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Indoor humidity of dwellings and association with building characteristics, behaviors and health in a northern climate

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ABSTRACT

Data from a nationwide survey on the status of the Swedish residential building stock and indoor air quality was placed in the public domain by the National Board of Housing, Building and Planning of Sweden. The current research investigates the indoor humidity conditions in Swedish residential buildings, single-family houses and apartments, assessing the measurements from the extensive BETSI-survey against adjusted relative humidity levels based on existing norms and Standards. The aim of this study is to investigate associations and correlations between relative humidity levels and multiple building and system characteristics, occupancy patterns and behaviors and health symptoms-complaints. The analysis uses 13 categorical and 9 continuous variables-parameters of the examined dwellings.

Analysis shows that low indoor relative humidity is a realistic issue in Swedish dwellings during the heating season. The issue is more prevalent in apartments than single-family houses. In addition, low indoor relative humidity seems to be more extensive in dwellings with higher indoor temperature, smaller volume, higher ventilation rate and frequent airing practices, lower number of occupants, constructed mainly after 1985, in city suburbs and in the northern parts of the country. The developed multinomial logistic regression model may predict very accurately the relative humidity level of the Swedish dwellings, during heating season. This analysis offers additional evidence to the scientific literature for possible correlation of low relative humidity with specific health symptoms, complaints and disturbances.

1. Introduction

The indoor environment is the microenvironment in which most people spend the major time of their daily life. People have always spent a considerable amount of time indoors, especially at home, which has seen a significant increase during the period of the *COVID-19* pandemic. High quality indoor environment for residential buildings is essential for good physical and mental health, high productivity and learning performance, and comfort of occupants [1,2]. Recent studies have shown that the cost of low-quality indoor environment for the employers, building owners and the society, is directly comparable with the cost of the energy used for the same building [1,2]. However, research effort focuses mainly on the assessment and rating of dwellings in terms of thermal comfort and pollutant concentrations, in association with building characteristics and renovation processes, systems and controls, occupancy behaviors and health symptoms [3–5]. An important quality factor of the environment of a dwelling, which influences comfort, health, stress level, sleep quality and the building construction itself, is the level of humidity indoors [6–8].

Humidity is frequently measured by psychrometer or hygrometer, integrated into a compact temperature sensor and is reported as relative (%; RH) or absolute humidity, (g/m^3; AH). Relative humidity always refers to a specific temperature at a defined pressure. Low, i.e. below 30–40%, and high, i.e. above 60–70%, relative humidity indoors may lead to physical discomfort, as relative humidity has a direct impact on how comfort is perceived [9,10]. High moisture content may cause structural damages, decreased thermal resistance and modification of the physical properties of building materials, deform materials and

Abbreviations: AH, Absolute humidity; BETSI, Bebyggelsens Energuanvändning, Tekniska Status och Innemiljö; CI, Confidence interval; OR, Odds ratio; RH, Relative humidity; VIF, Variance inflation factor.

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result in shorter service life of the building [11,12]. Common hygiene indicators of high RH are among others visible mold, damp stains, condensation on walls and windows, odors and smells [11,13,14]. Humidity analysis indoors is not mandatory for residential buildings, in contrast with other types of buildings, e.g. museums, churches and historical buildings [1,2]. The analysis is conducted primarily to prevent moisture damages (e.g. crawl spaces and attics), which are the main cause of building structure deterioration and poor environment ("dampness" complaints) in spaces with high occupancy like offices, schools and kindergartens [15,16]. A strong focus is therefore seen in current research on presence of high humidity and its impacts.

In response to new construction practices and airtightness levels in buildings for energy efficiency optimization, upper limits of RH have been recommended for thermal comfort and to mitigate growth of mold and fungi indoors [17,18]. On the other hand, there is no widely accepted boundary for low RH value, in parallel with acceptable exposure time [8,10,15]. Research studies and guidelines use 40% RH as a comfort-related limit value and others use 20–30% RH, as a health-related limit value [8,10,15,19,20]. Relative humidity level, below 50%, has been associated with a number of respiratory infections, asthma and allergies [8,16,21]. In addition, in health effects are included pathogens and disease transmission [8,21]. Relative humidity, below 30–40%, is associated with dryness of nasal and laryngeal airways (e.g. throat), dry hands and eye irritations [6,21–23]. The mechanism is not well understood. The effect of pollution to the mechanism should also be considered, however its effect is debatable and requires further investigation [20,22]. Decrease in morbidity and mortality of the lethal viruses (e.g. influenza, rhinoviruses and human rotavirus) and bacteria, is probably the most beneficial output of an increase in RH [10,15,24]. More specifically, water content affects the diameter, cell wall and the viral cover of a number of aerosols and as a result their suspension time [10,15]. Finally, low levels of RH have been related with static electricity complaints [8]. Extensive reviews of the effects of the low RH on biological and chemical factors (bacteria, viruses, fungi, house dust mites, formaldehyde, sulphur and nitrogen dioxides, ozone and other), as well as human factors are presented in Arundel et al. (1986) for studies before 1985, and in Derby et al. (2017) and Wolkoff (2018; [6,8,21]) for studies after 1985.

Dry air is common in Scandinavian countries because outdoor air cannot hold the moisture and it condenses. Indoor humidity appears to correlate better with outdoor AH values, compared with indoor-outdoor RH values [25,26]. In many residential buildings, in these climatic conditions (cool-temperate continental climate), indoor RH is lower than 20% for long periods during the heating season [8,27]. However, this is not the case for many new buildings [28]. The association of indoor humidity with different building-systems characteristics, behaviors and health symptoms or complaints has been investigated in the past [5,29]. In the majority of these studies, the humidity level is assessed either with the use of descriptive values for RH or AH (absolute minimum-maximum or average value of measurements over a period of time) or with the use of the moisture supply value, also referred to in the literature as moisture or vapor excess-increment or moisture balance, in combination with the period of occurrence. The current research investigates the humidity conditions in Swedish residential buildings, assessing the measurements from the extensive 2007/2008 BETSI-survey conducted by the National Board of Housing, Building and Planning (Boverket), against adjusted RH categories based on existing norms [1,2].

The objectives of this study are: a) to correlate the RH levels with the building and occupancy-user behavior characteristics and b) to associate the low RH levels with health symptoms and disturbances, using a comprehensive and extensive dataset from a nationwide survey. To our knowledge there is no previous research that assesses the indoor environment of residential buildings, in terms of indoor humidity, for these climatic conditions (cool-temperate continental climate), in a holistic way, i.e. based on RH levels and correlations with various parameters such as building and systems' characteristics, occupancy patterns and behaviors and health symptoms or complaints. The proposed methodology has been widely used in the past for thermal comfort, ventilation and carbon dioxide (total indoor environmental quality) assessment and it is described analytically in Chapter 2.3 [1,2,30,31].

2. Materials and methods

2.1. BETSI study and buildings' characterization

The BETSI (Bebyggelsens Energianvändning, Tekniska Status och Innemiljö) study was a reference project, which was commissioned by the Swedish National Board of Housing, Building and Planning (Boverket) in 2006 [32–42]. The target of the project was the data collection of the indoor environmental conditions, energy consumption and technical status of the Swedish residential building stock and the comfort and health condition of the users [33,39,43]. Thirty Swedish municipalities of a total of 290 were selected across the country through a stratified random selection (4 stages sampling, clustering and stratification) in respect of geographic and demographic characteristics [32,43]. The selected apartments (permanently inhabited) had minimum real estate value of 50,000 SEK and user area 50 m^2 [5]. The size limitation applied also to single-family houses. Detailed information about the survey can be found in Refs. [32–46].

A total of approximately 1400 residential buildings were inspected in the BETSI study. Measurements of indoor air temperature and relative humidity were taken during two-week periods. The current analysis includes 678 residential buildings, 520 single-family houses and 158 multi-family buildings, monitored between October 2007 and April 2008 (defined as heating season). The analysis uses only measurements of the indoor humidity level in living rooms, as the most representative room of the house. Dwellings with measurements during less than 10 days were also excluded from the analysis (data cleaning and pre-processing).

The inspection data used in the analysis were made available by Boverket and include the buildings' and systems' properties [40,41]. The heated area and volume of the rooms and windows of the building were calculated by the inspectors through drawings or in-situ. The heat transfer coefficient (U-value; W/m^2K) of the different construction materials and elements were calculated and the average overall U-value of the dwelling was estimated. Air change ventilation rates (h^{-1}) were calculated for the living room and for the dwelling (several gas sources were positioned throughout the dwelling) using the passive perfluorocarbon tracer gas method, as described in ISO 16000–8:2007 [5]. The tracer gases were collected passively in charcoal tubes for approximately two weeks. An average value for this period in each dwelling was calculated [5]. The air temperature (^oC) and RH (%) were measured using SatelLite20 TH sensors (Mitec Instruments, Säffle, Sweden) in 15 min steps [5]. Generally, the loggers were placed 1.6–1.8 m above the floor [44]. The measurement range was 10%–95% for RH and −40 to +80 °C for temperature [44]. The uncertainty for air temperature values was ±0.3 °C and for humidity ±3 RH% [44]. Outdoor temperature and RH were collected from the Swedish Meteorological and Hydrological Institute and refer to the nearest stations (SMHI).

Fig. 1 presents a graphic representation of the methodology of the analysis. The analysis uses 13 categorical and 9 continuous variables-parameters for the examined dwellings for possible correlations and associations with different RH levels (Fig. 1, Tables 1 and 2). The available options for the 13 categorical parameters are presented in Table 1. Descriptive statistics of the continuous parameters are presented in Table 2. Five classes of building construction periods were used in the BETSI study, as they represent major changes in building technology linked with upgrades of building codes [32–42]. There are four climate zones for examination (latitude 55^{o}N to 70^{o}N; Table 1). A higher number indicates a southern climate zone (Table 1). The location of the dwellings is classified into 4 categories (Table 1). Ventilation

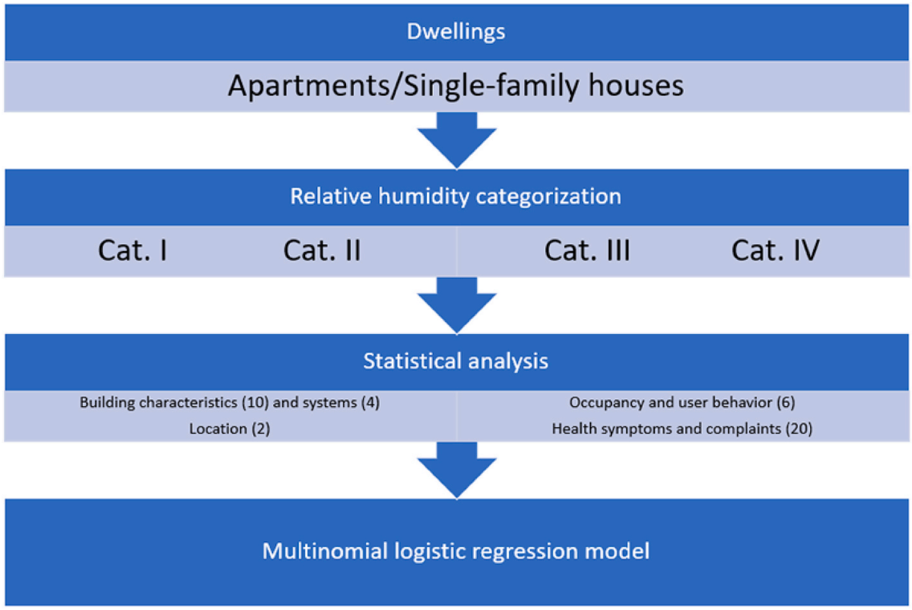


Fig. 1. Methodology of the analysis.

Table 1
Examined categorical variables and available options in the dataset.

a/a	Parameter (Number of cases)	Available options
1	Construction period (461)	before 1960, 1961–1975, 1976–1985, 1986–1995 and 1996–2005.
2	Heating system (676)	other systems, wood stove, directly produced electricity, own combustion boiler, electric boiler, electric resistances, electric radiator, district heating, stove, local produced district heating, fireplace, pellet stove and heat pump.
3	Ventilation system (640)	return only, supply and return, supply and return with heat recovery, exhaust air heat pump central (for apartment), exhaust air heat pump (for single-family houses), exhaust air heat pump local (for apartment) and natural ventilation.
4	Location (675)	city suburb (e.g. apartments), sparsely populated area, city center and residential neighborhood (e.g. single-family houses).
5	Climate zone (461)	inner regions of North Sweden (Norrland; 1), coastal Norrland and some inner areas of Svealand (2), Svealand (3) and Götaland (4).
6	Automated bathroom fan (454)	no and yes.
7	Window vents (452)	no and yes.
8	Closing kitchen area (457)	no and yes.
9	Pets (455)	no and yes.
10	Cooking (457)	1-3 times per month, 1–4 times per week, never and daily.
11	Airing frequency (454)	once per week, never/rarely, daily/almost every day and sometimes/once per month.
12	Airing practice (446)	windows open all day, windows open for a few hours, windows open for a few minutes and never.
13	Drying cloths indoor (455)	no and yes.

systems are classified into 7 categories and heating systems into 13 categories (Table 1). Six options for heating systems, ventilation systems, and cooking option are not represented with cases in the subsample used in the analysis. The analysis is conducted also for different types of dwellings (apartments and single-family houses).

Table 2
Examined continuous variables and descriptive statistics (mean, standard deviation, interquartile range, range, number of cases).

a/a	Parameter	Mean	Standard deviation	Interquartile range	Range	Number of cases
1	Indoor air temperature (°C; average)	21.77	1.35	21.75	11.10	678
2	Building volume (m^3; heated; average ceiling height of 2.4 m)	296	117	286	1094	672
3	Ventilation air change rate, building level (h^{-1})	0.40	0.23	0.36	2.36	646
4	Ventilation air change rate, living room level (h^{-1})	0.41	0.28	0.36	3.20	614
5	U value building (W/m^2K; average, thermal bridging)	0.53	0.24	0.46	1.65	678
6	U value windows (W/m^2K; average)	2.09	0.34	2.00	3.70	678
7	Delta absolute humidity or indoor moisture supply (g/m^3; in-out; average)	1.30	0.96	1.17	10.65	678
8	Window area to heated living area ratio (%)	0.15	0.07	0.14	0.86	678
9	Number of occupants	2.48	1.24	2.00	7.00	534

2.2. Indoor environment and health questionnaire

The air quality assessment and health questionnaire were developed from Uppsala University, Medical Science Department, based on previous research [44]. The questions reflect to the “MM-questionnaire”, which was developed at the Örebro University Hospital, in the early 1980’s [45]. The questionnaire was posted by mail to residents in Spring of 2008 (two reminders; [43]). Almost half (46%) of the adults participated in the project [44]. Information about demographic and medical information of the participants are presented in various past research articles [44–46]. The questionnaire is divided into six categories and includes 35 questions [43]. Questions in the first part referred to the general opinion of the individuals about the indoor environment and if certain problems appeared in their dwellings [43]. The following three parts referred to more detailed questions about occupants’ perception of thermal comfort, air quality and sound quality. The fifth part included questions about health and the sixth part information about the participants [43]. The main question of interest for the present analyses is: “During the last 3 months, have you had any of the following symptoms?”, followed by a list of symptoms [45]. The possible responses were: “yes, often (every week)”, “yes, sometimes” (merged together), or “no, never” [45]. The list of symptoms referred to three categories and a total of nine questions: general symptoms, mucous membranes symptoms and dermal symptoms [45]. Health symptoms and complaints that have not been reported in literature as being relevant to indoor humidity content (high or low values) are not used in this research. A list of 20 symptoms was collected for further analysis. Table 4 presents the health symptoms used in this analysis and the reference period (also number of responses).

2.3. Relative humidity assessment

The analysis aims to highlight the specific characteristics of the residential buildings with low indoor relative humidity. In order to classify the dwellings according to their measured humidity levels, we adopted a categorization based on recommendations in the European Standard EN 16798:2019 [1,2], which we adjusted to the focus of this study on low RH levels. Table 3 presents the four RH levels for every assessment category as used in this analysis. The lower limits of the categories are based on EN 16798:2019 (RH in a descending order). The upper limit of relative humidity for all the categories was set to 60%. This upper value is normal for indoor RH, during the heating season, for these climatic conditions (no issues to human health or the construction elements [1]). Dwellings with RH over 50% are only 5.8% of the sample. This subsample of the cases is small and referred almost exclusively to single-family houses. Deviation percentage for every category is set to 3% [1,2]. Assessment period is the monitoring period for every dwelling. The minimum period is 10 days and the maximum 3 weeks, always within the heating season.

2.4. Statistical analysis

All statistical analyses were conducted with SPSS software version 26.0 (SPSS Inc., Chicago, IL, USA). For the normality distribution check, the numerical Shapiro-Wilk method is used. To determine if there are statistically significant differences between group medians of an independent variable on a mainly continuous dependent variable, the Kruskal-Wallis test was used (Table A.1). The Kruskal-Wallis test is a rank-based nonparametric test. It is an alternative to the one-way ANOVA test or the Mann-Whitney *U* test, and it allows the comparison of more than two independent groups [47]. It can also be applied when the homogeneity of variance is not satisfied. The p-value is adjusted by the Bonferroni correction for multiple tests. In addition, all the p-values are asymptotic, computed by approximation with a standardized normal distribution [47]. The distribution shapes during the tests are similar in all groups for the entire analysis. The tests are conducted on all the available data for the given variable. In total, 6 combinations of the RH categories were calculated (Table A.1). The comparisons are considered statistically significant when p is lower to 0.05 (two-tailed tests). To detect the relationship or differences between categorical variables the Chi-Square test of independence is used [47]. The Chi-Square test is also a nonparametric test. For this analysis, the strength of the association is described by Cramer’s V [47]. For the health symptoms analysis, the Fischer’s Exact Test (Chi-Square analysis) is used.

Table 3
Relative humidity category boundaries used in this analysis.

Category	Upper and lower level of relative humidity (%)
I	30–60
II	25–60
III	20–60
IV	0–60

Table 4
Examined health symptoms and complaints and frequency of yes-responses for the optimum and non-optimum assessment groups of RH. In the parentheses are the number of responses for every health symptom.

a/a	Disturbances last 3 months (Number of responses)	Optimum group Cat. I-II (YES %)	Non-optimum group Cat. III-IV (YES %)	Exact significance (Chi Test -Fischer Exact Test)
1	Asthma[+] (217)	9.0	9.6	0.999
2	Cough (820)	33.9	27.8	0.091
3	Difficulty to concentrate (813)	22.6	20.3	0.467
4	Dry air (864)	23.1	24.0	0.796
5	Dry or red skin face (814)	18.4	13.1	0.057
6	Dry, itchy, red skin in hands (814)	19.5	13.5	**0.038**
7	Dust and dirt (862)	34.8	33.1	0.645
8	Eye sensitivity[++] (865)	25.8	24.7	0.802
9	Headache (815)	51.2	46.9	0.261
10	Heavy head (816)	46.4	41.6	0.201
11	Huskiness, throat dryness (820)	25.6	23.8	0.604
12	Irritated, stuffy or runny nose (818)	41.9	37.4	0.250
13	Itchiness, pain irritation eye (815)	23.1	28.1	0.138
14	Itchiness, peeling in hair, ears (814)	19.8	13.2	**0.023**
15	Nausea, dizziness (819)	16.3	16.1	0.999
16	Respiratory infection (870)	51.9	44.0	**0.034**
17	Static electricity (866)	4.9	9.1	**0.023**
18	Stuffy air (865)	25.6	16.4	**0.030**
19	Stuffy smell[++] (866)	24.3	12.8	*
20	Tiredness (822)	71.1	70.6	0.934

[+]12 months, [++] In general, * Lower than 0.0005.

To examine the relationship between the RH categories and the building, systems, location, and occupancy characteristics, multinomial logistic regression analysis was conducted. Multinomial logistic regression is a classification method [48–50]. It is mainly used to generalize logistic regression to multiclass problems [48–50]. The independent variables may be real-valued, binary-valued, categorical-valued or other. Instead of predicting the value of a variable Y from different predictor variables X_i, in multinomial logistic regression, a probability P (Y) of Y occurring is calculated using the Equation (1) [50]:

$$P(Y) = \frac{1}{1 + e^{-(bo+b1X1i+\ldots+bnXni)}} \qquad (1)$$

The multiple linear regression equation is expressed in logarithmic terms (“e” is the base of the logarithm). The output of this equation is a value between 1 and 0. Maximum likelihood estimation method is used for the estimation of each predictor variable [50]. Our approach considers an analysis of four groups or else three comparisons against one reference category, which is the group of “Cat. IV” (Table A.4). Associations are expressed as odds ratios (OR) with a 95% confidence interval (CI). The odds of an event occurring is defined as the probability of an event occurring divided by the probability of not occurring [50]. Again, the results are considered statistically significant when p is lower to 0.05 (two-tailed tests). The variance inflation factor (VIF) is used to explore the collinearity level between the predictors included in the models (VIF less than 10). Case with studentized residuals greater than 3 were reported. No outliers have been detected for this analysis. The interest is only on main effects of the multinomial logistic regression analysis. Only dwellings with full data on all the variables were included in this analysis.

3. Results

3.1. Dwellings' assessment

Assessment of the examined building sample in terms of RH categories shows that only 63.3% of the cases belong to the Cats. I and II (Fig. 2). The percentages of dwellings in Cats. III and IV are 61.4% for apartments and 29.2% for single-family houses (absolute frequencies). For apartments, the highest share belongs to Cat. III (36.1%) and then Cat. II (27.2%) and for single-family houses to Cat. I (38.1%) and then to Cat. II (32.7%). In Cat. IV belongs 25.3% of the apartments and 6.2% of the single-family houses (10.6% on average).

3.2. Building characteristics

Fig. 3(a–d) presents the boxplot diagrams of the average indoor air temperature (^{o}C), the total heated building volume (m^3), the building level ventilation air change rate (h^{-1}) and the average difference between indoor and outdoor absolute humidity (indoor moisture supply; g/m^3), for the four RH assessment categories. The bottom and the top of the box indicate the 25th and 75th percentiles. The black colored line near the middle of the band is the median. The ends of the whiskers are the 10th and 90th percentiles and the symbols show the outliers.

Increase of the indoor air temperature lowers the RH level and “increases” the assessment category level. Category I has lower mean indoor air temperature, 21.1 °C, compared with Cat. IV at 22.9 °C (Fig. 3a). Mean and median values are close to each other for every category. The boxplots are similar for all the categories. The mean values of the apartments are always higher than the values of the single-family houses for every category and in total. All the categories apart from Cat. I pass the Shapiro-Wilk test for normality with p-values higher than 5%. Statistically significant differences were found between the median values of almost all four categories, with asymptotic significances lower than 5% (Table A.1).

Increase of the volume of the dwelling tends to improve the indoor RH condition (Fig. 3b). The median values of the boxplots are 134.3 m^2 and 100.8 m^2, for Cats. I and IV respectively (average ceiling height of 2.4 m). The mean volume of single-family houses is almost double compared with apartment's volume for every assessment category. Again, mean and median values are close to each other for every category. Only Cat. IV values are normally distributed and the median differences between the assessed categories are statistically significant for four out of six combinations (pairs of categories; Table A.1).

Decrease of the ventilation air change rate improves the indoor RH levels in room (not presented) and building levels (Fig. 3c). At the building level, the mean values are 0.30 (h^{-1}) and 0.55 (h^{-1}) for Cats. I and IV respectively. The ventilation air change rates are higher for apartments in each category and in total. None of the samples is normally distributed and almost all the median differences between the categories are statistically significant at building and room level (5 out of 6 combinations; Table A.1). More than 70% of the cases, have an average ventilation air change rate for the assessment period that is

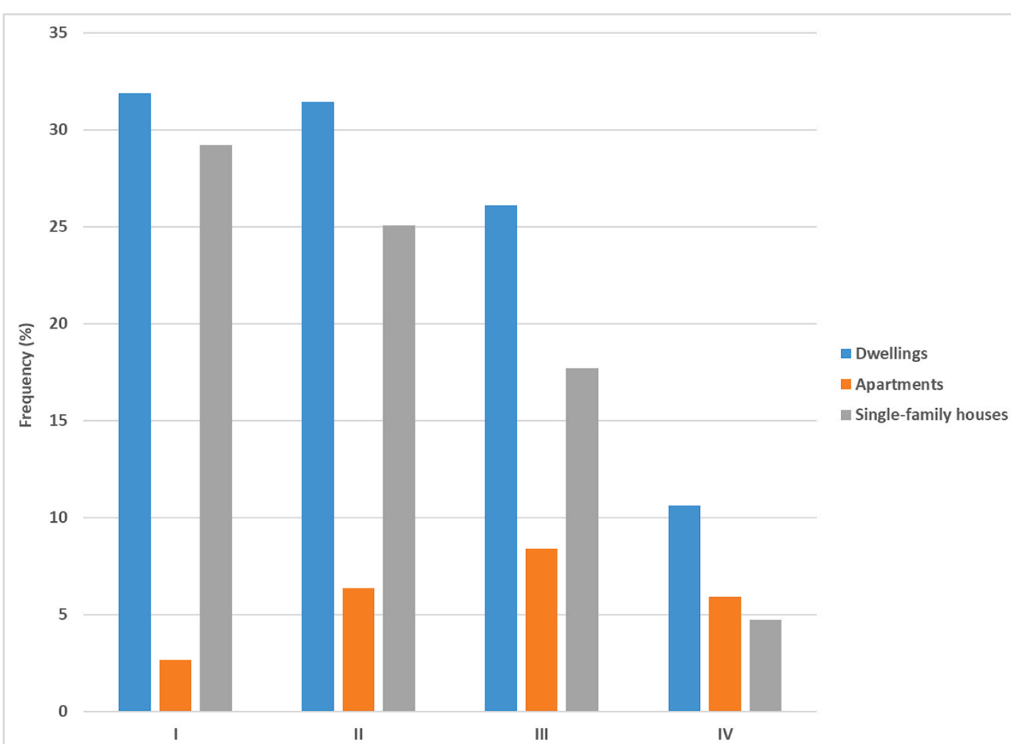


Fig. 2. Frequency bar chart of different building types (apartments and single-family houses) and in total (dwellings), for the four RH assessment categories (678 cases in total). Category I: >30%, Category II: >25%, Category III: >20%, Category IV: >0%.

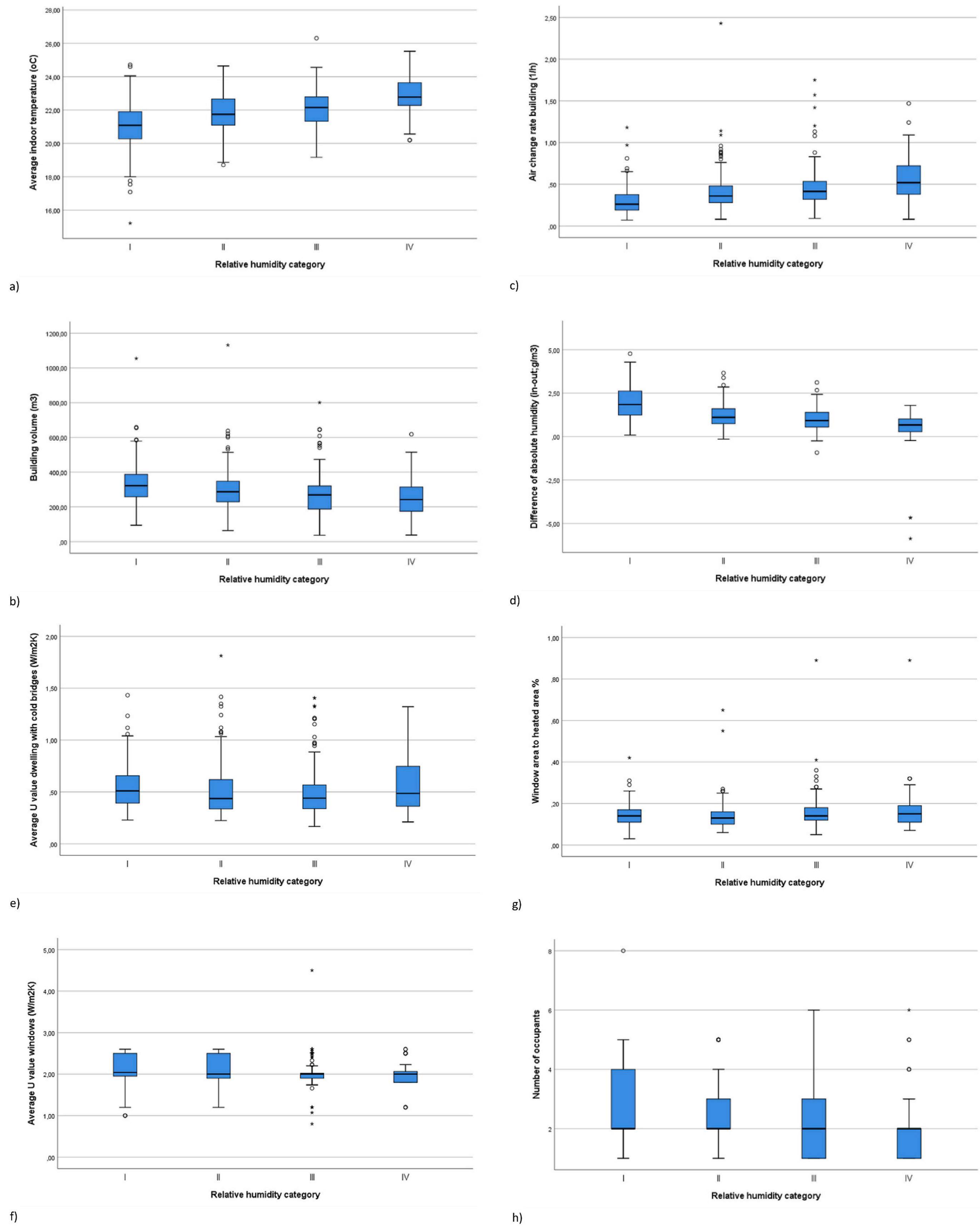
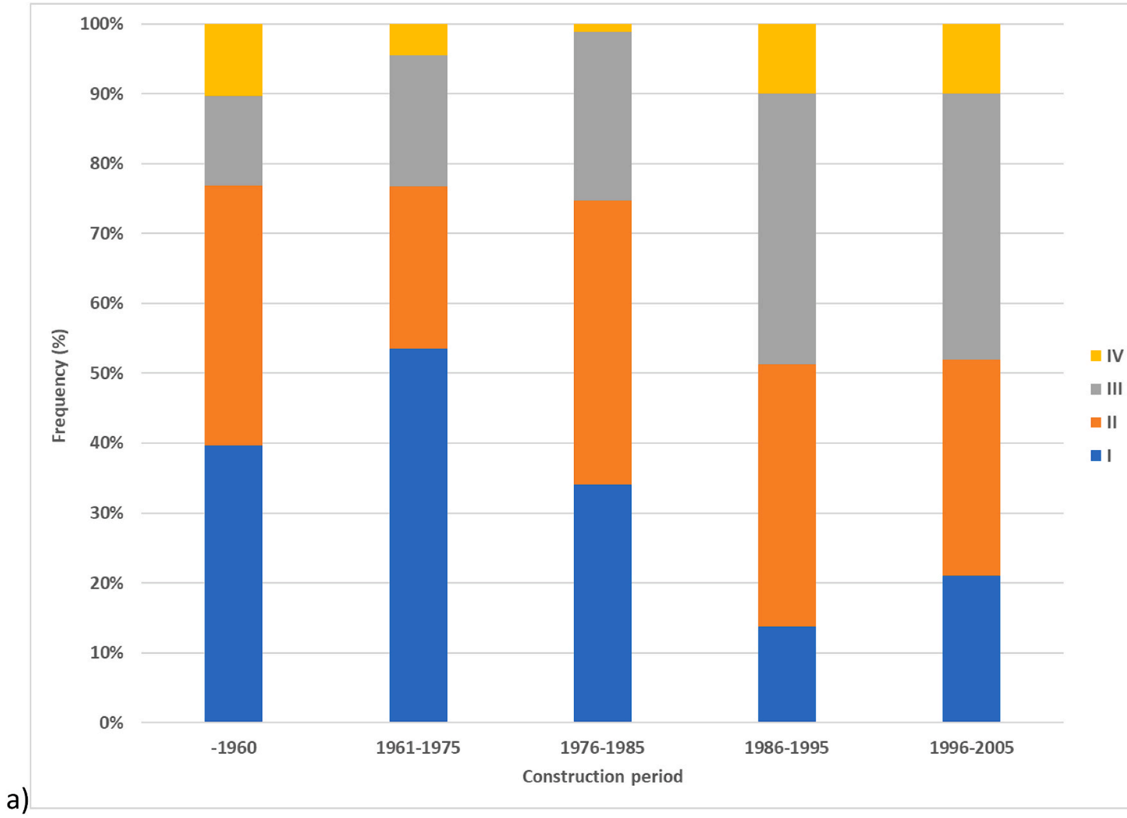


Fig. 3. Boxplots of different examined parameters: a) average indoor air temperature (°C), b) the total heated building volume (m^3), c) the building level ventilation air change rate (h^{-1}), d) the average difference between indoor and outdoor absolute humidity (indoor moisture supply; g/m^3), e) the average U-value of the dwelling (thermal bridges; W/m^2K), f) the average U-value of the windows (W/m^2K) g) the window area to heated area ratio and h) the number of occupants, for the four RH assessment categories. Category I: >30%, Category II: >25%, Category III: >20%, Category IV: >0%.



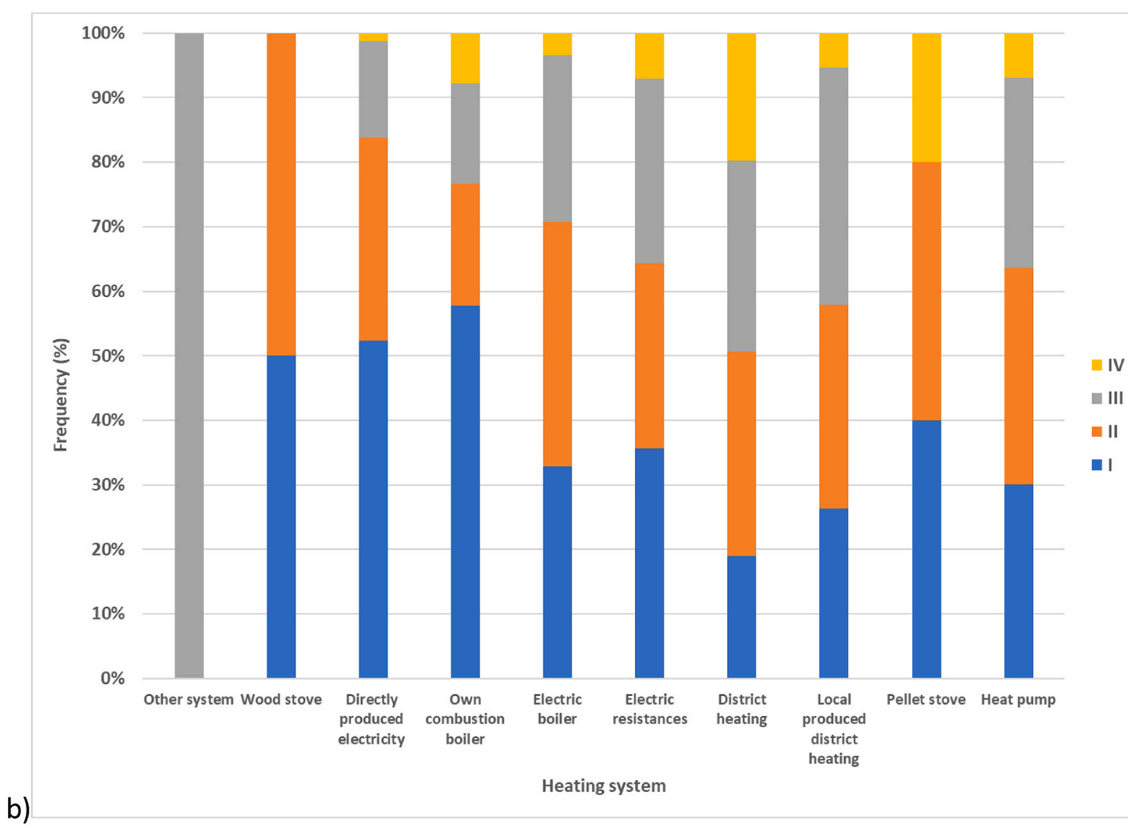


Fig. 4. Frequency bar charts of different examined categorical parameters: a) building construction period, b) heating systems, c) ventilation systems, d) Swedish climatic zones (Table 2) and e) building locations, for the four RH assessment categories. Category I: >30%, Category II: >25%, Category III: >20%, Category IV: >0%.

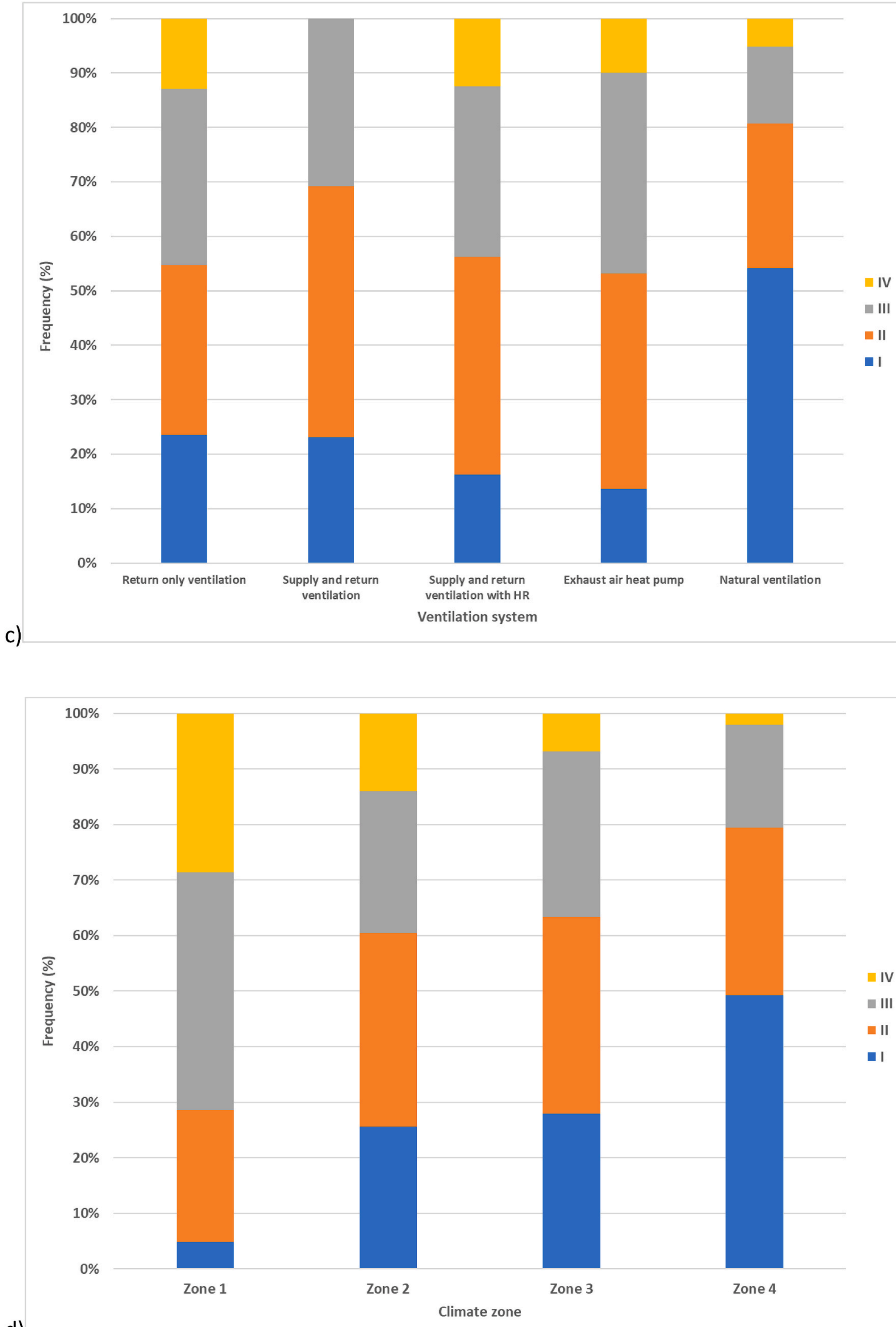


Fig. 4. (*continued*).

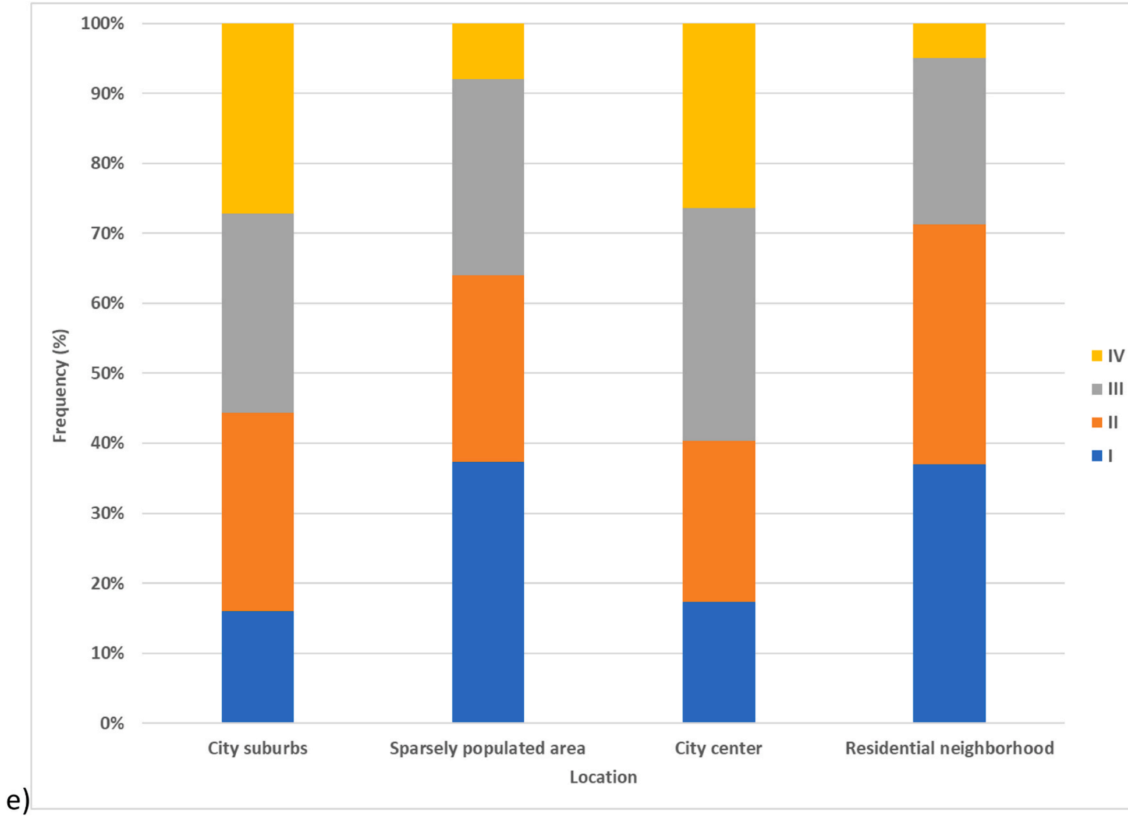


Fig. 4. (*continued*).

lower than the minimum benchmark of the guidelines, i.e. 0.5 h^{-1} [51]. Analytical correlations between ventilation and building characteristics or occupancy behaviors for the BETSI project may be found in Langer et al. (2013; [5]). Ventilation systems are analyzed in Section 3.3.

As expected, smaller difference between indoor and outdoor absolute humidity leads to lower RH levels (Fig. 3d). The conclusion is similar when we compare outdoor absolute and relative humidity for the different assessment categories (not presented). The values are higher for single-family houses compared with apartments for every category and in total. The negative values belong mainly to Cats. III and IV. All the categories apart from Cat. III do not pass the Shapiro-Wilk test for normality, with p-values lower than 0.05. Statistically significant differences were found between the median values for all the four categories (Table A.1). For single-family houses, a mean value for moisture supply for optimum conditions for indoor RH, higher than Cat. II, is 1.3 g/m^3 and for apartments equals to 1.0 g/m^3 (1.2 g/m^3 in total). The values are 84% and 85% (85% in total) and 5.3 g/m^3 and 5.0 g/m^3 (5.1 g/m^3 in total) for outdoor RH and AH respectively.

For the next three examined parameters: average U-value of the building with thermal bridges, average U-value of the windows and windows area to heated area ratio, no clear correlations and associations with the assessment categories could be concluded (Fig. 3e, f, g). All the samples are not normally distributed, and the number of outliers is considerable for every category and parameter. For the 3 analyses, there are no statistically significant differences between the median values of all four categories with asymptotic significances higher than 5%, almost in every comparison and examined parameter (4 out of 6; Table A.1). The average building U-value for every category is lower for single-family houses compared with apartments. The average U-value of the windows is 2 W/m^2K for every RH category. The window area to heated living area ratio is higher for single-family dwellings, for Cats I and II, and lower for the remaining two categories.

Fig. 4a presents the frequency bar chart of the four RH assessment categories for each of the construction age-period of the examined dwellings. Almost 50% of the recently built dwellings (after 1985) belong to Cats. III and IV. For the remaining construction periods the percentages are between 70 and 80% for Cats I and II. Similar results may be extracted also for the two different building types and the construction age. Dwellings constructed between 1961 and 1975, followed by dwellings constructed before 60's, present the highest shares in Cat. I. Buildings constructed before the 60's followed, by dwellings constructed after 1996, present also the highest shares in Cat. IV. The results of the statistical analysis regarding the Chi test of association, and more specifically the Cramer's V value and the approximate significance values, are presented in the Appendix (Table A.2). All the values are lower than 0.25 and 8 out of 13 examined parameters present p-values lower than 0.05.

Finally, the percentage of the closed-kitchen area responses is 39.9% and 25.8%, for Cat. I and Cat. IV respectively (not presented). This output probably related with the fact that the question refers to the structure of the dwelling not the actual behavior, i.e. close the door, of the users. For apartments, the shares are equal. For single-family houses the open space responses are more than double compared with the close-space responses. The Cramer's V is pretty low and the approximate significance higher than the benchmark (Table A.2).

3.3. Building systems

Fig. 4b presents the frequency bar chart of the four assessment RH categories for each of the heating systems of the examined dwellings. The systems with the highest share in Cat. I are the "own combustion boiler" followed by the directly produced electricity system (referred mainly to houses). On the other hand, the systems with the highest share in Cat. IV are the pellet stove, followed by the district heating system. District heating is the major heating system for apartments (80.4%). However, many single-family houses are connected to the system too.

For single-family houses, the systems with the highest percentages are heat pumps, district heating and directly produced electricity. District heating systems perform better, in terms of RH, in houses than in apartments. Heat pumps seems to be a trustworthy solution in houses for acceptable RH levels, with 63.6% in optimum categories.

Similar outputs were derived for the different examined ventilation systems (Fig. 4c). The ventilation systems with the highest share in Cat. I are natural ventilation, which is the most common system in single-family houses, followed by return only ventilation. On the other hand, the systems with the highest share in Cat. IV are return only ventilation followed by supply and return ventilation with heat recovery. The share of the optimum RH levels in naturally ventilated dwellings is more than 80% (Cats. I and II). This is further explored in Section 3.5. In 44.3% of the houses natural ventilation is being used as the only ventilation system of the building. Return only ventilation system is typical for apartments, with existence in 71.9% of the cases. This system exists also in many single-family houses (24.4%). Supply and return ventilation system without heat recovery is not found in many cases in the sample, but it performs well in terms of RH. Results related with exhaust air heat pumps were merged in one category (Table 1). The Cramer's V for heating and ventilation systems are higher than most of the other parameters and the approximate significance lower than 5% (Table A.2).

In approximately 75% of the examined cases automated fans in bathrooms are not being used. The share is similar for both apartments and houses. Analysis showed that the installation of automated fans in bathrooms increases the possibilities for the dwelling to have higher levels of RH and acceptable moisture content. The Cramer's V is relatively high and the approximate significance lower than the benchmark (Table A.2). Windows vents are common in apartments, at higher than 50%, but not in houses. No general conclusions may be extracted in terms of RH for the use of windows vents in dwellings. The Cramer's V is rather low and the approximate significance higher than the benchmark (Table A.2).

3.4. Location

Fig. 4d presents the frequency bar chart of the four assessment RH categories for each of the 4 different Swedish climatic conditions of the examined dwellings. The warmer the average outdoor conditions the higher the share of the optimum indoor conditions in terms of RH. Zone 4 (southern part of Sweden) shows the best outputs. The majority of the cases refers to single-family houses (82.9% of the examined population).

In terms of location, the residential neighborhoods (houses) and the sparsely populated areas show the highest shares for optimum humidity indoors (Fig. 4e). High Cat. IV shares are presented for the remaining two groups. The Cramer's V is again rather low and the approximate significance lower than the benchmark (both variables; Table A.2).

3.5. Occupancy and user behaviors

Fig. 3h presents boxplot chart of the number of occupants in the dwellings for the different assessment categories. Increase of the number of occupants increases the possibility for a dwelling to be at the optimum RH category. The average number of occupants in the examined apartments is 1.94 and in the houses 2.71. These numbers are close to the average numbers of occupants for optimum categories of RH for both types, 2.00 and 2.74 respectively. Two occupants per dwelling is a prevailing number and a median for all the assessed categories. The samples are again not normally distributed. The median differences between the assessed categories are statistically significant for three out of six combinations (Table A.1).

Analysis showed that the existence of pets increases the possibilities for an apartment to have higher levels of RH (not presented). The outputs are not so conclusive for houses. Similar conclusion was also derived for the cooking process in apartments (not presented). The daily cooking, compared with the cooking 1–4 times per week, improves the indoor environment in terms of RH. The results again are not so straightforward for single-family dwellings. For drying clothes indoors, the conclusions are straightforward for both types of the dwellings (not presented). The results of the statistical analysis regarding the Chi test of association, Cramer's V, and the approximate significance values are presented in the Appendix (Table A.2).

Apartments tend to ventilate their spaces daily or almost every day in a percentage of 70.9% compared with the houses in a percentage of 54.7% (airing frequency). Apartment users open their windows all day and for a few hours 25% and 46.1% respectively (airing practice). The percentages for houses are 15.4% and 35.1% respectively. The analysis for the different assessment categories and airing behaviors supports the conclusions analyzed earlier, whereby less frequent ventilation leads to higher RH levels. The Cramer's V values are rather low and the approximate significance values higher than the benchmark (both variables; Table A.2).

3.6. Health symptoms and complaints

The correlation and association of specific health symptoms and complaints with various building and system characteristics, occupancy behaviors and other parameters of the BETSI database has been conducted in many scientific publications in the past [43–46]. In these analyses, humidity is represented either as a maximum/minimum or as an average value. In this research study the indoor humidity condition during heating season of a building is assessed using the entire measurement datasets and based on the described RH categories (Section 2.3). In Table 4 the yes-response percentages for two aggregation groups, Cats. I-II (optimum) and Cats. III-IV (non-optimum) are presented. More than 800 responses, apart from the asthma responses, for every health symptom and complaint were used in this analysis. The reference period is 3 months in most of the cases. The reference period covers the monitoring period of the dwellings. For the optimum group, the "yes" percentage is higher in 16 out of 20 categories compared with the non-optimum (5 statistically significant differences). Asthma, dry air, itchiness-pain-irritation in the eyes and static electricity are the health complaints and symptoms with higher "yes" percentage for the non-optimum humidity group. In one out of four complaints, static electricity, the difference is also statistically significant. From the literature review it is clear that all these disturbances can be related with the humidity level indoors for shorter or longer periods or in parallel with other reasons (e.g. dust or pollution). Health symptoms such as tiredness, respiratory infections and headaches present very high yes-responses, for both aggregation groups. For symptoms like dry hands and irritated nose, which related with low RH, the optimum group percentage is higher than the non-optimum. The results of the statistical analysis regarding the Chi test of association, and the Cramer's V are presented in the Appendix (Table A.3).

3.7. Multivariate analysis

The statistical analyses of the previous Sections highlight the most significant and dominant parameters that determine the indoor RH level of the dwellings. For the multinomial regression analysis model 9 out of 21 parameters-variables of this analysis have been used (Tables 1 and 2). These parameters are easily obtained before the categorization process, for almost every residential building. Four of the variables are continuous (average indoor air temperature, total building volume, building ventilation air change rate and number of occupants) and 5 are nominal (construction period, heating system, ventilation system, location and climate zone). The remaining parameters based on the previous analysis are secondary and less important. Many of these parameters related with the building use and because they were not monitored systematically, they cannot be used for the development of a solid model and generalization purposes. The reference category was Cat. IV. The regression coefficients, the standard errors of the coefficients, the Wald test results (statistically significance), the antilogarithms and the 95% confidence interval bounds are presented for the 3 remaining categories in Table A.4. The model was run on 413 cases (data for 9 parameters). The results of the likelihood ratio tests are respectively: 343.5, 81, <0.0005 (Chi-square, df, p-value sig.). Seven out of nine variables are also statistically significant, apart from construction period and location (likelihood ratio tests). The pseudo-R^2 result is moderate to high, 0.616 (normalized Nagelkerke method; [52]). The average prediction percentage is 65.6% (81.6%, 63.3%, 44.2%, 73.9% for the 4 categories). The effectiveness of the model for the best and worst categories is very high, over 70%. The prediction percentage is 89.5% for the optimum categories. Both results verify the effectiveness of the model. The variables with the strongest effects are the number of occupants and the building volume for all the three combinations (continuous variables; Table A.4). As far as the categorical variables, for construction period is the 1976–1985 period, for the heating systems is the locally produced district heating, for the ventilation system the natural ventilation, for the location the sparsely populated area and for the climate zone the southern one.

For a larger model, with 20 out of 21 variables (apart from indoor moisture supply; Tables 1 and 2), the results of the likelihood ratio tests are respectively: 372.4, 129, <0.0005 (Chi-square, df, p-value sig.). The pseudo-R^2 result is moderate to high, 0.681, slightly higher than the previous model. This model predicts the 67.7% of the observed categories and more specifically the 81.2% of the Cat. I, the 65.1% of the Cat. II, the 48.4% of the Cat. III and the 81.0% of the Cat. IV (not presented).

4. Discussion

Analysis shows that low indoor RH, defined by categorization methodology, is a realistic issue in Swedish dwellings, mainly apartments, during the heating season. As the percentage of the apartments in the examined sample is lower compared with the entire Swedish stock, the low indoor relative humidity issue is expected to be more prevalent in reality.

Indoor low relative humidity seems to be more extensive in dwellings with higher temperature, smaller volume, higher ventilation rate and frequent airing practices, lower number of occupants and pets, constructed mainly after 1985, in city suburbs and in the northern part of the country. By definition, RH strongly related with indoor temperature. The temperature in apartments is higher than in single-family houses for similar categories and in total. In houses, the temperature is controlled mainly by the occupants-owners. In apartments the temperature is controlled centrally, and the utility costs are mostly included in the rent. In addition, the indoor humidity for apartments is lower, mainly because of the lower occupancy gains, the smaller volume or the ventilation processes and practices.

Ventilation seems to be a critical factor of controlling and optimizing indoor humidity levels in Swedish buildings. Decrease of the ventilation air change rate improves the indoor RH levels at room and building level. A possible explanation is the lower outdoor absolute humidity levels, compared with the indoor levels. The ventilation air change rates are higher for apartments (each category and in total). More than 70% of the examined cases, have an average ventilation air change rate for the assessment period that is lower than 0.5 h^{-1} [51]. Dimitroulopoulou reviewed a number of scientific articles reporting ventilation rates across Europe and concluded that the ventilation rates are generally higher in southern climatic condition compared to Scandinavian countries and in summer compared to winter [51]. This finding is similar with earlier ventilation studies in Scandinavia and northern countries [53]. Lower ventilation rates assure acceptable RH levels during heating period, but potentially non-acceptable conditions for hygienic reasons and pollutants (right balance target). The ventilation systems with the optimum performance, in terms of RH level, are natural ventilation (single-family houses) and return only ventilation (apartments). With the generally low outside absolute humidity during the measurement periods, this outcome suggests limited window opening behavior, leading to higher humidity levels compared to the dwellings with continuous ventilation. On the other hand, the systems with the less optimum performance are return only ventilation followed by supply and return ventilation with heat recovery. The performance of the exhaust air heat pump, for RH, is moderate. Finally, analysis shows that the installation of automated fans in bathrooms increases the possibilities for the dwelling to have acceptable moisture content.

District heating is the major heating system for apartments. District heating systems perform better, in terms of RH, in houses than in apartments. This output is related to the air temperature set points and the control of the system (central control in apartments). For single-family houses, the systems with the highest percentages are heat pumps, district heating and directly produced electricity. Heat pumps seems to be a trustworthy solution in houses, in terms of RH levels. In addition, directly produced electricity systems offer a sustainable and a highly effective solution in terms of relative humidity levels. The number of certain installed systems (e.g. wood stove, pellet stove, other systems) is too small and as a result no general conclusions for these systems may be extracted.

U-value of the building elements and windows, and window to living area ratio are not important factors associated with low humidity levels indoors. However, based on the analysis and dataset, the energy performance improvement of the façade windows for the dwellings during the renovation process should be number one priority for the future of the Swedish building stock.

The warmer the average outdoor conditions the higher the share of the optimum indoor conditions in terms of RH. The extremely dry conditions of the northern part of the country do not supply the indoor environment of the dwellings with moisture and higher humidity content from other sources and activities are necessary. In terms of location, the residential neighborhoods (houses) and the sparsely populated areas show the most optimum outputs. This output is probably related with the proximity of the dwellings to nature through gardens and forests or the rain conditions (i.e. evaporation process) and as a result higher outdoor absolute humidity content.

Occupancy (pets included), user behaviors and patterns in buildings are also crucial factors for the RH in indoor spaces. Indoor activities, like cooking and drying of clothes improves the indoor environment, in terms of RH, significantly. Smaller difference between indoor and outdoor absolute humidity leads to lower RH levels. The conclusion is similar when we compare outdoor absolute and relative humidity for the different assessment categories.

Additionally, the analysis offers evidence to the scientific literature for possible correlation of low relative humidity with specific health symptoms, and complaints: tiredness, respiratory infections and headaches. Further investigation is necessary to include all indoor spaces (i.e. office), occupants use during their daily life. However, in many specific health complaints, acclimatization and assimilation were assumed. This hypothesis needs further scientific investigation. The analysis method used in this study supports the findings and conclusions of previous scientific outcomes. As a result, this methodology may be used widely, not only in energy or air quality assessment research but also in epidemiological and health related campaigns.

Finally, the developed model (9 parameters) may predict very accurately the relative humidity level of the dwellings for the whole country, during heating season, for future interventions. The level of complexity of the second model (20 parameters) is extremely high, as it requires many inputs for the residential buildings. In addition, the improvement of the effectiveness in prediction of the extended model is small.

5. Limitations of the research

In this study there are certain limitations primarily related to the sample and methodology. For the BETSI-survey, humidifiers were not recorded along with other building systems. To our knowledge, humidifiers are not widely applied in the Swedish market for residential buildings, even today. The number of the apartments in the examined building stock population is under-represented. This limitation is fundamental for future research and related with the development of guidelines for residential buildings, as far as indoor relative humidity problems are concerned. In addition, the monitoring campaign was conducted during the extended heating season, which corresponds to autumn, winter and spring period in Sweden. It is widely acknowledged that the monitoring period for the dwellings, i.e. 10 days to three weeks, is short to include significant weather changes. Periods with intense wind speed and rain, or high indoor-outdoor temperature differences may significantly influence the ventilation rate of dwellings. Periods with low outdoor air quality or noise may influence the occupants' behavior and habits (e.g. window use) and the measured environmental parameters. This limitation is particularly important for the climatic conditions of Sweden. Furthermore, the outdoor conditions were extracted from meteorological stations few kilometers away from the dwellings (e.g. airports). As a result, the local microclimate and conditions were overlooked. Differentiation of the living routines over time is also an import reason for deviations. Regulations suggest longer periods for indoor humidity assessment, such as a month or a full heating season [1,2]. The high amount of examined cases in this research aimed to compensate for this limitation.

Finally, there is a time lag between the monitoring campaign and the questionnaire survey. The survey responses are based on personal anamnesis and thoughts of the users and not on documented evidence, written on logbooks or other recording tools. The reported health problems and complaints may have also been affected by this limitation in the research procedure. The logbooks can be also helpful for occupancy patterns documentation. These patterns cover indoor activities, users' habits (e.g. use of doors and windows) and systems' operation. For health symptoms correlations and associations, a holistic assessment of the indoor spaces used by the occupants is suggested for future analysis.

6. Conclusions

This research presents an assessment of the humidity conditions in Swedish dwellings, including apartments and single-family houses, based on the monitoring campaign of the BETSI-survey, following a state-of-the-art methodology. To our knowledge there is no previous research analysis that assesses the indoor environment in terms of humidity, in a holistic way, based on categories and their associations with various parameters, such as building-systems characteristics, occupancy patterns and behaviors and health symptoms-complaints. The methodology applied here is simple and easily communicated to developers, stakeholders, policy makers and building users.

Analysis shows that low indoor RH is a realistic issue in Swedish dwellings during the heating season. The issue is more prevalent in apartments than single-family houses. In addition, indoor low relative humidity seems to be more extensive in dwellings with higher indoor temperature, smaller volume, higher ventilation rate and frequent airing practices, lower number of occupants and pets, constructed mainly after 1985, in city suburbs and in the northern parts of the country. Lower ventilation rates assure acceptable RH levels during heating period, but potentially non-acceptable conditions for hygienic reasons and pollutants (0.5 ach benchmark). This leads to the challenging problem of achieving the right balance between air quality factors when designing new buildings or renovating existing ones. U-value of the building elements and windows, and window to living area ratio are not important factors associated with low humidity levels indoors. In dwellings with district heating (mainly apartments), exhaust heat pump systems or return only systems for ventilation and without bathroom fans are expected to have low relative humidity conditions. On the other hand, indoor activities, like cooking and drying of clothes improves, in terms of RH, the indoor environment significantly. Moreover, moisture supply values are suggested, for optimum levels to avoid dry air, for different residential building types. These values refer only to the Swedish climatic conditions or similar and during the heating season. The developed model may predict very accurately the relative humidity level of the dwellings for the whole country, during heating season. Finally, this analysis offers additional evidence to the scientific literature for possible correlation of low relative humidity with specific health symptoms, and complaints.

The conclusion and suggestions of the current research can be used for future planning of national survey campaigns of building stocks in Sweden or other countries with similar issues. The low relative humidity of the stock is a realistic air quality issue that has not been highlighted enough in the official publications of the project and drastically affects the building-users.

Declaration of competing interest

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

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Appendix A

Table A.1
Pairwise comparisons of relative humidity categories, independent samples Kruskal-Wallis test results (adjusted asymptotic significance values), for different parameters.

a/a	I-II	I-III	I-IV	II-III	II-IV	III-IV
Indoor air temperature	*	*	*	0.232	*	*
Building volume	1.000	**0.031**	*	0.093	*	**0.009**
Ventilation air change rate, building level	*	*	*	**0.036**	*	0.094
U-value, building level, thermal bridging	1.000	0.204	**0.003**	0.363	**0.008**	1.000
U-value windows	1.000	0.076	*	0.345	*	0.074
Delta absolute humidity or indoor moisture supply (in-out)	**0.016**	*	*	**0.018**	*	*
Window area to heated living area ratio	0.706	**0.008**	**0.042**	0.499	0.666	1.000
Number of occupants	0.215	**0.002**	*	0.266	**0.007**	1.000
Relative humidity outdoor	**0.031**	*	*	*	*	0.685
Absolute humidity outdoor	**0.023**	*	*	*	*	*

*Lower than 0.0005.

Table A.2
Chi-Square test results, Cramer's V value and approximate significance, for different categorical parameters.

a/a	Variable	Cramer's V value	Approximate significance
1	Construction period	0.210	*
2	Heating system	0.213	*
3	Ventilation system	0.234	*
4	Location	0.197	*
5	Climate zone	0.190	*
6	Automated bathroom fan	0.226	*
7	Window vents	0.115	0.111
8	Closing kitchen area	0.119	0.090
9	Pets	0.103	0.186
10	Cooking	0.132	**0.014**
11	Airing frequency	0.067	0.730
12	Airing practice	0.099	0.157
13	Drying clothes indoor	0.158	**0.010**

*Lower than 0.0005.

Table A.3
Chi-Square test results and Cramer's V value, for different health symptoms and complaints.

a/a	Variable	Cramer's V value
1	Stuffy air	0.123
2	Dry air	0.056
3	Static electricity	0.085
4	Stuffy smell	0.144
5	Tiredness	0.045
6	Heavy head	0.117
7	Headache	0.043
8	Nausea/dizziness	0.065
9	Difficulty to concentrate	0.039
10	Itchiness/pain/irritation eye	0.064
11	Irritated/stuffy or runny nose	0.068
12	Huskiness/throat dryness	0.039
13	Cough	0.104
14	Dry or red skin face	0.084
15	Itchiness/peeling in hair/ears	0.097
16	Dry/itchy/red skin in hands	0.078
17	Respiratory infection	0.075
18	Asthma	0.123
19	Eye sensitivity	0.091
20	Dust and dirt	0.020

*Lower than 0.0005.

Table A.4
Multinomial logistic regression model parameter estimates: regression coefficients, standard errors of the coefficients, Wald test results (statistically significance), antilogarithms and the 95% confidence interval bounds.

Relative humidity category[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
I	Intercept	79.165	1071.563	.005	1	.941			
	Average indoor temperature (OC)	−2267	.458	24.558	1	.000	.104	.042	.254
	Building volume (m^3)	-.010	.003	10.074	1	.002	.990	.984	.996
	Air change rate building (1/h)	−13.923	2355	34.945	1	.000	8.985E-7	8.887E-9	9.083E-5
	Number of occupants	1515	.415	13.332	1	.000	4548	2017	10.253
	[Construction period = 1]	-.614	1376	.199	1	.655	.541	.036	8028
	[Construction period = 2]	-.511	1272	.162	1	.688	.600	.050	7251
	[Construction period = 3]	2959	1615	3357	1	067	19.275	.813	456.696
	[Construction period = 4]	1474	1440	1048	1	.306	4367	.260	73.480
	[Construction period = 5]	0[b]	.	.	0	.	.	.	.
	[Heating system = 2]	18.432	7772.722	.000	1	.998	[c]	.000	.
	[Heating system = 3]	14.028	1606.969	.000	1	.993	[c]	.000	.
	[Heating system = 4]	−2048	1793	1305	1	.253	.129	.004	4329
	[Heating system = 5]	-.605	1745	.120	1	.729	.546	.018	16.712
	[Heating system = 6]	1563	2507	.389	1	.533	4772	.035	649.291
	[Heating system = 8]	−2228	1263	3114	1	.078	.108	.009	1280
	[Heating system = 10]	33.834	4067.140	.000	1	.993	[c]	.000	.
	[Heating system = 12]	−6083	3453	3103	1	.078	.002	2.626E-6	1983
	[Heating system = 13]	0[b]	.	.	0	.	.	.	.
	[Ventilation system = 1]	−1376	1358	1027	1	.311	.253	.018	3615

(continued on next page)

Table A.4 (*continued*)

Relative humidity category[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
	[Ventilation system = 2]	14.145	1272	123.683	1	.000	[c]	114.935.018	16.815.481.928
	[Ventilation system = 3]	−5560	1684	10.907	1	.001	.004	.000	.104
	[Ventilation system = 4]	−44.840	8226.250	.000	1	.996	3.360E-20	.000	.
	[Ventilation system = 5]	−7292	2044	12.735	1	.000	.001	1.240E-5	.037
	[Ventilation system = 7]	0[b]	.	.	0	.	.	.	.
	[Location of the building = 1]	−1176	1403	.703	1	.402	.309	.020	4821
	[Location of the building = 2]	2282	2207	1069	1	.301	9794	.129	741.005
	[Location of the building = 3]	-.079	1190	.004	1	.947	.924	.090	9509
	[Location of the building = 4]	0[b]	.	.	0	.	.	.	.
	[Climate zone = 1]	−24.605	1071.500	.001	1	.982	2.062E-11	.000	.
	[Climate zone = 2]	−21.023	1071.499	.000	1	.984	7.412E-10	.000	.
	[Climate zone = 3]	−19.622	1071.498	.000	1	.985	3.007E-9	.000	.
	[Climate zone = 4]	0[b]	.	.	0	.	.	.	.
II	Intercept	61.594	1071.560	.003	1	.954			
	Average indoor temperature (OC)	−1577	.444	12.623	1	.000	.207	.087	.493
	Building volume (m^3)	-.009	.003	8197	1	.004	.991	.985	.997
	Air change rate building (1/h)	−8132	2099	15.003	1	.000	.000	4.800E-6	.018
	Number of occupants	1069	.400	7156	1	.007	2912	1331	6372
	[Construction period = 1]	-.017	1300	.000	1	.990	.983	.077	12.564
	[Construction period = 2]	-.699	1210	.334	1	.563	.497	.046	5324
	[Construction period = 3]	3445	1558	4885	1	.027	31.328	1477	664.530
	[Construction period = 4]	2043	1333	2349	1	.125	7714	.566	105.192
	[Construction period = 5]	0[b]	.	.	0	.	.	.	.
	[Heating system = 2]	15.726	7772.722	.000	1	.998	[c]	.000	.
	[Heating system = 3]	13.942	1606.969	.000	1	.993	[c]	.000	.
	[Heating system = 4]	−4025	1778	5125	1	.024	.018	.001	.583
	[Heating system = 5]	-.852	1685	.256	1	.613	.426	.016	11.587
	[Heating system = 6]	-.105	2343	.002	1	.964	.900	.009	88.810
	[Heating system = 8]	−2113	1220	3000	1	.083	.121	.011	1321
	[Heating system = 10]	33.823	4067.140	.000	1	.993	[c]	.000	.
	[Heating system = 12]	−6424	3439	3490	1	.062	.002	1.919E-6	1371
	[Heating system = 13]	0[b]	.	.	0	.	.	.	.
	[Ventilation system = 1]	-.578	1316	.193	1	.661	.561	.043	7402
	[Ventilation system = 2]	15.806	.905	304.706	1	.000	[c]	1240967.583	43179092.108
	[Ventilation system = 3]	−3808	1584	5780	1	.016	.022	.001	.495
	[Ventilation system = 4]	−43.981	9693.650	.000	1	.996	7.933E-20	.000	.
	[Ventilation system = 5]	−4351	1910	5190	1	.023	.013	.000	.545
	[Ventilation system = 7]	0[b]	.	.	0	.	.	.	.
	[Location of the building = 1]	−1098	1323	.688	1	.407	.334	.025	4460
	[Location of the building = 2]	2427	2187	1231	1	.267	11.323	.156	823.608
	[Location of the building = 3]	-.595	1077	.305	1	.581	.552	.067	4554
	[Location of the building = 4]	0[b]	.	.	0	.	.	.	.
	[Climate zone = 1]	−20.773	1071.499	.000	1	.985	9.518E-10	.000	.
	[Climate zone = 2]	−19.553	1071.498	.000	1	.985	3.222E-9	.000	.
	[Climate zone = 3]	−18.281	1071.498	.000	1	.986	1.150E-8	.000	.
	[Climate zone = 4]	0[b]	.	.	0	.	.	.	.
III	Intercept	56.075	1071.559	.003	1	.958			
	Average indoor temperature (OC)	−1395	.441	10.016	1	.002	.248	.105	.588
	Building volume (m^3)	-.008	.003	6440	1	.011	.992	.986	.998
	Air change rate building (1/h)	−5842	2049	8128	1	.004	.003	5.236E-5	.161
	Number of occupants	.822	.394	4360	1	.037	2275	1052	4923
	[Construction period = 1]	-.764	1276	.358	1	.549	.466	.038	5685
	[Construction period = 2]	-.594	1166	.260	1	.610	.552	.056	5423
	[Construction period = 3]	2940	1539	3648	1	.056	18.922	.926	386.625
	[Construction period = 4]	1857	1314	1998	1	.158	6403	.488	84.065
	[Construction period = 5]	0[b]	.	.	0	.	.	.	.
	[Heating system = 2]	−2397	10.081.136	.000	1	1000	.091	.000	.
	[Heating system = 3]	13.694	1606.969	.000	1	.993	[c]	.000	.
	[Heating system = 4]	−3793	1782	4529	1	.033	.023	.001	.741
	[Heating system = 5]	−1583	1682	.886	1	.347	.205	.008	5550
	[Heating system = 6]	.319	2221	.021	1	.886	1375	.018	106.935
	[Heating system = 8]	−2078	1204	2979	1	.084	.125	.012	1325
	[Heating system = 10]	32.488	4067.139	.000	1	.994	[c]	.000	.
	[Heating system = 12]	−23.877	6708.774	.000	1	.997	4.268E-11	.000	.
	[Heating system = 13]	0[b]	.	.	0	.	.	.	.
	[Ventilation system = 1]	-.140	1303	.012	1	.914	.869	.068	11.167
	[Ventilation system = 2]	15.639	.000	.	1	.	[c]	6190734.476	6190734.476
	[Ventilation system = 3]	−3213	1559	4248	1	.039	.040	.002	.854
	[Ventilation system = 4]	−22.569	1071.502	.000	1	.983	1.580E-10	.000	.
	[Ventilation system = 5]	−3393	1884	3244	1	.072	.034	.001	1349
	[Ventilation system = 7]	0[b]	.	.	0	.	.	.	.
	[Location of the building = 1]	-.767	1301	.348	1	.555	.464	.036	5945
	[Location of the building = 2]	2930	2178	1809	1	.179	18.720	.262	1337.539
	[Location of the building = 3]	-.710	1058	.450	1	.502	.492	.062	3913

(*continued on next page*)

Table A.4 (*continued*)

Relative humidity category[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
	[Location of the building = 4]	0[b]	.	.	0	.	.	.	.
	[Climate zone = 1]	−19.151	1071.499	.000	1	.986	4.820E-9	.000	.
	[Climate zone = 2]	−19.101	1071.499	.000	1	.986	5.065E-9	.000	.
	[Climate zone = 3]	−17.641	1071.498	.000	1	.987	2.181E-8	.000	.
	[Climate zone = 4]	0[b]	.	.	0	.	.	.	.

a. The reference category is: IV, b. This parameter is set to zero because it is redundant, c. High value.

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