SPEECH INTELLIGIBILITY AND ACTIVITY NOISE IN OPEN PLAN EDUCATION SPACES

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1 INTRODUCTION

Today's trends of building open or semi-open education facilities introduce several acoustic and organizational challenges. Often there is a conflict between preserving optimum acoustic shielding, and maximum flexibility and visual openness. Also, the transition from conventional classroom-based education proves difficult for many teachers and students.

A case study is presented which focuses on these aspects. Speech intelligibility measures were calculated by combining measurements of different activity noise situations with impulse response measurements from typical talker positions to listener positions both within and outside the different education zones. Based on an analysis of the acoustic conditions coupled with the experiences made by the teachers, modifications of room partitions and added wall absorbers were suggested. Room acoustic measurements were repeated to analyze the effects of the modifications.

2 CHALLENGES IN OPEN PLAN EDUCATION SPACES

In Norway, as well as in many other European countries, open plan education spaces have become popular due to a wish for educational areas yielding high flexibility with regard to furnishing, group division and variable group sizes, and which support different teaching methodologies. Though acceptable properties with regards to aesthetics and visual shielding may be relatively easy to achieve, obtaining good acoustic conditions will often be challenging.

The main conflicting properties are the following: Users (teacher and students/pupils) and architects often want to obtain visual openness and to use flexible room dividers throughout large spaces, in some cases above 500 m^2. It is also desirable to easily be able to alter the sizes of the different zones, or subdivisions, of the open space. But on the other hand, teachers want to be able to lecture, play music and videos, and have discussions with the class without disturbing neighbouring groups working e.g. individually on tasks requiring high concentration.

Commonly, acoustic treatment is limited to a highly absorbing ceiling, typically a suspended ceiling using mineral fibre panels. Wall absorbers, absorbing curtains or absorbing room dividers are often not prioritized due to economical considerations, a demand for high degree of visual transparency, and a wish for robust surfaces that are easy to clean. Open slits between room dividers and low-height room dividers are also common.

Therefore, many education spaces that have been built do not support the intended functionality and flexibility, and complaints from teachers and pupils/students on high noise exposure, increased stress levels and reduced concentration ability are common.

3 REGULATIONS AND RECOMMENDATIONS

Norwegian governmental regulations limits specifications on quantifiable room acoustic properties[1] to maximum reverberation times and maximum noise levels from technical installations. General requirements on acoustic properties of buildings[2] and work environment regulations[3] states that buildings should be constructed in such a way that users are protected from noise that are health-damaging, reduces concentration or limits necessary communication, but it is in principle up to the acoustic consultant, the users, local health authorities and the owner to define what acoustic properties should be fulfilled in order to order to meet these requirements. It is also apparent that the resulting acoustic conditions for the users will also rely up on the use, organization and awareness of both teachers and pupils/students.

SINTEF Byggforsk has published recommendations for acoustic design of schools[4], which include detailed acoustic criteria for open plan education spaces. A suggested classification of different education spaces based upon floor area is also presented. These recommendations are partly based on corresponding work done in other European countries and the US, see e.g. [5,6]. Table 1 summarizes the recommended room acoustic criteria for open plan education spaces larger than 200 m^2.

Acoustic parameter	**Recommendations for larger education spaces**
Reverberation time, T (s)	0,3 – 0,4
Speech intelligibility, STI - without activity noise - within one educational group[1)] - between educational groups	 > 0,75 > 0,60 < 0,20
Distance damping (dB)	5-8
Damping between educational groups (dB)	15-20

[1)] Calculation based on total sound pressure level as background noise, that is including activity noise from teaching, group work, movement and equipment in the room.

Table 1. Recommended acoustic parameters for larger education spaces, from SINTEF Byggforsk paper no. 527.305.

More information on STI can be found in [7,8]. Distance damping is in this context defined as sound level reduction per doubling of distance.

Note that these recommendations imply both high sound absorption to reduce activity noise levels and unwanted reflections, and room dividers to increase the acoustic shielding between different educational groups. Effective acoustic shielding will both increase speech intelligibility within one educational group by reducing activity noise levels from adjacent educational groups, and decrease intelligibility in adjacent groups, which will reduce the risk of disrupted concentration.

4 CASE STUDY

The case study presented in this paper aim at illustrating a measurement procedure suitable for examining the parameters presented in Table 1, at investigating what figures that could realistically be obtained, and at evaluating whether the requirements presented in Table 1 correspond to acceptable conditions for flexible teaching methodologies within large open plan education spaces.

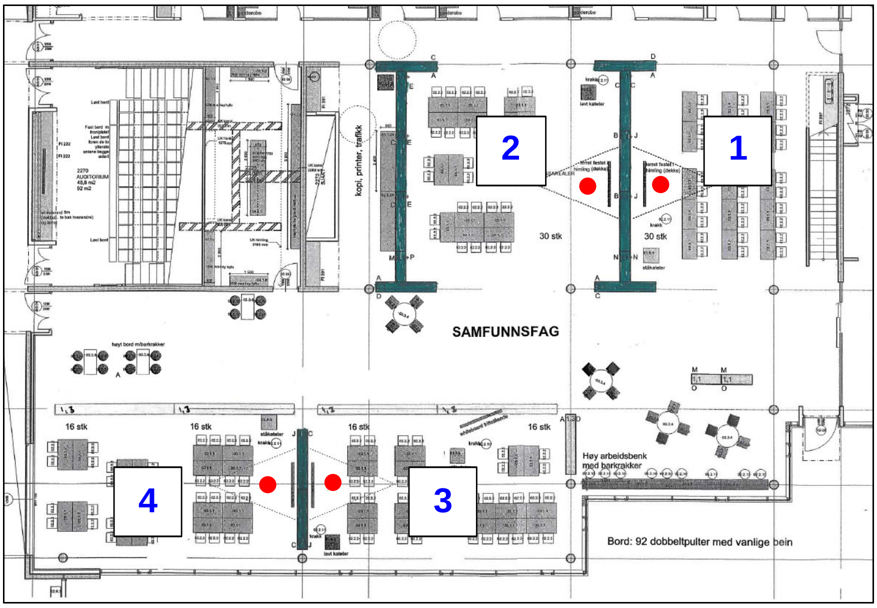

Figure 1. Overview of the education space prior to modifications. High room dividers (2.1 m) are colored green, and the different education zones are labeled 1-4. Normal teaching positions are indicated by red dots.

Figure 2. Zone 1 (left) and 4 (right), prior to modifications.

Figures 1 and 2 illustrate the situation prior to modifications. The total area of the open space is approx. 560 m^2, and was designed to accommodate up to 4 groups of 30 gymnasium (secondary school) students.

Acoustic treatment was limited to a suspended ceiling using mineral fibre panels (above zones 3 and 4) and directly mounted mineral fibre panels above a steel grid (above zones 1 and 2). Also, room dividers (bookshelves) of height 2.1 m was placed between the education zones to increase acoustic shielding, some of which also included additional acrylic glass panels extending to 2.4 m (see Figure 2). No curtains or other absorbing material (such as books) was present.

Teachers and students started reporting that they where dissatisfied by the acoustic conditions shortly after opening the school. They were annoyed by high noise exposure and disturbance from other groups, and felt that the education space limited their freedom to vary the educational methods, in stead of adding flexibility. But on the other hand, further investigations revealed that both teachers and students mainly continued to use the new education spaces as conventional classrooms, and only to a limited degree focused on adapting to the possibilities and limitations of the new facilities. According to the architect, the large education spaces were primarily intended for group work and so-called student-managed activity, while conventional teaching or lectures normally were to be performed in smaller surrounding rooms. An additional challenge and source of noise annoyance was that traffic zones were located in such a way that students frequently had to pass other education zones when leaving or entering the room. It should also be noted that one of the key statements in the Byggforsk recommendations is that larger education spaces are only partly suitable for lecturing. They are, on the other hand, well suited for student-managed activities and guidance in smaller groups, but this requires well-thought coordination and planning of teaching and activities in the areas, in addition to a well-functioning acoustic environment.

In order to examine the situation, and to obtain an objective analysis of the acoustic conditions, a measurement procedure based on the criteria summarized in Table 1 was chosen. Based on the objective analysis, modifications to improve the acoustic conditions were suggested. A fundamental limitation was that no modifications were to involve permanent walls or closed rooms, and that no modifications of the fire sprinkler or ventilation systems should be necessary.

4.1 Measurement procedure

All parameters given in Table 1 were investigated, except for distance damping. Distance damping was considered to yield little extra information regarding the acoustic properties of the room, as long as all other parameters in Table 1 were examined.

4.1.1 Activity noise

To obtain realistic activity noise measures, a total of 14 different noise situations were measured, and a subset was selected to model a span of the noise conditions. The selected noise situations are shown in Figure 3.

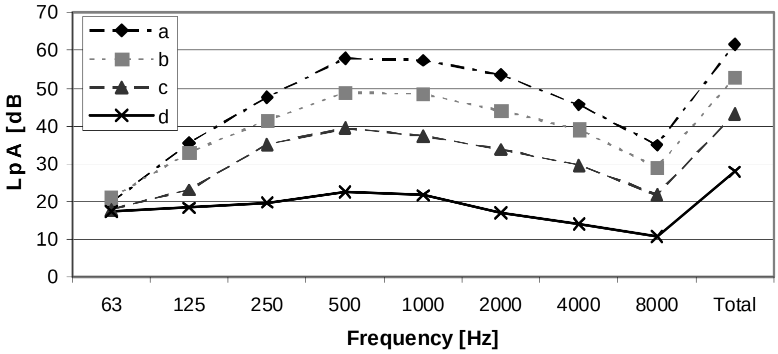

Figure 3. Measured activity noise situations, 10 seconds average.

Noise situations a) and b) correspond to student activity in three zones, and conversation/discussions within the groups with high and medium intensity, respectively (microphone located between zones). Situation c) corresponds to a teacher lecturing behind a room divider in a zone 10 m from the microphone, in addition to two students having a normal conversation about 7 meters from the microphone. In situation d) only scattered words was heard from the opposite end of the open space (nearly equal to the background noise level).

4.1.2 Speech intelligibility and distance damping

For all education zones, a loudspeaker mimicking talker directivity (Tivoli Audio Pal) was placed at the normal teacher position. Impulse responses were measured at two receiver positions within each zone, located in frontal and in rear half, respectively. A reference microphone position 1 meter in front of the speaker was also included for calculation of correct speech levels.

Simulated STI values for all source-receiver combinations, and for all noise situations presented in Figure 3, was calculated. A reference speech level of 67 dBA/1m using a standardized speech spectrum (STI) was chosen, in correspondence with [8]. Also, for each zone acting as the education zone (were the speaker is present), the average level difference between the education zone and the other three zones were calculated. These measures correspond to the term “Damping between educational groups” in Table 1.

In order to obtain realistic activity noise simulations, the following procedure was chosen: For each noise situation a) to d), it was assumed that an even noise level equal to the values shown in Figure 3 was present in all zones, except in the education zone. Assuming that students in the education zone are listening to the teacher, the reduction in noise level within the education zone was estimated as the minimum level difference relative to neighbouring zones for the speaker located within the neighbouring zone, minus a safety margin of 3 dB. This is not an optimal measure, but should give a relatively realistic and conservative estimate of the shielding effect of the room divider.

All impulse response measurements and STI calculations were done using WinMLS. By using sine sweeps, the distortion components of the Tivoli Audio loudspeaker at high levels could be removed, and sufficient SNR for robust activity noise simulations was possible for all measurement positions within the frequency region of interest (125 - 8.000 Hz).

4.2 Measurement results

Results for zone 1 and 4 acting as education zones are presented in this paper. From Figure 1 it can be seen that these are the zones most suitable for conventional lecturing, and the zones for which the acoustic shielding towards other zones could most easily be increased.

For easier comparison, results both prior to and after modifications are shown together. Se section 4.4 for further details.

4.2.1 Zone 1

The average level differences between the education zone and other zone with speaker in zone 1 is shown in Figure 4.

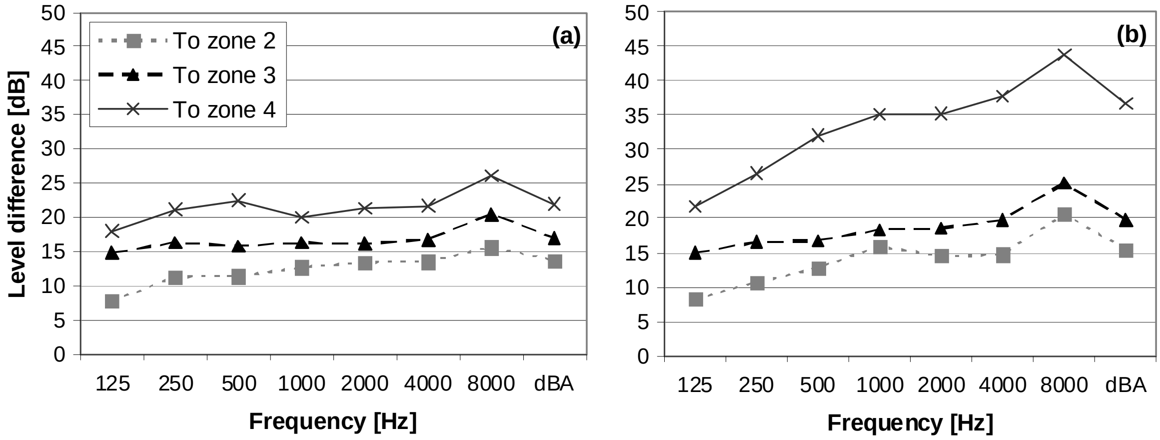

Figure 4. Average level differences between education zone and other zone with speaker in zone 1, situation prior to modifications (a) and after modifications (b).

Calculated STI values for different activity noise situations are shown in Tables 2 and 3. To improve readability the following colour coding is used, corresponding to the criteria given in Table 1:

 **STI > 0.6** (Acceptable speech intelligibility within an education zone.)

(red) **0.6 ≥ STI > 0.2** (Neither acceptable speech intelligibility within an education zone, nor acceptable shielding against other zones.)

(blue) **STI ≤ 0.2** (Acceptable shielding against other zones.)

	Noise situation			
Measuring position	a	b	c	d
1F	0.57	0.69	0.74	0.75
1B	0.55	0.67	0.73	0.74
2F	0.07	0.17	0.37	0.54
2B	0.05	0.15	0.34	0.52
3F	0.01	0.07	0.26	0.49
3B	0.02	0.08	0.27	0.48
4F	0.00	0.01	0.15	0.40
4B	0.00	0.01	0.16	0.42

Table 2. Situation **prior to modifications**. Calculated speech intelligibility STI in the different zones with speaker in zone 1.

	Noise situation			
Measuring position	a	b	c	d
1F	0.71	0.77	0.78	0.78
1B	0.59	0.68	0.72	0.72
2F	0.05	0.13	0.33	0.53
2B	0.04	0.08	0.25	0.49
3F	0.01	0.03	0.17	0.44
3B	0.01	0.03	0.20	0.46
4F	0.00	0.00	0.03	0.17
4B	0.00	0.00	0.03	0.18

Table 3. Situation **after modifications**. Calculated speech intelligibility STI in the different zones with speaker in zone 1.

The measured reverberation time prior to modifications was 0.6-0.7 seconds in the region 125 - 4.000 Hz. After modifications, the reverberation time was reduced to 0.4-0.55 seconds in the region 200 - 4.000 Hz, increasing to 0.7 seconds at 125 Hz.

4.2.2 Zone 4

The average level differences between the education zone and other zones with speaker in zone 4 is shown in Figure 5.

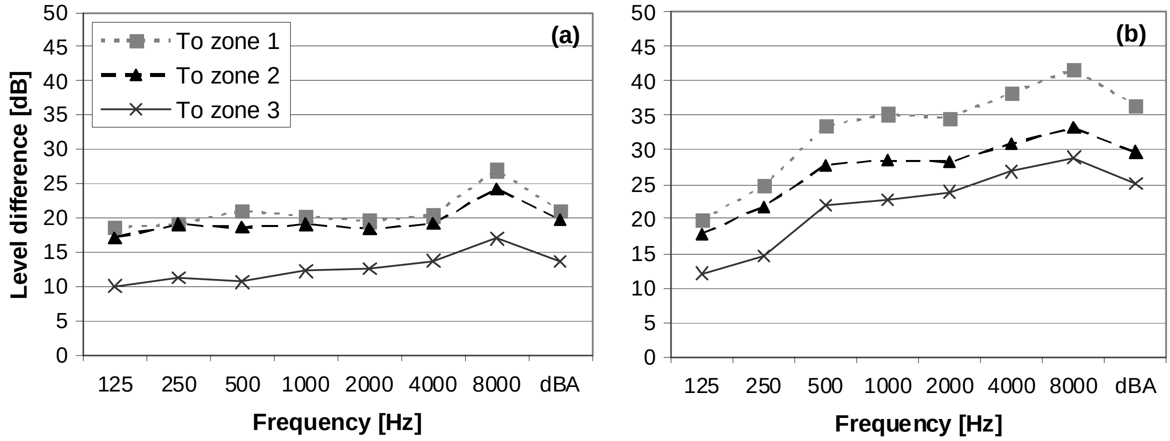

Figure 5. Average level differences between education zone and other zone with speaker in zone 4, situation prior to modifications (a) and after modifications (b).

Calculated STI values for different activity noise situations are shown in Tables 4 and 5.

	Noise situation			
Measuring position	a	b	c	d
1F	0.00	0.02	0.17	0.42
1B	0.00	0.03	0.21	0.45
2F	0.00	0.03	0.19	0.43
2B	0.00	0.03	0.19	0.40
3F	0.07	0.19	0.39	0.55
3B	0.04	0.14	0.35	0.54
4F	0.63	0.75	0.80	0.80
4B	0.56	0.71	0.79	0.80

Table 4. Situation **prior to modifications**. Calculated speech intelligibility STI in the different zones with speaker in zone 4.

	Noise situation			
Measuring position	a	b	c	d
1F	0.00	0.00	0.03	0.20
1B	0.00	0.00	0.04	0.25
2F	0.00	0.00	0.06	0.33
2B	0.00	0.00	0.07	0.34
3F	0.01	0.04	0.14	0.38
3B	0.01	0.04	0.17	0.45
4F	0.77	0.78	0.79	0.79
4B	0.74	0.77	0.78	0.78

Table 5. Situation **after modifications**. Calculated speech intelligibility STI in the different zones with speaker in zone 4.

The measured reverberation time prior to modifications was 0.7-0.9 seconds in the region 125 - 4.000 Hz. After modifications, the reverberation time was reduced to 0.4-0.55 seconds in the region 200 - 4.000 Hz, increasing to 0.7 seconds at 125 Hz.

4.3 Evaluation prior to modifications

The acoustic properties of the education space were analyzed with reference to the recommendations presented in Table 1. Based on measurement results presented in Chapter 6, and detailed analysis of the measured impulse responses, the following observations were made regarding the situation **prior to modifications**:

- Noise situation b) is the only situation where acceptable speech intelligibility within the education zone is achieved, while obtaining sufficient acoustic shielding towards other zones. For none of the zones, the acoustic conditions are within the recommendations listed in Table 1 for a broad range of activity noise situations.
- For a teacher located in zone 1, level differences satisfied the recommendations only towards zone 4. For zone 4, recommended level differences were obtained towards zones 1 and 2.
- In general, the correlation between level differences and speech intelligibility (STI) is high, especially for high noise levels. This suggests that level differences between education zones are good indicators for reduction in speech intelligibility, or obtained acoustic shielding, towards other zones.
- Level differences and reduction in speech intelligibility is low for situations where the teacher is standing directly behind a room divider. The is primarily caused by two effects:
    1) Limited height of the room divider (2.1 m) leads to significant diffraction contributions above the room divider toward the neighbouring zone.

2) All zones have a reflecting rear wall. Reflected energy reaches the ceiling at a near-gracing angle, for which the mineral fibre panels have very low absorption. This implies that the absorbing ceiling acts primarily as a reflector for sound from the teacher reflected from the back wall.

These effects are illustrated in Figure 6:

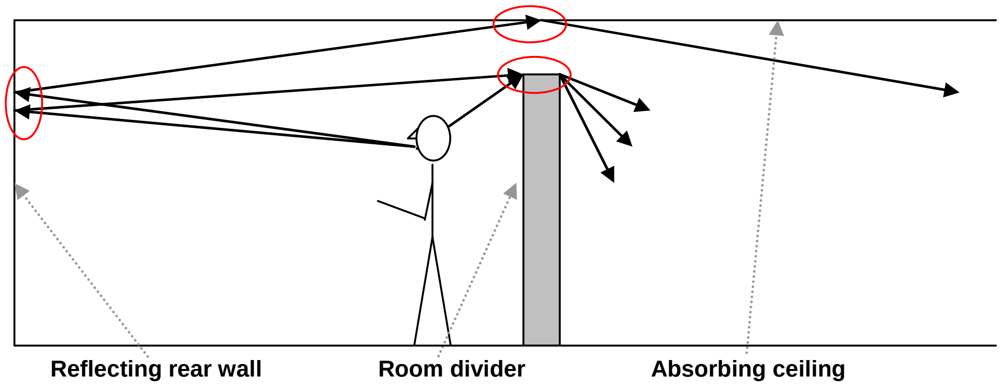

Figure 6. Vertical sound transmission paths.

- Horizontal reflections also contribute significantly to the sound transmission towards other zones. Due to the limited width and coverage of the high room dividers, reflecting walls and facades also yield significant horizontal reflection contributions. This can easily be verified by analyzing the horizontal reflection paths for a teacher placed in zone 4, using Figure 1.

  As an example, for a teacher located in zone 4, the measured speech intelligibility in the rear half of zone 2 was lower than in the rear half of zone 1, even if the source-receiver distance to zone 1 was more than twice the distance to zone 2. An analysis of the impulse response verified that the dominating contribution to zone 1 corresponded to a path length equivalent to a reflection from the real wall of zone 4 plus the rear wall of zone 1 (see Figure 1).

Teachers reported that the observations presented above corresponded well to their subjective experiences teaching in the different education zones.

4.4 Suggested modifications

Based on the analysis above, the following conclusions were drawn:

- Zones 2 and 3 should primarily be intended for group work and student-managed activity, and were therefore not modified further, besides adding absorbers on room dividers facing the education zones.
- The acoustic shielding around zones 1 and 4 should be increased in order to improve the conditions for lecturing and more traditional classroom education. The following modifications were suggested, based on the limitations stated in the introduction of chapter 4:

  1) Mount wall absorbers on all available rear walls and on the inner side wall of zone 4.

  2) Extend room dividers behind the teaching position in zones 1 and 4 up to the ceiling. The room dividers behind zone 4 should also be extended to cover the whole width of the zone, and fit tightly towards the façade. *Ventilation canals and the ceiling steel grid in zones 1 and 2 limited the possible height and increased effectiveness of the room dividers in zone 1.*

  3) Place room dividers of height 2.1 m along the sides of zone 1 and on the inner side of zone 4, covering the frontal half of each zone. The top plates of the room dividers should be made absorbing to reduce diffraction (see [9]), and all room dividers placed around each teaching position should be coupled together and fit tightly.

4) Add absorbers on the sides of the room dividers facing inwards which were located in the rear half of each education zone. *Not implemented at the time of measurement.*

5) Add absorbing panel curtains on the glass facades and internal glass walls. *Not implemented at the time of measurement.*

Figure 7 illustrates the design of the modified room dividers.

Figure 7. Zone 1 (left) and 4 (right), after modifications.

4.5 Effects of modifications

Based on the measurement results presented in section 4.2, the following observations can be made:

The effects of the modifications around zone 1 were limited. The main cause is the limited possibility to extend the room divider up to the ceiling absorber. Also, the placement of the room dividers around zone 1 was altered, limiting the possibilities for direct comparison between the two measurement series. In addition, the room dividers around zone 1 were extending partly around the zone also prior to modifications, reducing the achievable improvement.

For zone 4, the effects of the modifications were significant. Level differences toward all other zones were significantly increased. Also, speech intelligibility was increased within the education zone for higher activity noise levels, and reduced outside the education zone for all activity noise situations. The acoustic conditions with regard to level differences and speech intelligibility meet the requirements presented in Table 1 for all but the lowest activity noise levels, and this zone should therefore be suited for lecturing and more traditional classroom education.

It should also be noted that the reduction in reverberation time is significantly higher than what would be expected based merely on the added absorption expressed in m^2 Sabine. This clearly illustrates the importance of well-distributed absorption in larger education spaces, and in particular the use of wall absorbers. In addition to increasing the overall absorption in the room, wall absorbers increase the effective absorption of an absorbing ceiling, because the amount of near-gracing incident sound energy is reduced.

Teachers reported that the acoustic conditions of education space had been notably improved in both zone 1 and 4, but even when teaching in zone 4, many of the teachers did not feel satisfied by the possibilities for varied educational methods without worrying about, or annoying or being annoyed by other groups. They wanted their old classrooms back.

5 CONCLUSIONS

Obtaining well-functioning and flexible large open space education areas are challenging. Conflicting requirements with regard to flexible groups sizes and subdivisions of the space, visual openness, technical installations and acoustic privacy often limits their usefulness for lecturing and classroom education. Also, successful implementation of such education spaces relies on both high adaptation of teachers and students, well-planned teaching activity schedules, and a sufficient number of close-proximity supporting areas, such as group rooms and different sized lecture halls or class rooms.

The case study presented show that it is possible to obtain good acoustic shielding between different parts of an open education space without the use of closed rooms, but this requires well-planned acoustic treatment, and ceiling solutions plus location of traffic zones that offer the possibility for tight connections to walls and ceiling.

It has also been demonstrated how the recommendations for room acoustic properties given by SINTEF Byggforsk can be evaluated using sine-sweep based impulse response measurements and software capable of calculating STI values based on simulated noise and speech levels.

The experience made working on the presented case study is that large open education spaces should in general be discouraged, as long as the goal is to obtain flexible teaching facilities also suitable for lecturing or other teaching activities not involving a high degree of coordination between different zones.

6 REFERENCES

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