure

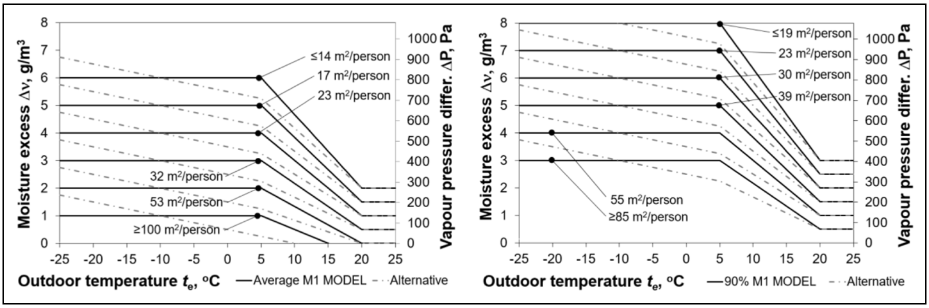

Figure 9. The average (left) and 90% design levels (right) for moisture excess levels as agreed against occupancy rates over the whole outdoor temperature range by using the Equations (5) and (6) (see also Figure 6, left).

difference) to outdoor air humidity. We propose the use of occupancy (as the most important factor influencing indoor humidity loads) as the basis for calculating the moisture excess level. For stochastic hygrothermal analysis, the average values can be applied (Figure 9, left); for the deterministic hygrothermal design of the building envelope, values at the 90% level are applicable (Figure 9, right). The dotted line represents an alternative model to be discussed which has a 1.5 g/m^3 moisture excess difference in the cold season, $-25 < t_e < +5$°C.

The dependency of design moisture excess curves on the outdoor temperature was determined from measurements (Figure 3). The moisture excess levels were calculated for three outdoor temperature intervals ($t_e \leqslant +5$ for the cold period, $+5 < t_e < +20$ for the intermediate period and $t_e > +20$°C for the warm period). The design value for moisture excess levels for other outdoor temperatures was calculated using the value for the cold period ($t_e \leqslant +5$°C). This also made it possible to obtain moisture excess values for the other periods. When moisture excess changed in different occupancy groups by steps of 1 g/m^3 during the cold period, it changed by 0.5 g/m^3 during the warm period. The number of rooms (bedrooms, living room, cabinets, etc., but not kitchen, entryway or toilet) is a simple rule of thumb used to calculate the number of persons when this may be unknown, for example, buildings which are still being designed. The dotted lines in Figure 9 represent a modification of the model which is to be discussed. This is something that would be in conflict with the current EN ISO 13788 (2012) standard, but it would certainly provide better agreement with the measurements.

The indoor climate for stochastic analysis of the dwellings can be calculated using the average moisture excess levels at different occupancy rates (Figure 9, left) with an SD of 1.6 g/m^3 (limitation: $\Delta\nu > 0$ g/m^3 during the cold period). The SD for hourly data for the moisture excess levels within one dwelling was 1 g/m^3 ($t_e > +5$°C), and this decreased linearly during the cold period to a value of 0.5 g/m^3 as $t_e = -25$°C (see Figure 10, left). Resolutions about the moisture excess levels

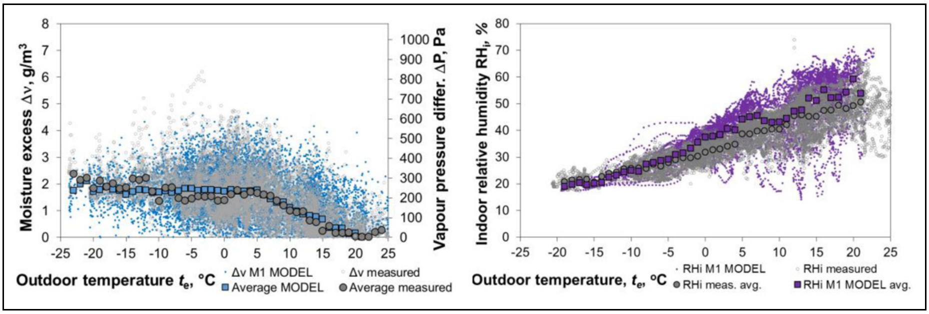

Figure 10. The comparison between measured hourly indoor moisture excess (left) and indoor RH levels (right) against calculated values for one dwelling unit using T2 and stochastic M1 models.

for different building types were doubtful when following the normal distribution pattern according to the EasyFit software. For instance, normal distribution in the case of wooden apartment buildings was placed 17 out of 37 distributions in total with the Kolmogorov–Smirnov statistic of 0.049.

Model M1 validation. The indoor RH levels as measured were used to validate the indoor humidity M1 model. First, the proposed model which was based on data for 237 dwellings was verified using the same sampling in order to ensure that the model was mathematically correct. Second, the model's performance was studied, and the model was validated using independent data from Finland. Indoor RH levels were calculated using the following procedure:

- While the actual occupancy is unknown (in the case of a new building which is still being designed), the total surface area of a dwelling unit is the only parameter available – hence, the latter was used as a basis for calculating the indoor moisture load.
- A representative running trend line between the number of occupants N against total surface area A of the dwelling unit was used to calculate occupancy –$N = 1.83*\ln(A)-6.51$.
- Using the calculated occupancy rates ($O = A/N$), the moisture excess curves were selected for the average indoor climate (Figure 9, left) or 90% level hygrothermal design (Figure 9, right).
- The moisture excess levels were added to outdoor humidity levels in order to derive the indoor humidity levels by volume.
- The indoor temperature was calculated using models T1 and T2 for both heating system types (central heating or stove/combined heating).
- The saturation humidity by volume was calculated using the indoor temperature.

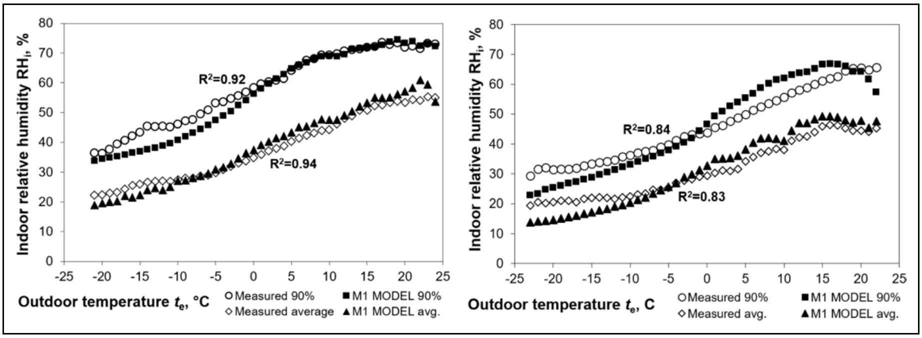

Figure 11. The verification results using Estonian data (left) and validation using the Finnish data via the measured average indoor RH levels as well as daily maximums at the 90th percentile using T1 and M1 models for dwellings which are equipped with central heating.

- The indoor RH levels were calculated using actual and saturation values for indoor humidity levels (see Figure 10, right).

Both verification and validation showed that all of the calculated indoor RH values (Figure 11, left) were somewhat lower than those measured at very cold temperatures and higher than those measured under warm outdoor conditions. This was due to a simplification of our moisture excess model which is taken horizontal during the entire cold period (up to a deflection point of + 5°C) while the measured values for moisture excess levels tend to rise at very low outdoor temperatures (see Figure 3). The temperature model for central heating systems showed less agreement, while that for a stove or combined heating system (not presented graphically) at cold temperatures showed greater agreement due to a lower indoor temperature profile (Figure 7), which caused higher indoor RH levels.

Indoor humidity M2 model based on moisture excess factors

Model description. Although occupancy has the greatest impact on moisture excess, other factors can also be taken into account when determining the average indoor humidity loads. Responses by residents to a questionnaire provided more information on those factors which can influence indoor humidity loads (such as the height of the ventilation stack or the age of windows), without requiring any actual measurements to be taken.

In addition to occupancy levels (the primary factor influencing moisture production indoors), the M2 model takes into account secondary factors: air change rate, air leakage rate, the height of the ventilation stack and the age of windows. In order to calculate the numerical values for moisture excess levels during the cold period, the average and SD rate for the design values for occupancy and other factors have to be assumed by the user of the M2 model (see Table 5).

The coefficients which were derived using linear regression analysis are expressed in equation (8)

$$\begin{aligned}\Delta\nu_{M2} &= \Delta\nu_{M1}(O) + \Delta\nu_{M1}(O)\cdot\\ &\left[-0.29\left(\frac{n_{user}-n_{default}}{\mathrm{SD}_n}\right) - 0.19\left(\frac{q_{50,user}-q_{50,default}}{\mathrm{SD}_{q_{50}}}\right) - 0.13\left(\frac{h_{user}-h_{default}}{\mathrm{SD}_h}\right)\right.\\ &\left.+\,0.12\left(\frac{A_{user}-A_{default}}{\mathrm{SD}_A}\right)\right]\end{aligned} \tag{8}$$

where $\Delta\nu_{M2}$ is the moisture excess level according to the M2 model, corrected using secondary factors, and $\Delta\nu_{M1}(O)$ is the base value for moisture excess levels as a function of occupancy (see the equation) n, q_{50}, h, A are all variables (see Table 5); and SD is the standard deviation for the variables given in Table 5 (n, q_{50}, h, A). Thanks to this, the procedure is as follows, according to the M2 model for calculating moisture excess levels $\Delta\nu_{M2}$ during cold periods:

Table 5. Factors affecting moisture excess levels in the M2 model.

Factor affecting moisture excess levels	Average	Standard deviation	Limitation
Occupancy, *O* (m^2/person)	32.0	18.9	⩾5.0
Air change rate (dwelling), *n* (1/h)	0.32	0.23	⩾0.05
Air leakage rate, q_{50} (m^3/(h m^2))	6.0	5.4	⩾0.8
Height of ventilation stack, *h* (m)	7.8	7.6	⩾1.0
Age of windows, *A* (‘1’ as >10 years, ‘2’ as <10 years)	1.6	0.42	1 or 2

- Determine the occupancy value as was carried out for the M1 model. A questionnaire is the safest and most reliable solution. If unavailable, the number of persons can be taken as being equal to the number of rooms.
- Calculate the moisture excess base value as a function of occupancy using the equations given in Figure 6 (left) or the levels in Figure 9 (left).
- Determine the values for the secondary factors given in Table 5. If information on secondary factors is unavailable, no correction for secondary factors can be applied, and the M2 model is not applicable.
- Calculate the moisture excess level $\Delta\nu_{M2}$ using equation (8).
- Note that moisture excess $\Delta\nu_{M2}$ is an average value. Conversion to 90% critical values for moisture excess levels can be carried out for the same occupancy (see Figure 6 (left) and Figure 9).

M2 model validation. The moisture excess value was calculated on the basis of occupancy using the M1 model. Secondary factors (such as air change rate, air leakage rate, the height of the ventilation stack and the age of the windows) were taken into account in the M2 model using average values (see Figure 12).

The deviation in calculated values from the measured values decreased due to the inclusion of secondary factors but was still relatively large – 49% of the data within

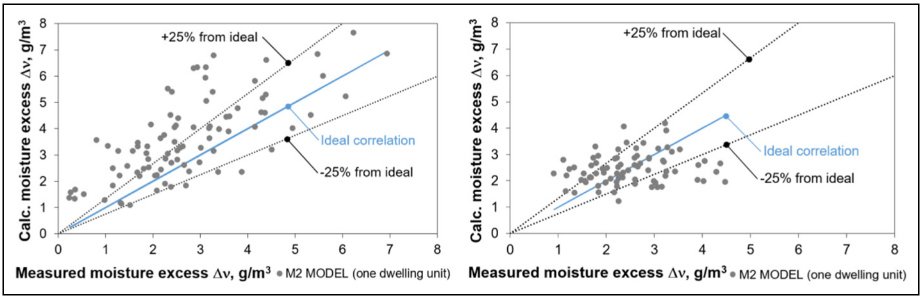

Figure 12. Measured and calculated moisture excess levels using the M2 model – verification using the Estonian data (left) and validation using the Finnish data (right).

a range ±25% in the case of Estonian dwellings and 53% of the data within a range ±25% using the Finnish dwellings. The rate of deviation remains in place due to the stochastic nature of the factors which have been affecting moisture excess levels.

The indoor M3 humidity model based on air change and moisture production rates

Model description. Indoor climate and energy simulation models calculate the indoor air temperature in a zone which takes into account internal and external heat sinks and sources and the thermal transmittance of the building envelope while the temperature is stabilised by the thermal capacity. The moisture balance in a zone depends upon moisture production, and the air change rate and is stabilised by moisture buffering due to interior surfaces (IEA Annex 14, 1991). Thanks to this, hygrothermal design using whole building simulation models requires moisture production and air change rates as input values in place of moisture excess levels, which are used in standardised hygrothermal calculations (EN 15026, 2007; EN ISO 13788, 2012). The M3 model provides such a solution.

As the measured air change rate in Estonian dwellings was found to be predominantly lower than the requirement for the whole dwelling $n = 0.5\,\mathrm{h}^{-1}$, similarly to what was found elsewhere in Europe (Dimitroulopoulou, 2012), hygrothermal analysis should be carried out using the measured levels. Hence, the proposed M3 model is based on the measurement results (Figures 4 and 5) for the average air change rate $n = 0.60\,\mathrm{h}^{-1}$ (SD = 0.43) and moisture production rates $G = 72\,\mathrm{g/h}$ (SD = 50) in bedrooms (see Figure 13). This corresponds to $n = 0.32 \pm 0.23\,\mathrm{h}^{-1}$ for the whole dwelling in this study (due to the flow of ventilation air from inlets towards rooms which have an exhaust outlet). Moisture excess levels which are measured in bedrooms can be assumed to be the same within a single apartment or detached house (except in the bathroom or sauna). If the air flow rate $\dot{V}$ (m^3/h) is

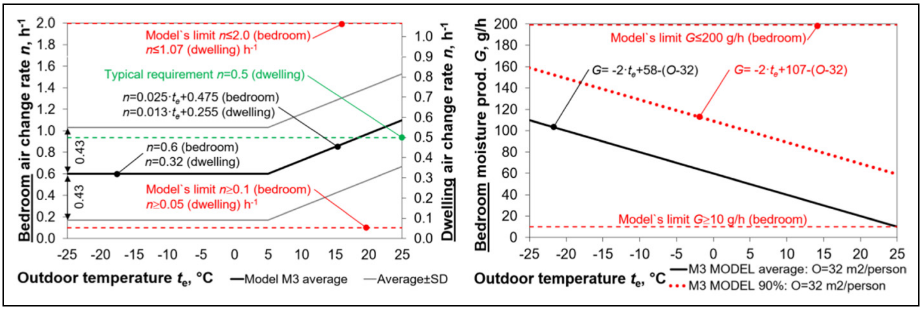

Figure 13. The dependency of air change rate levels for the bedroom (the primary *y*-axis) as well as for the entire dwelling (the secondary *y*-axis) on the left and moisture production levels for a bedroom as a function of occupancy *O* (right) according to the M3 model.

required, the designer will calculate this using the air change rate n and the geometrical dimensions for the dwelling as a whole. The critical load at the 90th percentile based on measurements in the bedroom was at $G = 121\,\mathrm{g/h}$. The air flow rate was calculated using $35\,\mathrm{m}^3$ as the representative effective volume of a master bedroom with a closed bedroom door. It was not proven that the air change rate corresponded to the normal distribution rate in Figure 4 when using Pearson's chi-squared test (with a p value of $0.002 < 0.05$) but was close to the limit value ($p = 0.026 < 0.05$) in the case of moisture production in Figure 5. However, the cumulative distribution curve for the measured air change rate as well as for moisture production was representative when compared against the cumulative distribution rates for an ideal normal distribution ($R^2 > 0.8$).

With this in mind, the procedure one should carry out according to the M3 model (see Figure 13) in order to be able to calculate the air change rate and moisture production levels is as follows:

- If the deterministic approach is taken, use the average air change rate ($n = 0.6\mathrm{h}^{-1}$ during the cold period) and an increased moisture production rate according to equation (9), depending upon the occupancy.
- If the stochastic approach is taken, use the average and SD for the air change rate and moisture production rate according to equation (10). Generate one curve for the air change rate and another for moisture production for each dwelling.

Equation (9) for 90% moisture production

$$G = -2 \cdot t_e + 107 - (O - 32)(\mathrm{g/h}) \tag{9}$$

Equation (10) for average moisture production

$$G = -2 \cdot t_e + 58 - (O - 32)(\mathrm{g/h}) \tag{10}$$

Validation for the M3 model. The performance of the indoor M3 humidity model was also studied by comparing measured and calculated indoor RH levels (see results in Figure 14). The verification procedure itself was similar to that used for the M1 model but was based on data for 88 Estonian dwellings, where information about the air change rate was available. Validation was based on 80 Finnish dwellings. The validation procedure was similar to that used for the M1 model and consisted of the following:

- Since the total surface area of a dwelling unit is the only parameter available in the case of a new building, the latter was used as the basis for calculating the indoor moisture load.
- A representative running trend line between the number of occupants N against the total surface area A of the dwelling unit was used to calculate occupancy –$N = 1.83 * \ln(A) - 6.51$.

- Using the calculated occupancy ($O = A/N$), the moisture production rates as depending upon the outdoor temperature were selected using equation (9) or (10).
- The moisture excess level was added to the outdoor humidity rates in order to derive the indoor humidity by volume.
- The indoor temperature was calculated using models T1 and T2 for both heating system types (central heating or stove/combined heating).
- The saturation humidity by volume was calculated using the indoor temperature.
- The indoor RH levels were calculated using actual and saturation values for indoor humidity levels.

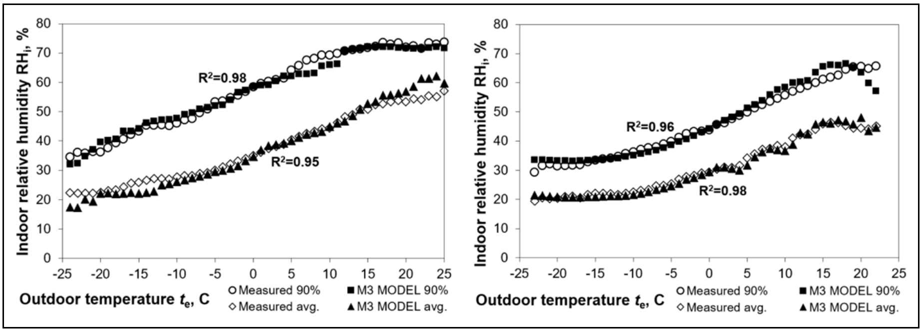

Figure 14. A comparison of measured and calculated indoor RH levels for Estonian dwellings which are equipped with central heating (left) and for Finnish dwellings (right) using the M3 model.

Discussion

Methodology

Indoor humidity is sometimes represented by the RH levels. Indoor RH levels, however, are highly dependent upon the temperature and outdoor climate and are therefore unsuitable for representing the indoor humidity load. The indoor absolute humidity level cannot be used either, since this value also depends upon the outdoor humidity level. Therefore, the moisture excess (or water vapour pressure difference) was used to evaluate moisture loads, as the latter is a driving potential for vapour diffusion.

Since the properties of indoor air had been measured, the data already take into account the buffering effect of the walls, floors and furniture. Mlakar and Štrancar (2013) also report that the presence of hygroscopic materials helps to reduce variations in RH levels. Hence, the values measured in the study are actually 'buffering corrected moisture excess' and 'buffering corrected moisture production', but shorter terms are used down the line for the sake of simplicity. Considering the uncertainties present in moisture production and air change rate, Glass and Tenwolde (2009) have evaluated the role of buffering to be rather insignificant and, therefore, simplified modelling is justified.

EN ISO 13788 review

A comparison of the proposed indoor M1 humidity model (Figure 9) with the existing model described by EN ISO 13788 (2012) shows that they are similar. This is because moisture excess depends upon outdoor air temperature – during colder periods, when moisture excess levels are higher. This is due in part to the lower ventilation rates which are set by the occupants in order to save heating energy and achieve better thermal comfort, but they are also due to an increased level of indoor activity. Since approximately half of the buildings studied had natural ventilation, a higher rate of air change should have been detected, driven by the difference between indoor and outdoor air densities during the winter. Our detailed analysis of the air change rate versus the outdoor temperature seems to show, however, that this stack effect is secondary to the effect shown by the behaviour of the inhabitants, with the latter resulting in a rather constant air change rate during the cold period. As revealed by responses to a questionnaire, residents took action to reduce the air change rate during the winter in order to reduce energy consumption levels and create a better thermal indoor environment. Higher moisture excess levels when the outdoor temperature was very low was due primarily to higher moisture production levels arising from indoor activity but also due to desorbed moisture. Wind velocity during the coldest period of the winter was rather low since climatic high-pressure systems were often present. Differences between the proposed model and that described by EN ISO 13788 (2012) include the turning points in the graphs (5°C vs 0°C) and the levels during warm periods. We propose that moisture excess levels be determined for warm periods according to the load during cold periods – a low base load such as 2 g/m^3 would result in about 0 g/m^3 (valid for low occupancy levels) and a high base load (valid for high occupancy levels), for example, a figure of 6 g/m^3, would result in 2 g/m^3 during the warm period. This latter high moisture excess level may result in very high RH levels in some cases during the warm period, but this should not be considered a failure of the model since a single hour or even a single day are not representative time units for mould growth as a criterion. Lower calculated indoor RH levels than those measured during the validation of the M1 model, but not in the case of the M3 model, indicate an increase in moisture excess levels when the outdoor temperature drops. The latter observation is also supported by our measurement results and by many previous studies. This means that some modification is advised of the EN ISO 13788 (2012) standard so that this perspective is accepted.

The measured air change rate is insufficient for roughly two thirds of dwellings, according to the European standard, EN 15251 (2007) (Figure 4, left). In the case of a few apartments, the low air change rate may have been due to the apartments being temporarily unoccupied. In the majority of cases, the insufficient air change rate (including infiltration) was indicative of comprehensive and serious deficiencies where air change was concerned. A similar problem was discovered by Kotol et al. (2014), who found that ventilation was insufficient in 73% of bedrooms in Greenland.

Novelty and contribution

Any given temperature profile was proven to be dependent upon the heating system being used – central heating or stove. A novel outcome of the approach presented in this article is the ability to choose the moisture excess level for any probability. This is valid both for an average based on all the data (Figure 3, left) and for a critical value (Figure 3, right) based on weekly maximums. It was found that average moisture excess levels during the heating period in bedrooms and living rooms, 2.8 g/m^3 (±1.6), were nearly the same or were somewhat higher than that reported in earlier studies. Although the availability of data on occupancy levels is very limited, occupancy in our sampling of buildings (with a median of 27 m^2/person with an SD of 15 m^2/person for apartments and 45±22 m^2/person for detached houses) was somewhat high, resulting in a rather high moisture excess level.

One of our aims was to examine those factors which were influencing moisture excess levels and moisture production. Although our finding that occupancy is the dominant factor was itself fairly predictable, we were able to quantify its relation to moisture excess and moisture production. We also found other factors which have a significant impact on moisture excess levels and which can be quantified using linear regression. Since we demonstrated that moisture excess levels depend upon occupancy rates, a baseline design value is recommended both for average and critical values. A simple or detailed model can be selected, depending upon data availability, and the ranges for moisture production and air change rates can be used for whole building modelling. Measuring the actual dynamic moisture production rates on a source-by-source basis is proposed for the future research.

The validated models can be applied to determine the hygrothermal boundary conditions for dwellings in cold climates, assuming similar climate conditions and comparable building characteristics. In order to use the results proposed in this article for other countries, it is recommended that comparisons be made of the data (Table 2) and results (Table 5) against findings for the country of origin.

Conclusion

The indoor hygrothermal loads for 237 dwelling units were analysed, determined upon the basis of hourly indoor and outdoor climate measurements which were carried out over a span of several years. The air change rate and moisture production levels in bedrooms were calculated on the basis of CO_2 measurements.

It was found that indoor temperature profiles vary depending upon whether a building has central heating or a stove or a combined heating system. The determined average moisture excess value, 2.8 g/m^3, with an SD of 1.6 g/m^3 for cold periods, can be used in stochastic calculations. Critical values for moisture excess at the 90th percentile, ranging predominantly between 3 and 8 g/m^3, depending upon occupancy rates, can be used in the deterministic analysis. Levels of moisture excess are reported at different percentiles for average and weekly maximums. It appears that moisture excess levels during warm periods depend upon the value during the cold period, marking a significant departure from the EN ISO 13788 (2012) standard. Moisture excess levels during the summer were close to 0 g/m^3 with a low moisture excess level of about 2 g/m^3 during the winter, but the result was in positive figures for higher moisture excess levels.

Average night-time moisture production in bedrooms during cold periods was at 72 g/h with an SD of 50 g/h. The critical value at the 90th percentile was 121 g/h. The average air change rate in bedrooms was $0.6 \pm 0.43\,h^{-1}$, and the critical value at the 10th percentile was $0.20\,h^{-1}$. The corresponding average air change rate for the entire dwelling unit was $0.32 \pm 0.23\,h^{-1}$, and the critical value at the 10th percentile was $0.11\,h^{-1}$.

Two indoor temperatures and three humidity models were proposed with different levels of detail. Our analysis of factors which may be affecting moisture excess and moisture production levels indicates that occupancy is the dominant factor. Therefore, occupancy should be the basis for the selection of the design value for any indoor humidity load. In addition to occupancy, the air change rate and air leakage rate, the height of the ventilation stack and the age of windows all had a significant level of impact. The temperature and humidity load determined using the proposed models can be used to calculate indoor hygrothermal boundary conditions for the building envelope of dwellings in cold climates.

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Declaration of Conflicting Interests

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