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Analysis of occupant satisfaction with IEQ in residential buildings

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Abstract. Multiple studies have shown that occupants' satisfaction with the indoor environmental quality (IEQ) is not always as high as expected from standards. Furthermore, consensus on methods for quantification of occupant satisfaction is still missing. Therefore, satisfaction assessment and further investigations into the relationships between occupant satisfaction and measured IEQ are needed.
This paper investigated the relationships between satisfaction ratings and IEQ parameters in mechanically ventilated residential buildings. This study used data from Belgian dwellings with a demand-controlled extraction system that was accompanied by a mobile phone application, enabling the users to adapt the ventilation system settings.
In this study, we evaluated the residents' satisfaction with the IEQ in their main living room. The satisfaction assessment approach consisted of (1) a retrospective survey and (2) the implementation of satisfaction rating scales into the mobile application of the ventilation system, allowing the residents to evaluate their satisfaction with the thermal environment or IAQ. The satisfaction rating option was active for two weeks during winter conditions. Simultaneously, IEQ-related parameters (i.e., air temperature, relative humidity and CO_2 concentration), and residents' interactions with their ventilation system (e.g., changing airflow rates or CO_2-thresholds) were monitored. We investigated the relationships between the satisfaction ratings and the IEQ- and interaction-related parameters through mixed-effect model analysis.
130 residents filled in the retrospective survey, and over 800 satisfaction ratings were submitted by approximately 60 different dwellings. Results of the retrospective survey and satisfaction ratings show that the participating residents were in general satisfied with the IEQ in their living room. The mixed-model analysis shows that the indoor temperature was the main parameter affecting residents' satisfaction with both IAQ and thermal environment. Furthermore, the results illustrate that the satisfaction ratings are mostly related to the specific resident, making it challenging to determine an aggregated model without personal and contextual information.

Keywords. Occupant satisfaction, indoor environmental quality, residential buildings, mixed-effect models
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1. Introduction

The occupants' satisfaction with the indoor environmental quality (IEQ) is not always as high as expected and often does not reach the 80%-requirement of standards [1], [2]. The main reason for this performance gap is that occupants' satisfaction with the IEQ is complex to predict since it is influenced by both IEQ- and non-IEQ related parameters, e.g. demographic information, perceived control, time of day [2]. Becker and Paciuk [3] found a discrepancy between the thermal comfort expected with the PMV-PPD method and the actual thermal comfort of residents. The discrepancy is attributed to contextual factors such as control over the IEQ and local climate. The study of Zalejska-Jonsson and Wilhelmsson [4] also showed differences in residents' satisfaction based on characteristics of the building and resident. At present, most studies regarding occupants' satisfaction focus on commercial buildings like offices while satisfaction in residential buildings remains underexplored [1], [5]. Therefore, further investigation in residents' satisfaction with attention to personal and context-related factors is needed.

This paper evaluates occupants' satisfaction with the IEQ in residential buildings in Belgium. In addition, this study investigates which IEQ- and context-related parameters influence the residents' satisfaction with the IEQ and how personalized residential satisfaction is. Lastly, this paper determines if residents' interactions with their ventilation system (e.g., changing airflow rates or CO_2-tresholds) can be used as a predictor for satisfaction with IEQ.

2. Methods

This study focusses on residents' satisfaction with the IEQ in one representative space of a house, i.e. the main living room. The living room was chosen as monitoring room type since the IEQ in this space is the least influenced by specific occupant activities (e.g., cooking in kitchen, showering in bathroom) and we assumed it is the room in which residents spend the most time in when awake and not doing active tasks. Our study was performed during heating season conditions.

2.1 Ventilation system and user application

All participating dwellings of this study were equipped with a mechanical demand-controlled exhaust ventilation system. In these dwellings, outside air was supplied through inlet grilles above the windows and air was mechanically extracted in different rooms of the house. Extraction grilles were mostly present in the bathroom, toilet, kitchen and bedroom in the majority of the dwellings. The ventilation system was also accompanied by a mobile application consisting of multiple functions that the residents could use, e.g., viewing historical data, adapting CO_2-thresholds, changing ventilation flow rates.

The ventilation system measured four IEQ parameters, namely, air temperature, relative humidity, CO_2 and VOC. The IEQ parameters of the extraction air were measured by the extraction valve in the ventilation system unit. Different types of extraction valves were used each measuring different IEQ parameters. The type of extraction valve used, was depending on which room type the air was extracted from. Air temperature and relative humidity were measured in all rooms, in contrast to the CO_2 and VOC-levels. CO_2-levels were only monitored in the kitchens, living rooms and bedrooms, while VOC-levels were only measured in the bathrooms and toilets. The ventilation systems were online connected and the IEQ data was stored with a timestep of 5 minutes in a database.

2.2 Satisfaction surveying and IEQ monitoring

Both subjective satisfaction ratings and objective IEQ parameters were gathered in this study in order to analyse the parameters influencing the residents' satisfaction. A two-step approach was used, firstly, a retrospective survey was designed and distributed among the ventilation system users. The retrospective survey started with an informed consent procedure in which the residents could indicate if they were willing to participate in the study. Only residents who gave their informed consent were able to fill in the retrospective survey. The survey was divided into three main parts: (1) resident demographics, dwelling and house information, (2) residents' perception and satisfaction with the IEQ in their living room during past winter period and (3) residents' usage of the user application. At the end of the survey, residents were given the option to indicate whether they wanted to participate further with the study using the satisfaction rating options. The retrospective survey was distributed among all residents using the mobile application. The survey was active from 06/04/2021 until 18/04/2021. Each resident could fill in the retrospective survey only once.

Secondly, two satisfaction rating options were implemented in the mobile application of the residents, who indicated to be willing to participate in this next step. The results of the latter were combined with IEQ monitoring data coming from the connected ventilation systems that were present in the dwellings. The two satisfaction rating options were implemented from 26/04/2021 until 10/05/2021. During this period the residents were able to evaluate their immediate satisfaction with the thermal environment and IAQ in their living room on a 5-point ordinal scale. Up to six evaluation ratings could be casted each day, three regarding the thermal environment and three regarding the IAQ. One of the two rating options appeared randomly on the screen of the user application when the resident opened the application. Before the implementation of the rating options, participating residents were informed about the procedure and asked to use the rating option at least three times throughout the day, i.e., morning, afternoon and evening.

2.3 Dataset construction and cleaning

In total 839 valid satisfaction scores were gathered from unique 62 residents during the two-week long satisfaction surveying. These raw satisfaction data were combined with IEQ data. The combined dataset consisted of the residents' satisfaction ratings and the nearest IEQ measurement in time. Only IEQ data measured from extraction air from living rooms, open or closed kitchens were used. Preference was given to measurements from living rooms. However, a majority of the dwellings did not have an extraction grille in their living room. In this case measurements of the extraction airflow from the open kitchen were taken. If measurements of both the living room and the open kitchen lacked, the data from the closed kitchen were used. One dwelling did not have IEQ measurements of one the three rooms available, as a result, 32 datapoints were deleted out of the dataset.

The dataset contained some repetitive datapoints, which could be due to an error in the system or due to the resident quickly responding to the same rating option multiple times in a row. To eliminate bias due to this effect, satisfaction ratings on the same IEQ-domain (thermal environment or IAQ) that were passed on by the same resident within 10 minutes, were excluded from the dataset. As a result, 182 datapoints were dropped out of the dataset. Afterwards, the time between the casting of the satisfaction rating and the nearest IEQ measurement was calculated and checked. One datapoint was excluded due to a large time difference which exceeded four hours. This was the result of a gap in the IEQ data monitoring. Lastly, it was checked if the IEQ measurements had realistic values. One datapoint, which consisted of an unrealistic high airflow rate, was excluded from the dataset. The final dataset consisted of 623 datapoints of both a satisfaction score and the nearest IEQ-related parameters. The cleaned dataset was separated into two datasets of IAQ and thermal satisfaction scores containing 308 and 315 datapoints, respectively.

2.4 Statistical analysis

The survey results and IEQ data were further analysed to investigate the statistical relationships between the residents' satisfaction with the IEQ. The following parameters were included: demographics and context-related information (e.g., gender, age, building type of house), IEQ-related parameters (i.e., air temperature, relative humidity and CO_2-concentration) and residents' interactions with their ventilation system (e.g., boosting ventilation flow rate, adapting CO_2-thresholds, activating a silent ventilation operation). The results of the statistical tests were determined to be statistically significant if a $p<0.05$ was obtained. Statistical analyses were performed using R software [6].

Firstly, a non-parametric correlation analysis was performed to determine the relationships between the different retrospective survey questions, i.e., residents' perception and satisfaction with the IEQ. The retrospective survey primarily consisted of questions answered on a Likert scale, which resulted in ordinal data. The Spearman's ρ correlation coefficient was used for the correlation analysis, since it is suitable for ordinal data [7]. The effect sizes of Spearman's ρ were categorized as follows: neglectable ($\rho < 0.2$), weak ($0.2 < \rho < 0.5$), moderate ($0.5 < \rho < 0.8$) and strong ($\rho > 0.8$) [7]. The correlation matrix was visualized using the ggcorrplot [8] package.

The relations between the context-related parameters and the residents' satisfaction in their living room was analysed using the results of the retrospective survey. The non-parametric Kruskal-Wallis H and Mann-Whitney U tests were used to determine whether there was a significant difference in the satisfaction scores, casted on 5-point ordinal scales, between the subgroups of the context-related categories (e.g., gender, age group, and building type). The first test was for context-related categories with more than two groups, the latter was used to determine a statistical difference between two groups (i.e., male vs female). If the Kruskal-Wallis test showed a statistically significant difference among the subgroups of a context-related category, a post-hoc test was done to find out, which of the subgroups were significantly different. The post-hoc pairwise comparison consisted of a Mann-Whitney U test with a Bonferroni correction [9].

The influence of IEQ- and interaction-related parameters on the residents' satisfaction with the thermal environment or IAQ in the living room were analysed using the dataset from the longitudinal satisfaction surveying and IEQ monitoring. The dataset consisted of dependent datapoints, since the same residents could cast multiple ratings during the two-week period. Furthermore, the amount of casted ratings was different for each resident. Therefore, a mixed-effect approach was used in which the residents' unique ID was used as a random effect and the IEQ- and interaction-related parameters as fixed-effects variables (see **Table 1**). By using the unique ID as a random effect, the models also considered the differences between the residents, such as personal preferences. Mixed-effect regression analysis has been used in other studies to investigate occupant satisfaction [10], [11] and behaviour [12], [13].

The IAQ and thermal satisfaction ratings, assessed on a 5-point ordinal scale, were used as dependent variables. The 'clmm' function from the 'ordinal' package [14] was used to fit ordinal logistic mixed-effect regression models. A forward selection procedure was done using Akaike information criterion (AIC) [15], which balances the model's complexity and goodness of fit, as an evaluation metric. A lower AIC-value represents a better model fit. Furthermore, the intraclass correlation coefficient (ICC) was used to quantify the proportion of variance due to the grouping of the random effect, which was in this case the residents' ID [16]. The forward selection procedure started with the null model which consisted of no fixed effects and only a random intercept with the residents' ID as random effect. In step 1, models with one fixed effect variable (see **Table 1**) and the residents' ID as random intercept were fitted and evaluated. It was determined if the difference in AIC of the fitted models in step 1 and the null model were statistically significant. Furthermore, it was required that all fixed effects in the models are statistically significant. In the following steps, the most suitable model, the model with the lowest AIC, from the last step was made more complex by adding one of the remaining fixed effects to the model. This process was repeated until no statistically significant improvement can be achieved. The last step in the selection procedure, step X, consisted of the addition of one or more random slopes to the most suitable model. The model fit was again evaluated by the AIC. The model selection procedure was done two times, i.e., for thermal satisfaction and IAQ satisfaction as dependent variable. Afterwards, the satisfaction ratings were recoded into binary variables, i.e., ratings <3 were coded as "Dissatisfied" and ratings ≥3 as "Satisfied". The same selection procedure was repeated for thermal and IAQ satisfaction ratings as binary variables, in order to analyse the distinct difference between satisfaction and dissatisfaction. The 'glmer' function of the 'lme4' package [17] was used to fit binary logistic mixed-effect models.

Table 1. - Overview fixed-effect variables in mixed model analysis. Including indication of variable types C= continuous variable, B= Boolean and Cat= categorical.

Category	Name	Description	Unit	Type
IEQ-related variables	T	Indoor air temperature	°C	C
	RH	Relative humidity	%	C
	EA	Specific air enthalpy	kJ/kg	C
	CO_2	CO_2-concentration	ppm	C
	AF	Airflow rate	m^3/h	C
Interaction-related variables	Boost	Temporarily increase/ decrease AF	/	B
	Breeze	Passive cooling function which increases AF at a user-defined temperature setpoint	/	B
	Silent	User function to temporarily decrease AF	/	B
	Program	Set nominal AF to 70%, 100% or 120% of the standard AF	/	Cat
	CO_2_min	Lower CO_2-concentration threshold set by user	ppm	C
	CO_2_max	Upper CO_2-concentration threshold set by user	ppm	C

Multicollinearity among the fixed-effects variables was checked using the variance inflation factor (VIF). The VIF values exceeded the threshold of 5 when T, RH and EA were all three included in the model, showing the occurrence of multicollinearity. Therefore, models with all three predictors (i.e., T, RH and EA) were not further analysed.

3. Results - Analysis of retrospective survey

3.1 Residents demographics

Table 2 gives an overview of the demographics and context-related parameters of the 130 residents that completed the retrospective survey. The total amount of residents using the ventilations system and accompanying mobile application exceeds 6000, however, only around 600 residents are frequent users, leading to an acceptable response rate of approximately 21.6%.

Table 2. – Overview demographics and context-related parameters of residents participating in retrospective survey (n=130)

	Options	Rate [% of residents]
Residents gender	Male	82.3
	Female	17.7
Residents age	18 – 29 years	20.00
	30 – 39 years	36.2
	40 – 49 years	21.5
	50 – 59 years	9.2
	60 – 69 years	9.2
	70+ years	3.9
Dwelling size	1 person	12.3
	2 persons	35.4
	3 persons	20.8
	4 persons	20.0
	5 persons	9.2
	6 persons	1.5
	20 persons	*0.8*
Average daytime occupancy	0	14.6
	1	38.5
	2	36.2
	3	6.1
	4	4.6
Building type	Apartment	29.2
	Terraced house	13.1
	Semi-detached house	25.4
	Detached house	32.3
Residents' mindset*	Energy efficiency	3.1
	Comfort	13.8
	Equally important	83.1
	No opinion	0

* Statement that was most important for resident: house must be as energy efficient as possible, IEQ must be as comfortable as possible, energy efficiency and comfort are equally important, no opinion

3.2 Survey data reliability

Prior to the data analysis of the retrospective survey, the reliability of the survey data is evaluated through a Cronbach's alpha calculation. Cronbach's alpha is a metric to determine the internal consistency or scale reliability [18]. An alpha value of >0.7 is required to categorize the results as reliable. A Cronbach's alpha of 0.77 is obtained, showing an acceptable consistency among the different satisfaction questions scales. Thus, the survey data can be considered as reliable.

3.3 IEQ and control satisfaction overview

Figure 1 shows the frequency of the satisfaction scores from the retrospective survey. The satisfaction with the overall IEQ, IAQ, user application control, thermal, acoustic and visual comfort is assessed on a 5-point ordinal scale. The residents were in general very satisfied with the IEQ in their living room and the control possibilities in the user application during winter conditions. Residents were the least and most satisfied with the acoustic and visual (e.g. daylight, lighting) comfort of their living room respectively. The main cause for acoustic dissatisfaction was noise from outside the building. This effect is probably due to the air inlet grilles that are situated above the windows, which are typical for extraction ventilation systems.

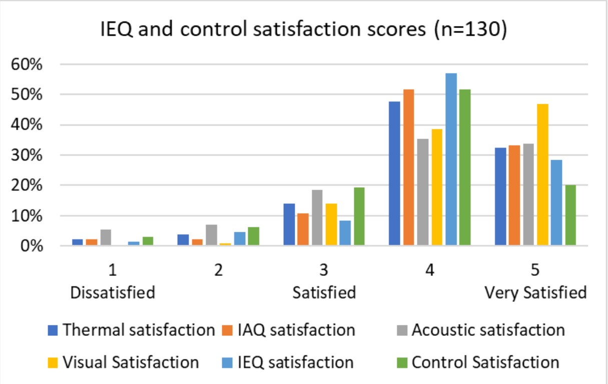

Figure 1. - IEQ and control satisfaction scores from retrospective survey – the votes correspond to the living room

The survey also asked the residents in which rooms of their house they were the least satisfied with the IEQ. The 'others' option gave residents the opportunity to clarify which room they were the least satisfied. However, 13 residents did not mention a room and filled in answers as 'none' or 'not applicable'. These 13 answers are not considered in the overall voting rates in **Table 3**.

Table 3. - Overview answers room least satisfied with IEQ (n=117)

Room	Rate [% of answers]
Living room	15.4
Dining room	1.7
Kitchen	7.7
Bedroom	29.1
Bathroom	23.9
Others (e.g., storage, attic, toilet, garage,…)	22.2

Table 3 shows that bedroom was the room with least satisfaction, followed by bathroom. Different room types were mentioned under 'Others' option, none of the other room types were mentioned more than the living room. Therefore, living room was the third in rank of rooms in which the residents were the least satisfied with the IEQ. The main reasons for dissatisfaction with the IEQ in the bedroom were noise nuisance (27.1%), a too warm (17%) or too cold (15.3%) environment and stuffy air (11.9%).

3.4 Correlation analysis

A Spearman correlation analysis was performed to investigate the relationship between questions of the retrospective survey related to occupants' satisfaction and perception of the IEQ. The results of the correlation analysis are visualized by a correlation matrix in **Figure 2**. The highest effect size was found between the occurrence of noise and acoustic satisfaction (ρ = 0.64), which shows that

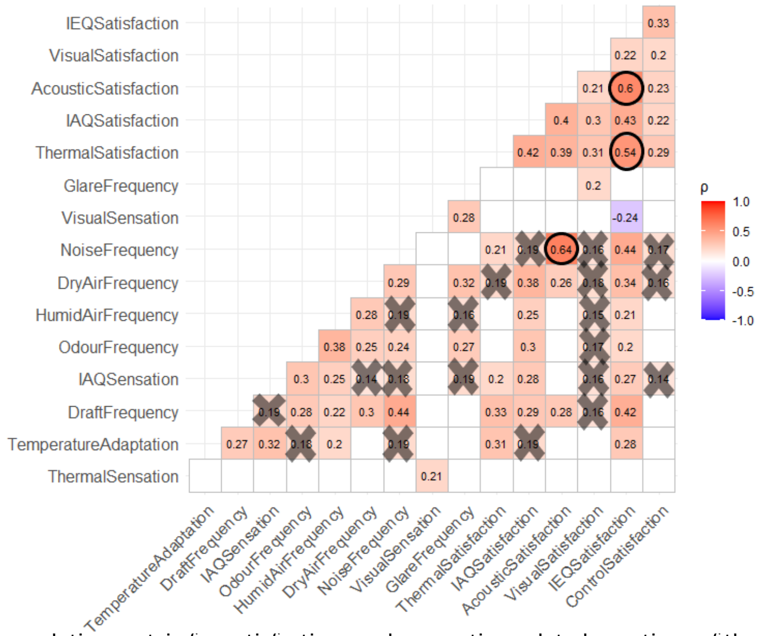

Figure 2. - Spearman correlation matrix for satisfaction- and perception related questions of the retrospective survey in which negligible and moderate effect sizes are crossed out and encircled, respectively. ($p<0.05$)

residents who perceive noise less often are more satisfied with the acoustic comfort in their living room. Residents' satisfaction with the overall IEQ in their living room was the strongest related to the satisfaction with the acoustic ($\rho = 0.6$) and thermal ($\rho = 0.54$) environment. The overall IEQ satisfaction was also related to the IAQ ($\rho = 0.43$), control ($\rho = 0.33$) and visual ($\rho = 0.22$) satisfaction. This ranking of IEQ domains on the overall IEQ satisfaction is in line with the determined weighting for dwellings by Leccese et al. [19].

3.5 Context-related differences

The Kruskal-Wallis H test shows that there are statistically significant differences in the mean IEQ satisfaction scores among the subgroups of "Average daytime occupancy" (p=0.031) and "Building type" (p=0.005). Furthermore, the non-parametric test determines a statistically significant difference in the mean control satisfaction scores among the subgroups of "Building type" (p=0.021) and "Residents' mindset" (p=0.019). No other statistically significant differences in IAQ, thermal, acoustic and visual satisfaction scores were found for the context-related categories. The post-hoc test results show no statistically significant difference in the mean IEQ satisfaction scores between two of the subgroups of "Average daytime occupancy", i.e., 0, 1, 2, 3 and 4. **Table 4** shows the remaining subgroups for which the post-hoc test was statistically significant together with the mean satisfaction score for that subgroup.

Table 4. - Results of the post-hoc test with the mean satisfaction score for the subgroup

	Building type	**Residents' mindset**
IEQ satisfaction	Apartment (3.7) ~ Detached house (4.3)	/
Control satisfaction	Apartment (3.4) ~ Semi-detached house (4.0)	Equally important (3.7) ~ Comfortable indoor climate (4.3)

Table 4 shows that the type of building in which the resident lives, is the only resident-related information that affects the overall IEQ satisfaction and the control satisfaction. The residents living in apartment buildings show lower satisfaction levels with the overall IEQ and control satisfaction compared to detached and semi-detached houses, respectively. However, the mean differences in satisfaction scores are minor. Residents who prioritize comfort over energy efficiency are slightly more satisfied with their control possibilities compared to residents who ranked comfort and energy efficiency as equally important. It should be mentioned that the number of residents who indicated comfort as the most important characteristic is far lower than the number of residents indicating that energy efficiency and comfort are equally important (see **Table 2**).

4. Results - Analysis of longitudinal surveying

4.1 Data overview

Figure 3 shows the distribution of the gathered satisfaction votes during the longitudinal surveying period. As with the results of the retrospective survey, the majority of the votes represent satisfaction (score ≥ 3) with the thermal environment and IAQ in the living room.

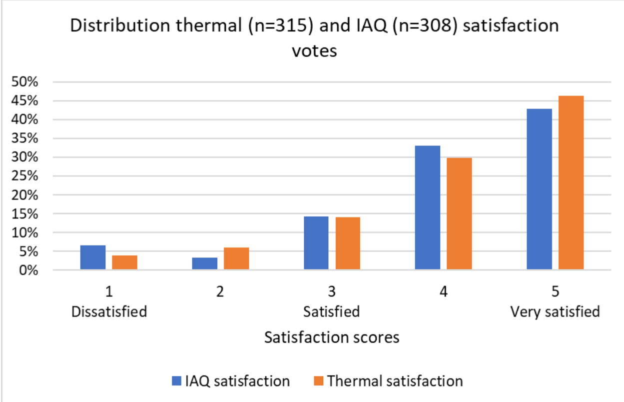

Figure 3. - Overview thermal and IAQ satisfaction scores during longitudinal study

4.2 Parameters influencing occupants' satisfaction

We performed a mixed-effects regression analysis to determine which IEQ and interaction-related parameters influenced the occupants' satisfaction. The results of the forward model selection procedure are summarized in **Table 5**.

Table 5. - Forward model selection summary showing the statistically significant fixed effects (FE), AIC and ICC. NS = non-significant model improvement
NC = no model convergence

FE AIC ICC	**Thermal satisfaction**		**IAQ satisfaction**	
	Ordinal	**Binary**	**Ordinal**	**Binary**
Null model	/ 691.02 0.496	/ 170.47 0.627	/ 627.65 0.6	/ 123.06 0.928
Step 1	T 685.69 0.452	T 165.71 0.490	T 619.8 0.58	T 119.02 0.919
Step 2	NS	NS	NS	NS
Step X	NS	NS	NC	NS

Based on the results in **Table 5** it can be stated that the indoor temperature has the strongest relationship with thermal and IAQ satisfaction of all IEQ and interaction-related variables. The addition of a random slope to the models did not improve the model fit, which indicates that, although the residents casted different satisfaction ratings at the same indoor temperature, the trend between indoor temperature and thermal and IAQ satisfaction is likewise among the different residents. All models have a negative relationship between the indoor temperature and the residents' satisfaction, meaning that a higher indoor temperature leads, in this case, to a higher probability of residents' dissatisfaction with the thermal environment and IAQ.

The assumption for mixed effect models is legitimate based on the high ICC values which vary from 0.496 to 0.928 for the null models. The high ICC values show that a major part of the variance in the models is explained by the random effect, in this case, the residents' ID. The ICC is higher for the binary models than for the ordinal models in which the dependent variable was the 5-point satisfaction rating. This indicates that the residents during the two-week long monitoring period changed their satisfaction rating, but that it mostly stayed within the same category, i.e., satisfied (3 – 5) or dissatisfied (1-2). This is especially the case for the IAQ satisfaction in which the ICC has values above 0.9 for the binary models, indicating that nearly all IAQ satisfaction ratings were the same (satisfied or dissatisfied) for a resident. The addition of indoor temperature as a fixed effect did just marginally decrease the ICC for the IAQ models compared to the thermal satisfaction models. The high ICC values could also be due to short monitoring period in which IEQ parameters did not change dramatically. Therefore, a longer monitoring campaign is needed to investigate the potential change in residents' satisfaction due to varying IEQ conditions.

The high ICC-values among the different fitted models demonstrate that the probability of satisfaction with IEQ is mostly influenced by the residents' ID instead of environmental or interaction-related parameters. Consequently, it is quite difficult to establish an aggregated model to explain residents' satisfaction with IEQ, while a resident-specific approach that considers personal and contextual information would be more appropriate. The study of Langer et al. [20] made a similar conclusion, stating that information regarding residents and building type helped to explain residents' perception of the IAQ. Therefore, the use of personal comfort models [2], which focusses on identifying personal comfort preferences, could be beneficial to more accurately determine residents' satisfaction with IEQ.

5. Conclusion

In this paper we analysed occupants' satisfaction with the IEQ in the living rooms of residential buildings equipped with a demand-controlled extraction ventilation system. Satisfaction data was gathered in two steps, firstly, through a retrospective survey, secondly, by two rating options that were implemented in a mobile application used by the respondents. The latter was combined with indoor environmental parameters, measured by valves of the ventilation system, into one dataset.

Results showed that the inhabitants of the participating dwellings were in general satisfied with the indoor environment in their living rooms during the survey period. Residents living in apartment buildings were slightly less satisfied with the overall IEQ and control possibilities compared to residents living in detached and semi-detached houses. Correlation analysis showed that acoustic and thermal satisfaction had the strongest relation with the overall IEQ satisfaction.

The logistic mixed-effect regression analysis showed that the indoor air temperature was the most influencing parameter for IAQ and thermal satisfaction. Interaction-related variables were not found to be suitable predictors for residents' satisfaction in this case. A large proportion of the variance in the mixed-effects regression models was due to the random-effect of the residents' ID, which shows the importance of accounting for resident-specific information in determining a satisfactory IEQ. However, it should be noticed that the monitored IEQ parameters in this study were rather limited and the dataset fairly small. More data from different dwellings and during different weather conditions are needed to generalize the insights of this paper. Furthermore, this study only focused on residents' satisfaction in the main living room, while residents' preferences regarding the IEQ could change depending on the room type. Therefore, further research should investigate other types of rooms than the main living room to get an overall assessment of residents' satisfaction with IEQ in their homes.

6. Acknowledgments

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7. Data access statement

The datasets generated and analysed during the current study are not available because of ethical and legal restrictions but the authors will make every reasonable effort to publish them in near future.

8. References

[1] L. t. Graham, T. parkinson, and S. schiavon, "Lessons learned from 20 years of CBE's occupant surveys," *Build. Cities*, vol. 2, no. 1, pp. 166–184, 2021, doi: 10.5334/bc.76.

[2] J. Kim, S. Schiavon, and G. Brager,

“Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control,” *Build. Environ.*, vol. 132, pp. 114–124, 2018, doi: 10.1016/j.buildenv.2018.01.023.

[3] R. Becker and M. Paciuk, “Thermal comfort in residential buildings - Failure to predict by Standard model,” *Build. Environ.*, vol. 44, no. 5, pp. 948–960, 2009, doi: 10.1016/j.buildenv.2008.06.011.

[4] A. Zalejska-Jonsson and M. Wilhelmsson, “Impact of perceived indoor environment quality on overall satisfaction in Swedish dwellings,” *Build. Environ.*, vol. 63, pp. 134–144, 2013, doi: 10.1016/j.buildenv.2013.02.005.

[5] M. S. Andargie, M. Touchie, and W. O’Brien, “A review of factors affecting occupant comfort in multi-unit residential buildings,” *Build. Environ.*, vol. 160, no. April, p. 106182, 2019, doi: 10.1016/j.buildenv.2019.106182.

[6] R Core Team, “R: A Language and Environment for Statistical Computing.” Vienna, Austria, 2020, [Online]. Available: https://www.r-project.org/.

[7] C. J. Ferguson, “An Effect Size Primer: A Guide for Clinicians and Researchers,” *Prof. Psychol. Res. Pract.*, vol. 40, no. 5, pp. 532–538, 2009, doi: 10.1037/a0015808.

[8] A. Kassambara, “ggcorrplot: Visualization of a Correlation Matrix using ‘ggplot2.’” 2019, [Online]. Available: https://cran.r-project.org/package=ggcorrplot.

[9] P. Dalgaard, *Introductory Statistics with {R}*, Second. New York: Springer, 2008.

[10] S. Lechner, C. Moosmann, A. Wagner, and M. Schweiker, “Does thermal control improve visual satisfaction? Interactions between occupants’ self-perceived control, visual, thermal, and overall satisfaction,” *Indoor Air*, no. April, pp. 1–21, 2021, doi: 10.1111/ina.12851.

[11] T. Cheung, S. Schiavon, L. T. Graham, and K. W. Tham, “Occupant satisfaction with the indoor environment in seven commercial buildings in Singapore,” *Build. Environ.*, vol. 188, no. October 2020, 2021, doi: 10.1016/j.buildenv.2020.107443.

[12] F. Haldi, D. Calì, R. K. Andersen, M. Wesseling, and D. Müller, “Modelling diversity in building occupant behaviour: a novel statistical approach,” *J. Build. Perform. Simul.*, vol. 10, no. 5–6, pp. 527–544, 2017, doi: 10.1080/19401493.2016.1269245.

[13] M. Schweiker, M. Hawighorst, and A. Wagner, “The influence of personality traits on occupant behavioural patterns,” *Energy Build.*, vol. 131, pp. 63–75, 2016, doi: 10.1016/j.enbuild.2016.09.019.

[14] R. H. B. Christensen, “ordinal---Regression Models for Ordinal Data.” 2019, [Online]. Available: https://cran.r-project.org/package=ordinal.

[15] H. Akaike, “A New Look at the Statistical Model Identification,” *IEEE Trans. Automat. Contr.*, vol. 19, no. 6, pp. 716–723, 1974, doi: 10.1109/TAC.1974.1100705.

[16] S. Nakagawa, P. C. D. Johnson, and H. Schielzeth, “The coefficient of determination R2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded,” *J. R. Soc. Interface*, vol. 14, no. 134, 2017, doi: 10.1098/rsif.2017.0213.

[17] D. Bates, M. Mächler, B. Bolker, and S. Walker, “Fitting Linear Mixed-Effects Models Using {lme4},” *J. Stat. Softw.*, vol. 67, no. 1, pp. 1–48, 2015, doi: 10.18637/jss.v067.i01.

[18] M. Tavakol and R. Dennick, “Making sense of Cronbach’s alpha,” *Int. J. Med. Educ.*, vol. 2, pp. 53–55, 2011, doi: 10.5116/ijme.4dfb.8dfd.

[19] F. Leccese, M. Rocca, G. Salvadori, E. Belloni, and C. Buratti, “Towards a holistic approach to indoor environmental quality assessment : Weighting schemes to combine effects of multiple environmental factors,” *Energy Build.*, vol. 245, p. 111056, 2021, doi: 10.1016/j.enbuild.2021.111056.

[20] S. Langer, O. Ramalho, E. Le Ponner, M. Derbez, S. Kirchner, and C. Mandin, “Perceived indoor air quality and its relationship to air pollutants in French dwellings,” *Indoor Air*, vol. 27, no. 6, pp. 1168–1176, 2017, doi: 10.1111/ina.12393.