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Acoustic comfort assessment in heavyweight residential buildings: acoustic data associated to subjective responses.

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ABSTRACT

This article presents a study aiming to explore and evaluate acoustic comfort in residential multistory buildings in Sweden. Acoustic data was associated to self-reported responses acquired by a survey: a questionnaire was setup researching the response to noise annoyance from multiple sources in a flat and the emotional reactions of tenants to the acoustic climate at home. An assessment of acoustic comfort in the test apartments was performed utilizing the circumplex model of affect. A sample of 353 residents offered their ratings on 12 bipolar scales regarding their feelings towards their living sound environment. Two dimensions were identified: pleasantness and activation. Statistical models were developed using acoustic and structural variables. $L'_{nT,w,100}$ predicted best pleasantness and number of flats per building predicted best activation. A new acoustic comfort indicator is suggested based on the pleasantness model and four novel acoustic comfort classes are proposed as: AC-1: Very good, AC-2: Good, AC-3: Acceptable, AC-4: No comfort.

Keywords: Acoustic, Comfort, Responses

1. INTRODUCTION

The Cambridge dictionary defines comfort as "a pleasant and satisfying feeling of being physically or mentally free from pain and suffering, or something that provides that feeling" (1). Seemingly, comfort is described as a state of feelings towards a situation. Acoustic comfort is defined in (2) as: "a concept that can be characterized by absence of unwanted sound, desired sounds with the right level and quality, and opportunities for acoustic activities without annoying other people".

Acoustic comfort issues have been treated entirely as noise annoyance problems so far. Usually acoustic data (sound insulation descriptors) were associated to self-reported noise annoyance of the residents (3-6). A detailed review of field surveys following that approach is provided in (7).

Another approach for the evaluation of acoustic environments has been taken with soundscapes. Soundscape is: "an acoustic environment as perceived or experienced and/or understood by a person or people, in context" (8). Background ambience and several random sounds can comprise a soundscape (9). It can be an outside public space: a street or park. The same for indoor climates, such as the living sound environment of an apartment. Assessment of soundscapes can utilize empirical data (interviews) or surveys (questionnaires), as in this study. Subjects can offer ratings on certain scales about a soundscape. Then statistical analysis can reveal the underlying dimensions describing how subjects perceive it. In (10) principal components analysis (PCA) was performed for soundscape perception from ratings on 116 attribute scales of 50 recorded outdoor urban soundscapes. The dimensions of pleasantness, eventfulness and familiarity explained most of the total variance. In (11) visual and acoustic experiments were conducted for the perceived similarity of soundscapes, using 50 recordings from (10). Multidimensional scaling (MDS) revealed three dimensions: distinguishable -indistinguishable sound sources, background-foreground sounds and intrusive-smooth sound sources. In (12) a prediction model was developed for the dimension of vibrancy in soundscapes based on acoustic and visual parameters. There is experimentation with the soundscapes approach in overall, for the evaluation of outdoor spaces, but less applications of soundscapes for indoor spaces.

In this study, we approach acoustic comfort in apartment buildings utilizing soundscapes and

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focusing on human perception and emotions. We explore how the residents feel in their living sound environment. A model of underlying dimensions was employed, namely the circumplex model of affect, a tool developed in psychology to study emotional reactions of subjects (13). The affect circumplex has been applied in assessment of core affects (13,14) and soundscape studies (10-12).

2. METHODS

The study sample includes 31 structures of various types: heavyweight or lightweight. The term heavyweight (HW) refers to typical concrete frame structures and the term lightweight (LW) refers to wooden buildings (cross laminated timber frame). In total there are 94 building units from 31 blocks (1 or more units each) of a certain structure: 24 HW types and 7 LW. Sound transmission measurements took place in the test structures between two typical adjacent rooms, one above another, bedrooms or living rooms. Current standardized methods for airborne sound reduction and impact sound level measurements were followed to characterize insulation of building components according to ISO (15,16). The measurement data were collected from the Green Buildings database, which concerns a Swedish national program about acoustic conditions in dwellings. An overview of the acoustic variables is provided in Table 1. Most structures fulfil the Swedish BBR criteria, which set minimum $D'_{nT,w,50}$=52dB from outside to inside a house and maximum $L'_{nT,w,50}$=56dB (17).

Table 1 – Single number quantities of acoustic descriptors for the sample structures.

		Airborne sound descriptors		**Impact sound descriptors**	
		$D'_{nT,w,50}$	$D'_{nT,w,100}$	$L'_{nT,w,50}$	$L'_{nT,w,100}$
Structure type	N	Mean (Range)		Mean (Range)	
Heavy-weight (HW)	24	58.3dB (51-64)	58.7dB (52-65)	49.6dB (40-53)	49.1dB (39-52)
Light-weight (LW)	7	55.5dB (48-63)	56.3dB (48-65)	52.4dB (49-59)	49.5dB (47-54)
All structures	31	57.6dB (48-64)	58.1dB (48-65)	50.2dB (40-59)	49.2dB (39-54)

Furthermore, self-reported data was collected with the development of a questionnaire, for the residents of the test structures, developed according to ISO 15666 (18). The survey aimed to capture several aspects relevant to acoustic comfort. It was distributed using post mail (one copy for every test flat, a web link was provided too): an invitation letter was firstly sent with the questionnaire, then two reminder letters followed within a month. Table 2 presents the question items analyzed in this article.

Table 2 - Question with semantic differentials as presented a survey the about acoustic environment at home. Original version presented in Swedish language as developed in (14).

Different environments can affect the way we feel and our well-being. What effect does your home have on you? Answer each one by circling the number that most accurately describes the way you feel when you come home. Don't spend too much time on each question – we are looking for your immediate reaction. These are scales of opposites, so if you feel more drowsy than alert, circle either number 1 or 2 on the scale. If you are right in between, circle number 3.

a. Sleepy	1	2	3	4	5	Awake
b. Displeased	1	2	3	4	5	Pleased
c. Bored	1	2	3	4	5	Interested
d. Tense	1	2	3	4	5	Serene
e. Passive	1	2	3	4	5	Active
f. Sad	1	2	3	4	5	Glad
g. Indifferent	1	2	3	4	5	Engaged
h. Anxious	1	2	3	4	5	Calm
i. Dull	1	2	3	4	5	Peppy
j. Depressed	1	2	3	4	5	Happy
k. Pessimistic	1	2	3	4	5	Optimistic
l. Nervous	1	2	3	4	5	Relaxed

With a response rate of 27%, 353 observations were collected (158 male, 188 female, 7 unreported). The subjects are 18-85 years old and have spent at least 12 months in their flat. Those who use hearing aids at home were filtered out of the dataset. Tenants living on the top floor were filtered out too, since they do not have neighbors on the floor above and their sound conditions are probably different.

The question items regarding the emotional reactions and perception evaluation of the participants are presented in Table 2. It is simply formulated as: What effect does your home have on you? The questionnaire was entitled “Research project on sound environment in residential buildings”. The introduction text as well as most of the questions concerned acoustic issues at home. The results were analyzed in SPSS Statistics 24. PCA was performed for dimension reduction. Linear regression was applied the component loadings in order to develop prediction models for the identified dimensions. Non-parametric Mann-Whitney U-tests were applied to compare independent groups of observations.

Figure 1 depicts the circumplex model of affect as defined in (13,14). It refers to a psychological construct composed of two orthogonal dimensions: pleasantness and activation. They were found sufficient to express the emotional state of subjects and the 12 items of Table 2 were established and validated after experiments for Swedish wording in a study by Västfjäll et al. (14).

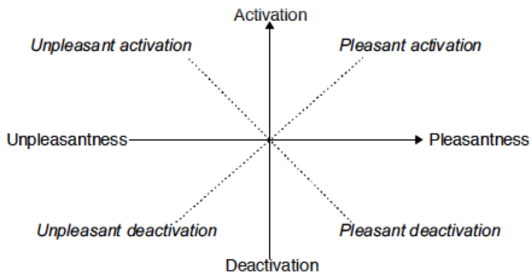

Figure 1 - The affect circumplex model presented in (14).

3. RESULTS AND DISCUSSION

3.1 Individual observations analysis

The mean responses of the residents for the question under study are illustrated in Figure 2. From the total 353 observations, 327 were included in this analysis due to missing values. As can be observed all self-reported rating averages of the participants are on the positive side of the scale (>3), meaning on the side of the reaction scales with the affirmative emotions.

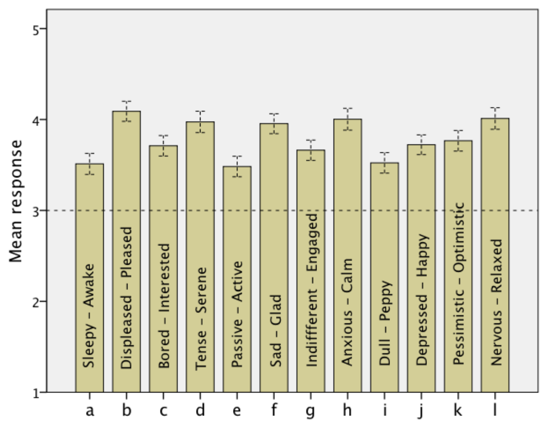

Figure 2 – Mean responses for the sub-items of the question: What effect does your home have on you? Error bars represent 95% C.I.

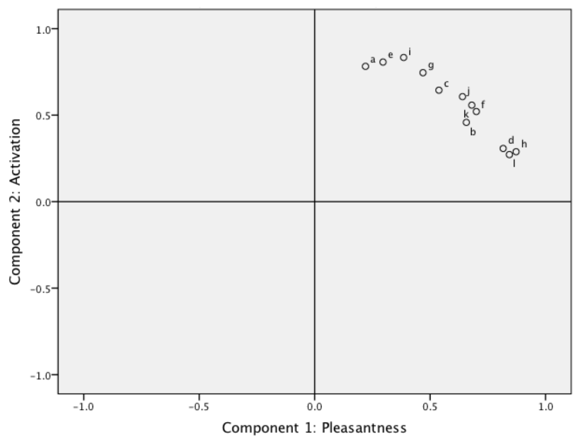

Figure 3 – Component loadings plot for the two dimensions: 1-pleasantness and 2-activation.

Principal components analysis was performed and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy offered a sufficient value of 0.948. Varimax rotation was applied to achieve an optimal orthogonal solution. Twelve components were extracted in total but only two of them were selected, after applying a scree criterion based on a minimum eigenvalue of unity. The percentage of the total variance explained was 39.4% and 36.2% for the first and second components respectively. That is a satisfactory solution explaining a cumulative 75.6% of the total variance. The component loadings are presented in Table 3 and their plot on two dimensions is illustrated in Figure 3. The components can be directly interpreted as the two dimensions of pleasantness and activation, as suggested by the valence-activation construct analyzed in (14).

The first component corresponds to the dimension of pleasantness since the adjective pairs: displeased-pleased, sad-glad, depressed-happy load higher on that and they are designed to measure pleasantness emotions (Table 3). The adjective pairs that load higher on the second component are: sleepy-awake, dull-peppy, passive-active, which supposedly measure the dimension of activation.

Table 3 – Component loadings of final the PCA rotated solution.

Semantic differentials	**Component 1 (Pleasantness)**	**Component 2 (Activation)**
a. Sleepy – Awake		0.782
b. Displeased – Pleased	0.657	0.458
c. Bored – interested	0.538	0.644
d. Tense - Serene	0.816	
e. Passive – Active		0.807
f. Sad – Glad	0.700	0.521
g. Indifferent – Engaged	0.469	0.746
h. Anxious – Calm	0.872	
i. Dull – Peppy		0.833
j. Depressed – Happy	0.640	0.607
k. Pessimistic – Optimistic	0.680	0.558
l. Nervous - Relaxed	0.843	
% of variance explained	39.38%	36.16%

Coefficients below 0.40 are suppressed.

All the components load on the positive region for both dimensions (Figures 1 and 3). That is specifically the area of "pleasant activation" as explained in (14). Consequently, the residents perceive their sound environment at home as having a high degree of acoustic comfort in overall. This is expected since most sample buildings comply with the Swedish criteria (17).

Further, we explored possible predictor variables for modeling the identified PCA dimensions. The component loading scores of every observation were used as dependent variables. Other variables from the survey's dataset can be used as independent variables to establish statistical associations with the use of linear regression models. The aim is to develop a prediction model for acoustic comfort using acoustic descriptors and building construction data. The determination coefficients R^2 for linear models predicting the components' loading scores are shown in Table 4. The R^2 represent the total variance explained by the predictor variable. All R^2 values are very low, indicating lack of strong linear relationships probably due to the high variability between all 327 observations. Consequently, no further conclusions could be drawn using the individual responses.

Table 4 - Determination coefficients R^2 for linear predictors of Pleasantness and Activation (individual observations case).

Predictors	**Component 1 Pleasantness**	**Component 2 Activation**
$L'_{nT,w,100}$	0.005	0.033*
$D'_{nT,w,100}$	0.001	0.007
$L'_{nT,w,50}$	0.003	0.006
$D'_{nT,w,50}$	0.002	0.011
Size (m2)	0.001	0.077*
#Flats	0.014	0.039*
#Tenants	0.012	0.002

* *(Model parameters significant with p<0.05)*

3.2 Clustered observations analysis for heavyweight buildings

The observations are clustered in structure types such as: heavyweight (HW) concrete structures and lightweight (LW) wooden ones. It has been indicated previously that HW and LW structures have quite different acoustic behavior and the perception of residents varies according to structure type

(3,5,21). In this survey, the mean responses for of LW structure groups are higher than HW ones and for 5 items there are statistically significant differences. That was suggested by non-parametric Mann-Whitney U-tests, which indicated significance specifically for items: a ($Z=-3.769$, $p<0.001$), c ($Z=-2.738$, $p<0.01$), e ($Z=-2.132$, $p<0.05$), g ($Z=-2.016$, $p<0.05$) and i ($Z=-2.540$, $p<0.05$).

Additionally, there are not equal sample sizes of observations in the various structure blocks. Thus HW and LW structures are studied separately. Also, the responses are now averaged per structure block: so the replies from a certain structure type are represented by their mean value. For the concrete structures, the same analysis was attempted with better results than in Table 4. However, the R^2 values went as high as 0.2, which is not a sufficient level of correlation. Thus all groups with small sample size were filtered out completely and 9 HW buildings having a sample size n more than 10 observations were analyzed. Finally, 181 observations were included from 9 blocks of heavyweight structures (85 male, 96 female). The initial PCA statistics provided: KMO=0.934, 37.3% and 34.6% of total variance explained by D_1:pleasantness and D_2:activation respectively. Using the 9 blocks (n>10) led to better linear associations for the tested variables, as seen in Table 5.

Table 5 – R^2 for linear predictors of Pleasantness and Activation in concrete buildings (HW clustered observations).

Predictors	**Component 1** **Pleasantness**	**Component 2** **Activation**
Size (m2)	0.270	0.136
#Flats	0.117	0.538 *
#Tenants	0.108	0.017
$L'_{nT,w,50}$	0.345	0.248
$L'_{nT,w,100}$	0.478*	0.192
$D'_{nT,w,50}$	0.009	0.351
$D'_{nT,w,100}$	0.002	0.264
$D'_{nT,w,50}$ + $L'_{nT,w,50}$ + *Size* + *#Flats*	0.479	0.708
$D'_{nT,w,100}$ + $L'_{nT,w,100}$ + *Size* + *#Flats*	0.573	0.647

** (Model parameters significant with p<0.05)*

The impact sound index $L'_{nT,w,100}$ is a statistically significant predictor of Pleasantness while the number of flats in a building is a significant predictor of Activation. As for the other acoustic indicators, the airborne sound reduction indices $D'_{nT,w,100}$ and $D'_{nT,w,50}$ associate well with the dimension of activation only, though with moderate R^2 values. However, number of apartments in a building unit (variable denoted *#Flats*) correlates high enough with activation.

Combinations of the predictor variables were tested in order to develop multiple regression models. The best determination coefficient R^2 is achieved for the relevant variables: both descriptors $L'_{nT,w,100}$, $D'_{nT,w,100}$ (or $L'_{nT,w,50}$, $D'_{nT,w,50}$) the size of flat and the number of flats in a building. But those models do not have statistical significance for their model parameters (Table 5). The same applies to most variables regardless the R^2 indicated in the models, simple or multiple. Only the univariate models of $L'_{nT,w,100}$ and *#Flats* predicting pleasantness and activation respectively have statistically significant parameters ($p<0.05$). A backwards regression process was performed for a model with all variables of Table 5. The results confirmed that the only significant predictors are $L'_{nT,w,100}$ for D_1 and #Flats for D_2. Only those can formulate reliable prediction models of the PCA dimensions as:

$$D_1 = 4.171 - 0.084 \cdot L'_{nT,w,100}$$

$$D_2 = 0.321 - 0.009 \cdot \#Flats$$

Furthermore, using size for a linear model with averaged responses per structure block would not be that reasonable. Size of flats varies within a building and an average size might not be representative of the conditions for all subjects. But the number of flats in a structure is constant (at least in this dataset) and relevant to average responses. Also more flats and residents in a building mean more activity and sounds between apartments, so *#Flats* is sensible to correlate with activation.

Reasonably the impact sound descriptor associates higher with pleasantness, which is related to quietness and noise annoyance. Impact sound descriptors $L'_{nT,w,100}$ or $L'_{nT,w,50}$ have been found to be highly correlated to impact noise types in apartments. The latter have been reported as the most disturbing noise type during numerous subjective annoyance surveys (3-7,19-21).

3.3 Proposal of acoustic comfort index for heavyweight buildings

An acoustic comfort index can be constructed based on the aforementioned models for the prediction of pleasantness and activation. A parametric analysis was performed illustrating the acquired component loadings for various values of $L'_{nT,w,100}$ and #Flats in the models for D_1 and D_2 respectively (Figures 4 and 5). The desirable values for component loadings lie in the region of "pleasant activation" (Fig.1), which corresponds to positive loadings for both dimensions. Loadings bigger than 0 are necessary for positive emotional reactions and good acoustic comfort evaluation. Values bigger than 0.5 would indicate a very good evaluation in the affect circumplex and a high sense of acoustic comfort.

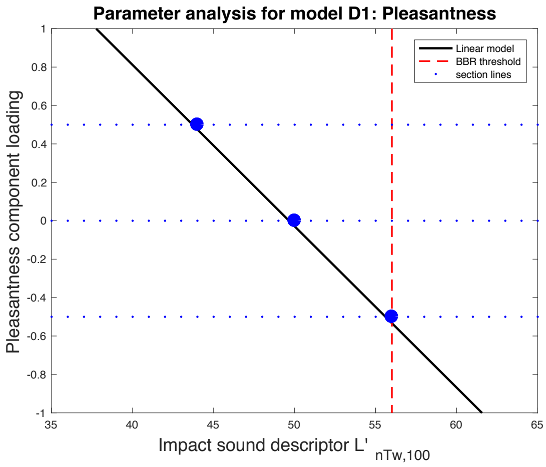

Figure 4 - Parameter analysis in the model of D_1:Pleasantness predicted by $L'_{nT,w,100}$.

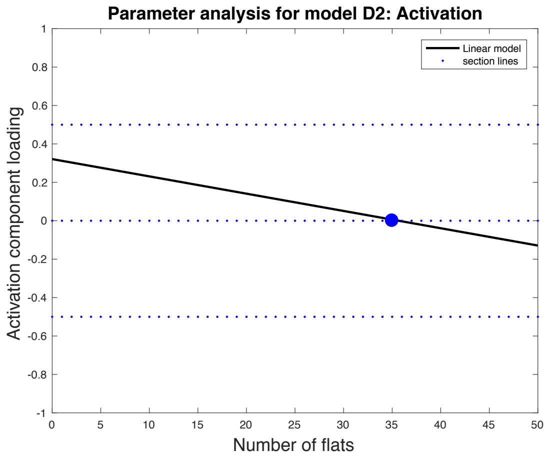

Figure 5 – Parameter analysis in the model of D_2:Activation predicted by #Flats.

For the case of the impact sound index as predictor of D_1:Pleasantness, it is observed that the value of zero corresponds to 50dB, so above that there is a region of good acoustic comfort with positive ratings in the affect circumplex. Then above a threshold of 0.5 there is a region of very good sense of acoustic comfort, which corresponds to $L'_{nT,w,100}$ values lower than 44dB. Below a component loading of zero there is a suggested region for an acceptable comfort level between 51-56dB. The 56dB value is due to the highest limits set in the Swedish regulations for noise transmission (17), also known as BBR value of Boverket. However, the 56dB maximum impact noise level is established with the descriptor $L'_{nT,w,50}$, including the low frequency range from 50Hz. Overall, Table 6 summarizes those regions, according to which an acoustic comfort index with distinct comfort classes is proposed.

For the number of flats predicting the dimension of activation (D_2), the parametric analysis does not offer very clear results (Fig.5). The linear model intersects the zero line at 35, meaning that less than 35 apartments per building unit would be required for good acoustic comfort sense. Then the limit of 0.5 is out of the scope of comparison and no further conclusions can be made about the number of flats and the activation loadings. Further, 35 is not a small number for total flats per building thus it is questionable if that number can really be a parameter for an acoustic comfort index. Considering all that, the acquired linear model for predicting D_2:Activation was neglected. To formulate a new acoustic comfort descriptor, only the model of $L'_{nT,w,100}$ predicting pleasantness was utilized. The equation for the new proposed acoustic comfort indicator is then:

$$AC_{index} = 4.171 - 0.084 \cdot L'_{nT,w,100}.$$

Noticeably the new acoustic comfort index should take values between -1 and 1, an assumption compliant with the maximum or minimum component loadings. The linear model can return values outside the reasonable limits [-1,1] but such values are neglected. Positive values are needed for a good evaluation. The condition AC_{index}>0 can help identify the suggested acoustic comfort classes: AC-1 or AC-2, as tabulated in Table 6. The threshold value of 0.5 for an average component loading separates AC-1 and AC-2 characterized as "Very Good and "Good" respectively.

The negative values correspond to the lower comfort classes AC-3 and AC-4, that being the categories characterized as "Acceptable" and "Not acceptable" respectively (Table 6). The AC-3 region (AC_{index} values between -0.5 and 0) relates to low comfort evaluation but still acceptable according to the Swedish regulation limits (17). The index values below -0.5 denote the worst region for acoustic comfort perception, that is the class AC-4.

Table 6 presents also a comparison with the acoustic classes established by the Swedish acoustic standard (21) which uses $L'_{nT,w,50}$ instead for impact sound level descriptor. Class D has the same maximum limit as the suggested AC-4: impact sound level index more than 56dB correspond to the worst class. Then Class C is defined for $L'_{nT,w,50}$ values between 56-53dB, Class B for values 52-48dB and Class A for $L'_{nT,w,50}$ values lower than 48dB. The values of the suggested classes AC-3, AC-2 and AC-1 are a bit lower, meaning that the acoustic comfort classes derived in this study have stricter criteria than the standardized classes.

Table 6 - Acoustic comfort index and classes suggestion for heavyweight structures. Comparison with Swedish classification of SIS SS 25267 standard (21).

Comfort category	**No comfort**	**Acceptable**	**Good**	**Very good**
Index class	**AC-4**	**AC-3**	**AC-2**	**AC-1**
$\boldsymbol{AC_{index}}$	< -0.5	-0.5 - 0	0.01-0.5	> 0.5
$\boldsymbol{L'_{nT,w,100}}$	> 56dB*	56-51dB	50-45dB	< 44dB
Swedish standard (23)	Class D	Class C	Class B	Class A
$L'_{nT,w,50}$	> 56dB*	56-53dB	52-48dB	< 48dB

** BBR minimum value (17)*

3.4 Clustered observations analysis for lightweight structures

The same analysis was performed for the case of LW structures in order to find variables that predict the PCA dimensions and formulate a similar acoustic comfort model as before. Namely, 77 observations from 6 blocks of LW structures were included. A minimum sample size of n=5 per LW block was applied, due to less groups and observations. Initial PCA provided: KMO=0.923, 45.2% and 34.8% of total variance explained by D_1:pleasantness and D_2:activation respectively. However, no linear model had statistical significance in model parameters to be reliable enough. Hence, a concluding acoustic comfort model for LW structures could not be proposed.

4. CONCLUSIONS

The acoustic comfort was investigated in a sample of Swedish apartment buildings. A comfort assessment was performed, based on the emotional reactions of the residents towards their sound environment at home. The circumplex model of affect (14) was deployed for evaluation. The results indicated a very positive perception in overall according to the semantic differential scales used in model, indicating affirmative emotional states of the residents in their apartments.

Principal component analysis was performed and two dimensions were identified: pleasantness and activation, which explain 39.4% and 36.2% of the variance respectively, namely 75.6% of the total variance. This is a confirmation of the dimensions suggested by the affect circumplex model (13) and especially for the Swedish version with 12 sub-items used in this study case (14).

The development of statistical models was attempted based on the prediction of component loading scores by variables relevant to the structure and the acoustic conditions. The acoustic descriptors $L'_{nT,w,100}$ and $D'_{nT,w,100}$, the size of apartments, the number of occupants in a flat and the number of total flats in a building were tested.

Linear models could not be developed for the case of individual observations due to high variability in the dataset. However, when the observations were treated as grouped in structures and their responses were averaged per structure block, sufficient correlations could be established. For the case of heavyweight (HW) concrete buildings, prediction models were developed for the two identified dimensions. $L'_{nT,w,100}$ was the best predictor for D_1:pleasantness and number of flats predicted best the dimension D_2: activation. Multiple regression models were tested as well, but they failed in terms of statistical significance for their estimated model parameters.

Furthermore, a novel acoustic comfort index for concrete buildings is suggested, based on the statistical model for the prediction of pleasantness. The suggested descriptor is formulated as: AC_{index}= 4.171-0.084$\cdot L'_{nT,w,100}$. Based on the new index and its scale, 4 classes of acoustic comfort are suggested as AC-1: Very good, AC-2: Good, AC-3: Acceptable, AC-4: No acoustic comfort.

For the lightweight (LW) wooden building structures of this survey, the statistical results were not sufficient for prediction models. The total observations and the sample size of LW blocks were much lower than for the HW data groups. Further individual research should be applied in lightweight structures to establish a separate model for acoustic comfort.

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