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Comparison of Acoustic Performance and Subjective Evaluation in Residential Buildings

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ABSTRACT

The "Regulation on Protection of Buildings against Noise" was issued by the Turkish Ministry of Environment and Urbanization in May 2017. The regulation was put into force partially in May 2018 obliging all new buildings to follow acoustical requirements. In May 2019, acoustical project by an acoustical expert will be obligatory for large scale or multifunctional buildings. The regulation aims to introduce a scheme for acoustical performance evaluation, ranging from A to F following the EU/COST TU 0901 project outcomes and ISO-CD19488.

This study aims to demonstrate the application of the regulatory requirements with field measurements and a survey. Airborne and impact sound insulation, indoor noise level, service equipment noise level and reverberation time were measured in 6 residential buildings and acoustic performances were analyzed according to the classification scheme. A survey was conducted with the residents of the buildings. The results were compared and the applicability of the regulation was discussed.

Keywords: Acoustic, Performance, Classification, Regulation

1. INTRODUCTION

The new regulation of Turkey "Regulation on Protection of Buildings against Noise" settles the limit values for sound insulation and sound levels in buildings; provides methods for noise protection of buildings and introduces acoustic performance evaluation [1,2]. The regulation is prepared in accordance with EU/COST TU 0901 Harmonization Project and ISO/AWI TS 19488 Acoustics and proposes 6 classes for evaluation of acoustic performance [3,4]. According to the regulation all new buildings should provide Class C performance while existing buildings should provide Class D performance in the event of a renewal project. The acoustical class of a building is inferred from the minimum of performance parameters: airborne and impact sound insulation between neighboring units, façade sound insulation, airborne sound insulation inside the dwelling unit, service equipment and indoor background noise levels and reverberation time. The insulation rating descriptors accepted for use are $D_{nT,w} + C$ ($D_{nT,A}$), $D_{2m,nT,w} + C_{tr}$ ($D_{nT,A,tr}$), and $L'_{nT,w}$. If low frequency sounds are in question, an acoustic consultant may also use $D_{nT,w} + C_{50\text{-}3150}$ ($D_{nT,50}$), $D_{2m,nT,w} + C_{tr,\ 50\text{-}3150}$ ($D_{2m,nT,50}$), and $L'_{nT,w} + C_{I,50\text{-}2500}$ ($L'_{nT,50}$). The service equipment noise level limits are defined in $L_{Aeq,nT}$ for continuous noises and $L_{AFmax,nT}$ for intermittent noises. The interior background noise limits are defined in L_{Aeq}. The limit values are defined for each acoustic performance class. In order to comply with a class measurement results should not show more than 2 dB adverse deviations from the limit. The regulation defines only one reverberation time limit for acoustic performance classes from A to D. This limit must be satisfied for a building to be classified in acoustic performance class A to D.

Although the after-construction measurements are not kept obligatory, an acoustic performance certificate can be granted upon proving performance with acoustical measurements. In this study, acoustic performances of 6 buildings were evaluated after measurements in selected dwellings. Occupants' opinions were gathered with a survey. Some of the pre-results were discussed in [5,6].

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2. METHODOLOGY

2.1 Selection of buildings

6 Buildings were selected for the study (Table 1). A preliminary analysis was made regarding to plan layout and surrounding in order to select buildings that were exposed to different noise conditions. Two of the buildings Yildiz Technical University lodge [YTU] and Istanbul Technical University Lodge [ITU] were located in university campuses, and consisted of 3+1, 2+1 and 1+1 housing units. The main noise issue was neighboring noise. One of the buildings Ruyakent [RUY] was located in a quite surrounding and consisted of units that share only one common wall in kitchens; therefore floors were the main concern for noise evaluation. Another building Finanskent [FIN] had moderate environmental noise and a plan layout that contained neighboring bedrooms. Floor and façade evaluation may be critical for occupants' comfort. Last 2 buildings Kuleli [KUL] and Erka Konsept [ERK] consisted of 3+1, 2+1 and 1+1 housing units and they were located next to main roads. Performance related to both exterior and interior building elements were expected to be important.

Table 1 – Selected buildings

Buildings		City	Bld. Height category *		Environmental noise level **	Floor share ***	Critical building elements	Construction materials
YTU	Yıldız Technical University Lodges	İstanbul	5 floors	apartment	Category A (L_{day}= 54,1)	complex	floor | wall | .	Reinforced concrete tunnel formwork
RUY	Rüyakent Housing Estate	Ankara	9 floors	high bld	Category A (L_{day}= 49,9)	few dwellings	floor | | .	Brick wall - floor with pumice fill-blocks
ITU	Istanbul Technical University Lodges	İstanbul	7 floors	apartment	Category A (L_{day}= 52,5)	complex	floor | wall | .	Brick wall -Reinforced concrete floor
FIN	Finanskent Housing Estate	İstanbul	25 floors	very high bld	Category B (L_{day}= 57,1)	few dwellings	floor | | façade	Reinforced concrete tunnel formwork
KUL	Kuleli Apartment	İstanbul	8 floors	high bld	Category C (L_{day}= 70,6)	complex	floor | wall | façade	Brick wall - floor with EPS fill-blocks
ERK	Erka Konsept Apartment	İstanbul	14 floors	high bld	Category B (L_{day}= 56,4)	complex	floor | wall | façade	Composite brick wall - floor with clay fill-blocks

* Zoning Regulation for Planned Areas (2017) classifies buildings ≥ 21.5 m as high rise; buildings ≥ 51.5 m as 'very' high rise buildings.
** Environmental Noise Assessment and Management Regulation (2010) classifies noise exposure for new residential areas in 4 categories Category A (Lday <55 dBA), Category B (Lday 55- 64 dBA), Category C (Lday 65- 74 dBA), Category D (Lday >74 dBA)
*** Complex floor sharing: Number of dwellings on the same floor > 4 (multiple common partitions)

2.2 Measurements

One dwelling (housing unit) and its neighbors were measured in each building. Sound insulation of building elements was measured according to ISO 16283-1-3 [5-7]. The results were given in $D_{nT,A,tr}$, $D_{nT,A}$, $L'_{nT,w}$. Partitions between neighbors and partitions inside the dwelling were measured separately. The regulation aims not only the noise passing from neighbours but also noise that occur inside the dwelling. The environmental noise level was measured according to ISO 1996-2 during 24 hours [8]. L_{den} value was calculated to represent the outside conditions. Service equipment noise levels were measured according to ISO 16032 [9]. Tap water, flush and ventilation (if existed) sounds were used for evaluation. For each case, these bathroom sounds were analyzed in a bedroom that belonged to the same dwelling. The service equipment noise from parent's bathroom was also measured. Although the regulation doesn't leave this type of noise out of the scope, it was kept informative in this study. Finally, reverberation time was measured according to ISO 3382-2 inside the apartment corridors and rooms [10]. The results were corrected if the room was unoccupied during the measurement.

2.3 Survey

A questionnaire form was prepared to address different noise issues in buildings by reviewing the socio-acoustic survey principles referred in ISO 15666 [13] and several other studies [14-20].20 residents were randomly selected and were interviewed face to face in 10 - 15 minutes of meetings. Several questions were asked involving overall comfort issues related to building and surrounding, demographic issues, time spent in house, noise related problems and reactions. Hearing conditions of various noise sources were investigated and resulted annoyance was rated. Both 5 point likert scale and numerical scale from 0 to 10 were used. The annoyance was marked as "0" if the noise source was unheard. This gives a coherent result for some sources that can be assumed to affect each occupant, such as traffic or footstep. However, some other sources depend on life style, such as music and tv. Evaluation of these annoyances will be further researched. The results were eliminated if the resident reported a hearing-related problem. In one case 2 responses were eliminated because of inconsistency in their responses.

2.4 Acoustic performance evaluation

The measurement results were compared to regulatory limits and an acoustical performance class was assigned to each measurement result. Deviations up to 2 dB were neglected as stated in the Regulation. The overall acoustic classes were assigned according to minimum of the results.

For classification of an entire building, random sampling would be necessary. However; the buildings were occupied at the time and permission was limited. Only in RUY and ERK additional measurements were possible in other dwellings. Since sampling criteria required by the regulation and ISO/AWI TS 19488 could not been met the measurement and survey results were put into an importance-performance matrix for comparison. Only the minimum measurement results were used for each acoustic performance parameter.

3. Results

3.1 Measurement results

The measurement results are given in Figure 1. The regulatory limit values differ according to the function of the room. For a clear comparison of cases, bedroom results were plotted on chart and limit values for Acoustical Performance Class-C were shown. If more than one sample was measured for a performance, the adverse result was plotted on chart. In some cases this did not correspond to a bedroom result, so the second measurement was also marked on the chart. Further research is required on which of these performances was more influential for occupants' judgement. Only the corridor reverberation times were put on the chart since occupied rooms already met the regulation limits.

3.2 Acoustic performance evaluation

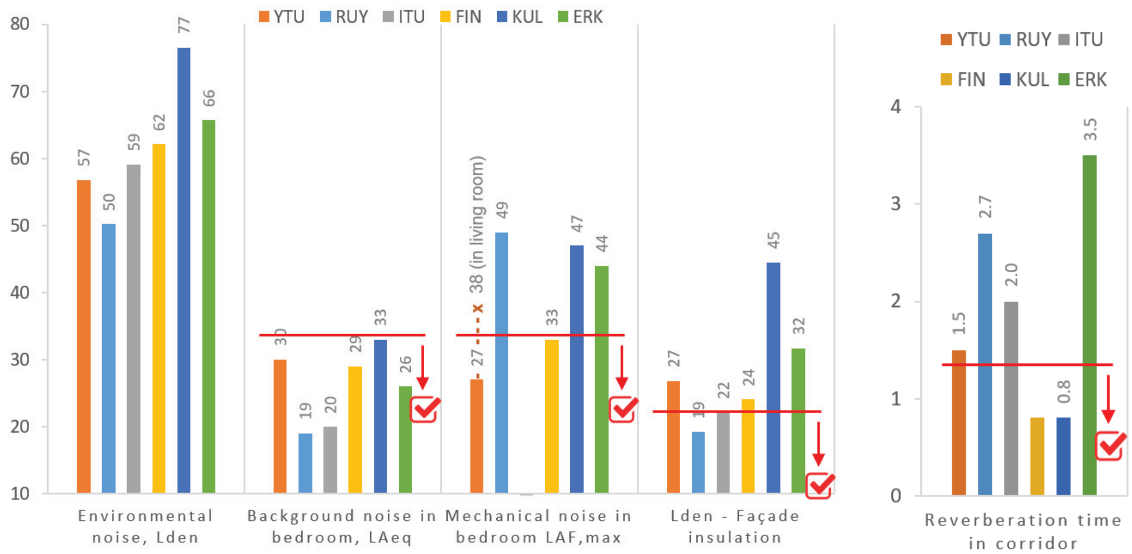
Dwelling in Yildiz Technical University lodge (YTU):

- YTU provided Class C airborne sound insulation performance between neighbours. The partitions between the bedrooms of the same dwelling were Class C, however partition between living room and bathroom was Class D with 2 dB deviation from the Class D requirements. The impact sound insulation was classified as Class C although there was 2 dB deviation from the limit value. Building's façade met Class D. However the main noise issue was the children's playground and there was no road nearby in this case. When C adaptation term was applied instead of C_{tr} in correspondence with ISO 717, the performance met Class C. This issue should be further studied with spectral analysis.
- The indoor background noise level was found as Class B. The service equipment noise level was found Class B in the bedroom, and Class D in the living room. Also, the sound from parent's bathroom was measured in parents' bathroom and found as Class C.
- All rooms met reverberation time criteria except for the apartment stairwell.
- The overall sound insulation class was Class D due to lower performance of the wall between the living room and the bathroom. The overall acoustic performance assessment was Class E because of long reverberation time in apartment stairwell.

Dwelling in Ruyakent Housing Estate (RUY):

- Airborne sound insulation of partitions between neighbours was evaluated based on the measurement between two (secondary) living rooms of upstairs and downstairs, since the regulation and ISO/AWI TS 19488 states that unoccupied rooms shall not be selected as receivers [1,4]. The preliminary results were 58 dB corresponding to Class B. However, due to unfavorable measurement conditions and contradictory results of annoyance reported by occupants, the measurement was repeated and results decreased to 52 dB, corresponding to Class C. Wall between two adjacent kitchens was Class B and wall that separates the common corridor from the dwelling was found Class D but these results were kept informative. According to the regulation the limit values are 14 dB lower for walls with doors and this was applied to the latter case. The partitions inside the dwelling were evaluated as Class E based on the minimum of the results. The impact sound insulation was Class C. The façade airborne sound insulation was Class B.
- The indoor background noise level was measured in a bedroom and an unoccupied living room. The measurement result in unoccupied room was standardized to a reverberation time of 0,5 sn. Both resulted as Class A. The service equipment noise level exceeded Class F requirements.
- The reverberation time of apartment's common corridor exceeded the limits.

(a)



(b) (c)

Figure 1 – Measurement results a) sound insulation, b) sound level, c) reverberation time

- The overall sound insulation class was <u>Class E</u> due to partitions inside the dwelling. The overall acoustic performance of the dwelling was <u>below Class F</u> due to the service equipment noise.

<u>Dwelling in Istanbul Technical University lodge (ITU):</u>

- Airborne sound insulation of partitions (walls and floors) between neighbours was found as Class D with the performance of the weakest wall, i.e. the wall that separated the living room of a dwelling from the kitchen of the neighbor. Airborne sound insulation of partitions inside the dwelling and impact sound insulation was Class D. Façade was found as Class C.
- The indoor background noise level was found as Class A. Bedroom of an empty apartment was also measured and standardized. The service equipment noise was not evaluated because; the bathroom and bedrooms were separated in plan layout. Sound level from parents' bathroom was measured in parents' bathroom and found as Class F.
- The corridor hall reverberation time exceeded the limit value of 1,2 s.
- Overall sound insulation class was <u>Class D</u>. Overall acoustic performance of the dwelling was <u>Class E</u> due to reverberation time. Service equipment noise level was not evaluated.

<u>Dwelling in Finanskent Housing Estate (FIN):</u>

- Airborne and impact sound insulation of partitions (walls and floors) between neighbors was found as Class C as well as the partitions inside the dwelling. Façade was also measured as

Class C. The airborne sound insulation of floor and façade elements were measured in living room as distinct from other cases where they were measured at least in one of the bedrooms. Both regulatory limits and sizes differ for bedrooms; therefore results were supported with additional measurements for clear comparison of cases. The results were Class C.

- The indoor background noise level was found as Class B. The service equipment noise was measured as Class C. Sound level from parent's bathroom was Class E, but it was not involved in overall evaluation.
- The reverberation time of apartment corridor was 0,8 providing the limit value of 1,2s.
- Both sound insulation class and the overall acoustic performance were found as Class C.

Dwelling in Kuleli Apartment (KUL):

- Airborne sound insulation of partitions between neighbors was evaluated as Class D. The partition between two bedrooms of the same dwelling was measured as Class E. Another partition with a sliding door separates bedroom from living room and was found as Class F. The impact sound insulation was Class E. The façade sound insulation was rated below Class F. The environmental noise levels were high in this area and required sound insulation was higher.
- The indoor background noise level was Class C. The service equipment noise was Class F. A strong tonal component was noted around 500 Hz, caused by ventilation system of bathroom.
- The reverberation time was sufficient in the apartment hall.
- Sound insulation and the overall acoustic performance were below F because of the façade.

Dwelling in Erka Apartment (ERK):

- Airborne sound insulation of partitions between neighbors was evaluated as Class F. The partitions inside the dwelling were found as Class E. The impact sound insulation was Class C with 2 dB deviation from the required value. The façade sound insulation was Class E.
- The indoor background noise level was measured in an unoccupied bedroom and after standardization it was found as Class A. The service equipment noise level was found as Class E. Sound level from parent's bathroom was below F, but it was kept informative.
- The apartment corridor reverberation time exceeded the reverberation limits.
- Both sound insulation class and the overall acoustic performance were Class F.

3.3 Survey results

The respondents' ratio who rated their annoyance more than 3 in scale of 0 to 10 are plotted on a chart in Figure 1. There were 20-25 participants from each building. At total 136 occupants participated in the survey and 131 responses were found valid.

- YTU results showed that mechanical noises (radiators 55%, pump 50%, elevator 32%, water from neighbor 45% and water from own dwelling 35%), occupant's own noise coming from next room inside the dwelling (35%) and speech sounds coming from apartment hall (35%) were the noise issues in the building. Amongst outdoor noise sources children sound coming from outside was rated as annoying by 53%. The pump noise was especially efficient at lower floors. All occupants living at ground and 1st floor were annoyed with the average of 9 / 10.
- RUY results showed that occupants of this building complained more about speech sound coming from upstairs/downstairs (61%), footstep (52%) and neighbor's water sound (50%). Upstairs child running was rated by 42% and speech from apartment hall was rated by 45%.
- ITU results showed that the most important noise issue was speech sounds from next-door (58%). Both footstep sound from upstairs and occupant's own noise coming from next room was rated by 47%. Upstairs-child run was rated by 40%, speech from apartment hall by 42% and speech from up/downstairs by 37%. Amongst outdoor noise sources, construction sound was rated by 42%. Considering that dwellings at the farthest edges of the building were more advantageous regarding the plan layout, next-door speech annoyance was re-analyzed excluding these dwellings and the annoyance rating rose up to %75.
- FIN results showed that main noise issue related to the building was the speech sounds coming from apartment hall (55%). Upstairs child run (40%) and speech sound from upstairs/downstairs (32%) created also noise issues. Additionally, the annoyance related to elevator sound rose to 33% when only the dwellings adjacent to the elevator were in question.
- KUL results showed that occupant's own noise coming from next room was rated by 39% and music coming from upstairs or downstairs was rated by 32%. The most common noise problem in this case was the outside noises (traffic 67% and construction 50%). The building consisted

of two blocks, Block A faced a highway and Block B faced dense urban settlement. The building had T-shape plan layout and Block A provided a barrier for Block B. Consequently, traffic related annoyance rose up to 85% in Block A while it was 45% in Block B. In Block B, annoyances related to outside speech and outside music were 31% and 45% respectively. The outside construction noise was important in both Blocks (38% in Block A and 64% in Block B).

- ERK results showed that 56% of occupants rated speech sounds from next-door, 55% rated speech sounds from apartment hall and 50% rated footstep from upstairs. Footstep from apartment hall (41%), upstairs child run (35%) speech sound from upstairs/downstairs (36%), music from next-door (%31) were other issues. Water sound from both neighbor and own dwelling annoyed 36%. Amongst outdoor noise sources, traffic was rated by 45%, speech coming from outside was rated by 32% and construction was rated by 32%. Considering that buildings higher than 21,5 m are classified as high-rise buildings in Zoning Regulation for Planned Areas [21] , the responses from 8th and upper levels were grouped and the annoyance related to outside noise sources were analyzed in two steps. The variance was important for outside-speech results. Reported annoyance was 50% in lower levels while none of the residents in upper levels was annoyed by this source.

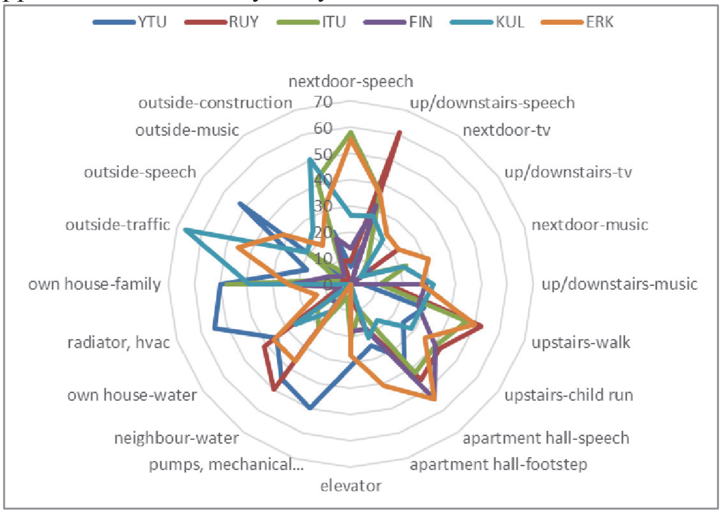


Figure 2 – Survey results corresponding to the percentage of annoyance 3 or more.

3.4 Importance – performance analysis of the results

Importance-performance matrix is an analysis method usually used in marketing in order to provide efficient source management. In the matrix, y-axis shows the achieved performance and x-axis shows the relative importance given by the customer to that performance. Based on this approach sound insulation-annoyance matrix is prepared. Sound insulation is given in y-axis and annoyance is given in x-axis. According to the Regulation, Class C acoustical performance is mandatory for new buildings [1]. Deviation of the result from the Class C sound insulation limit value is plot on y-axis. According to [17] fraction of respondents responding 3 or higher should be under 20%. Following this assumption the axis intersection is driven from 20%. As a result, 4 cells are occurred in the graphic.

The results are expected to fall in 1st (favorable situation) and 3rd (primary improvement required) cells. 4th cell represents low annoyance in spite of the weak performance. The reason of a data in this cell can be that the noise source is inactive or active for only a small period or that it has lower level than expected. 2nd cell represents observations where there's high annoyance although the regulation requirements are met. The reasons should be analyzed. It may be due to characteristics of the noise of interest or a wrong assumption in the study. More samples should be measured, and subjects should be interviewed. A possible misinterpretation is that building element in question may be different than the one effecting subjects' evaluation. If annoyance due to a specific noise source falls in this cell in all studies, regulation requirements should be reviewed.

Survey and measurement results were plot on the matrix. The horizontal (represented as 'H') and vertical (represented as 'V') sound transmissions between neighbors and corresponding annoyance were shown in Figure 3. The outdoor noise sources (represented as 'OUT') and annoyance were shown in Figure 4. Only the speech, footfall and traffic sounds were analyzed because they tend be more consistent throughout the building.

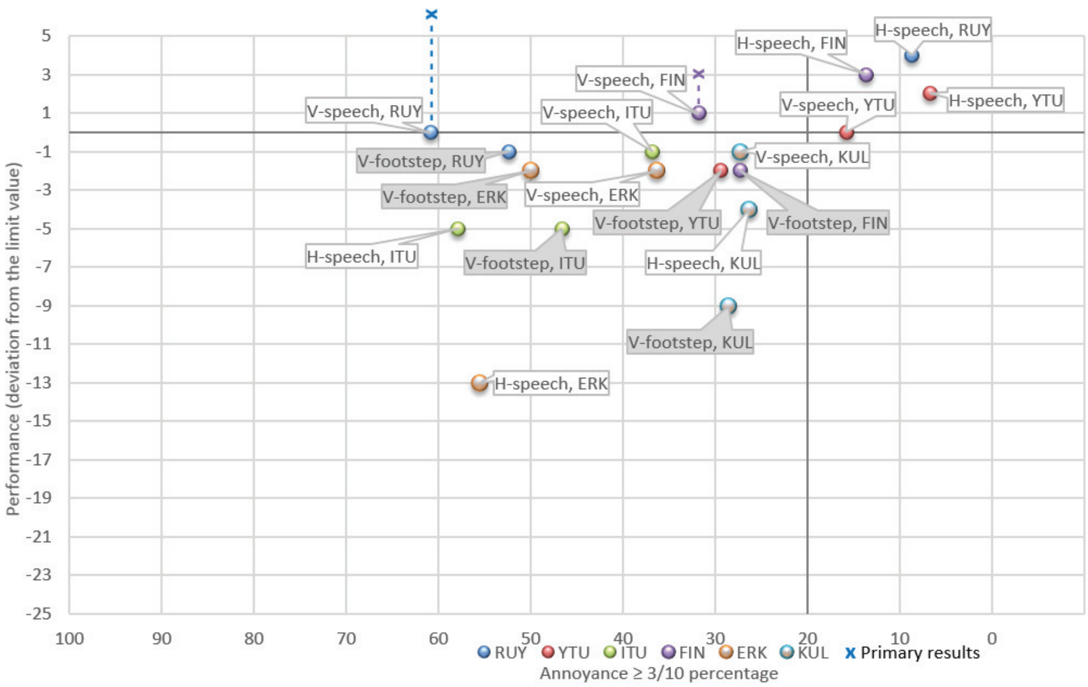


Figure 3 – Survey results corresponding to the percentage of annoyance 3 or more for indoor noises.

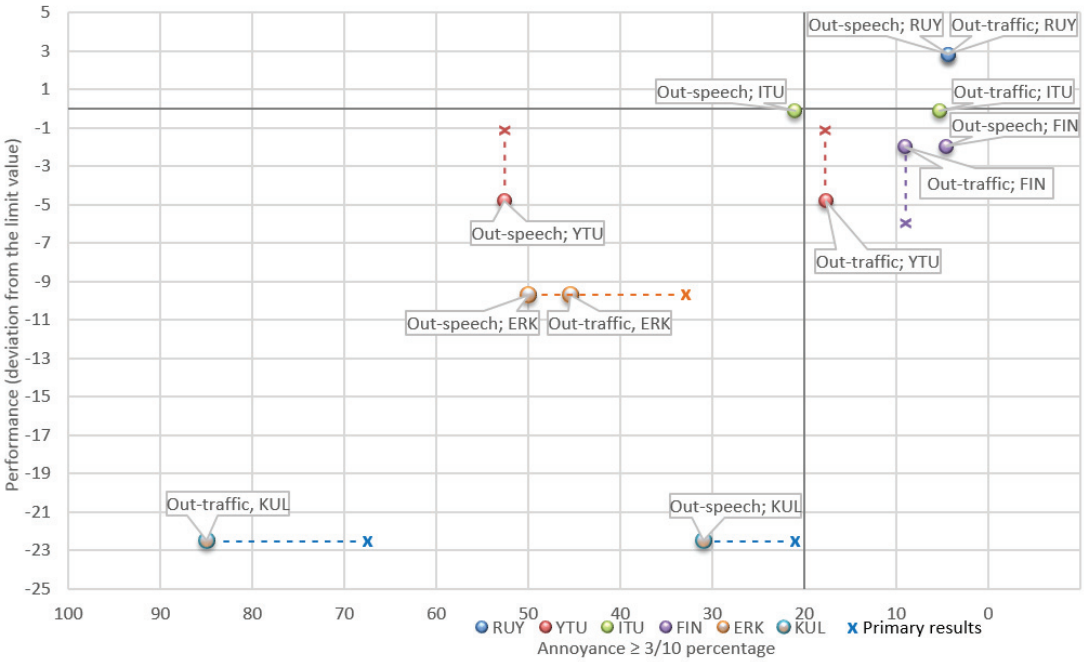


Figure 4 – Survey results corresponding to the percentage of annoyance 3 or more for outdoor noises.

In occupied buildings, sampling criteria suggested by the regulation is not always feasible due to restrictions brought by occupants. The importance-performance analysis can be a way of verifying the acoustic performance evaluation of the building. In figure 5 and 6, the 'X' marks represents the primary results that were used in the graphic, later replaced with additional measurements or group analysis as explained earlier.

Annoyance related to vertical speech transmission was high in RUY, however sound insulation measurement results were relatively high, contradictory to the annoyance. When the room conditions were changed, and measurements were repeated, results were more satisfactory. The vertical speech transmission and façade insulation were measured in a living room in FIN and they did not correlate to the annoyance levels. The results were replaced by bedroom results in competence with all the other cases. In YTU, there wasn't any main road nearby and the main noise source was the playgrounds. $D_{nT,A}$ was used in primary results but later replaced by $D_{nT,A,tr}$ for clear comparison and to be further discussed. The survey results were analyzed according to plan layouts of the building and residents were grouped according to their exposition level. In ERK, upper levels were not exposed to speech sounds from outside; therefore the percentage was replaced with the percentage of floors up to 7. KUL consisted of two Blocks, Block A was exposed to traffic noise and Block B to the outside-speech noise and the percentages are re-calculated separately for each Block.

4. CONCLUSIONS

Acoustical performances of 6 buildings were evaluated based on the acoustical measurements. Façade sound insulation, airborne and impact sound insulation between neighbors, airborne sound insulation inside the dwelling, background noise levels, service equipment noise levels and reverberation time results were compared to the regulatory limits and an acoustical performance class was assigned for each performance. A survey study was conducted with the residents of the buildings. The results were compared in importance-performance matrix and relevancy of annoyance to the results that were selected as basis for acoustic performance evaluation was discussed.

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