BNAM 2018
Baltic-Nordic Acoustics Meeting
15-18 April 2018
Harpa, Reykjavík, Iceland

Acoustics of Open-Plan Schools – Master of Science Thesis (2017)

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Finnish national curriculum for primary school is undergoing changes to become more progressive aiming to improve learning process and creativity of pupils. This has encouraged to build open-plan classrooms instead of traditional classrooms. Current issue is though, that there is yet no common national rules or standards to guide acoustic designing or to give instructions about minimum acoustical requirements. This article presents the methods and results of the study briefly. As other Nordic countries have already their own standards and regulations about acoustics of open-plan schools, purpose with this study was to provide the first national information about the subject. Discussion focuses on room acoustic modelling, field measuring and acoustic designing of open-plan schools. Instructors and financiers of the study are presented in the book of abstracts.

1 Introduction

Open-plan ideology in school environments is increasing in Finland. Main reason for this is a new Finnish national curriculum for primary schools, which encourages more progressive ways of teaching; this aims to improve learning process and creativity of pupils [1]. In view of acoustics there is yet no common national rules or standards guiding acoustic designing of open-plan schools or classrooms. This is an exception when compared to other Nordic countries, which all have their own regulations and recommendations already [2]. Purpose of this study was to research current literature about acoustics of open-plan schools and to investigate the current situation of open-plan schools in Finland.

2 Literature research in master thesis

2.1 History of open-plan schools

Open-plan school ideology began to form between 1930 and 1945 in Italy and United States by Maria Montessori and John Dewey, who researched pupil centered pedagogy. During that era in Finland architects Eliel Saarinen and Alvar Aalto designed schools, which had air quality, brightness, learning in out door spaces and easy passing between spaces as designing criterion [3]. Some research papers of there era do point out, that primary school curriculum should base on activity based and experiencing based teaching and the classroom should be seen as a playground rather than a limited space [4].

Open-plan schools become more common after the Second World War especially in United States [3]. In United Kingdom open-plan schools were seen as a solution for economical issues. First open-plan schools in United Kingdom were partly open-plan, where learning spaces were connected with hallways and screens [5, 6]. In 1960 – 1980 one of ten schools in United Kingdom were open-plan schools and in United States every other [6]. At that time movable space dividers such as furniture and screens were recognized [7, 8]. In UK more progressive ways of teaching began to develop. New learning spaces and new teaching methods did not guarantee solid and open information transferring, which may have been caused by poor orientation of teachers or internalize problems of the open-plan ideology [7].

At 1970s and 1980s there was globally a lot of dissatisfaction, which was mainly caused space utilization and acoustics. Because of dissatisfaction partition walls became more common and spaces were transformed into traditional classrooms [7, 9, 10, 8, 11, 12, 13, 14]. The same progress was occurring in Denmark [15, 2, 16]. Acoustic problems focused mainly on high sound levels in open-plan spaces and the lack of sound barriers, which caused free acoustic fields [4, 7, 9, 17, 18, 8, 11, 19, 13, 14]. Since 2002 in United States there has been an intention to limit the construction of open-plan schools because of high background noise levels, which are perceived to have a negative impact on learning process of pupils.

In 21th century open-plan schools have became more common once again. Difference to earlier experiments is the developed acoustical design regulations created specifically for open-plan schools.

2.2 Acoustics of open-plan schools

Main issue in acoustics of open-plan schools is sound decaying. Through decades this has been caused by the lack of space dividers and insufficient amount of sound absorption area [20, 7, 21, 22, 8, 23, 19]. The lack of space dividers and other obstacles have also impact on visual distractibility [6]. Poor sound decaying in open-plan classroom can cause high noise level in space and non-existent acoustical privacy. Acoustical privacy means, that the surrounding noise does not contain original information [7, 22].

Importance of acoustical ceiling was noticed in 1960s but at that time there was issues in accomplishing. Researching about the acoustical issues in open-plan schools began in 1960s and 1970s. In the researches were noticed, that teaching methods do have impact on surrounding noise levels, need of sound absorption materials and space dividers, importance of sound insulation of acoustic screens and space dividers, importance of height of space dividers, possibilities of sound masking system, need for space diversity and the impact of sound source and its directivity [7, 22, 23, 24, 25]. There was also pointed out that location of the open-plan school and sound insulation of façade should be taken in account [7, 26].

2.3 Acoustical Terminology

There has been developed several singulars to describe the information content of sound. These usually take in account sound level and spectrum of the sound source, reverberation time of the space, early decay time of the space, surrounding noise level and its spectrum and sound level and its spectrum at receiving point. One of the oldest singulars is articulation index AI, which was used in 1970s and was created originally in 1950s. In United States there is commonly used singular called Speech Intelligibility Index SII. In Europe and Nordic countries there is commonly used singular called speech transmission index. Value range in SII and STI are the same and they work somewhat the same way, but they do have differences in weighting different values [27, 28]. Because STI was more commonly used in Europe and the current acoustic regulations in Finland include speech intelligibility values in different sections as STI, STI was chosen as a value to present acoustical functionality of open-plan classroom [29].

For STI there is three different values to keep in mind: 0.2, 0,5 and 0,75. The first one stands for the sound intelligibility value of privacy distance, which means the distance, that emitted sound does not transfer anymore information. This can be used as a designing value between two different learning spaces. The second value 0.5 presents a reasoned interface, where values beyond that are considered distracting. The value is used to present the length of distraction radius from the sound source. The last STI value 0.75 presents excellent speech information, which could be used as a designing value inside a learning space [29] as a minimum value; in Iceland and Denmark this value is currently 0,6 [2].

Another measuring parameter that can be examined in open-plan schools is spatial decay of sound. This can be used to evaluate rate of speech decay. Commonly used parameter for this is $D_{2,s}$, which presents spatial decay of sound pressure level per distance doubling [30].

2.4 Voice ergonomics in open-plan schools

The amount of voice ergonomics researches available is rather small. In Finland there is only studies from traditional classrooms. Below a few outcomes of traditional classrooms in Finalnd to be compared with open-plan classrooms in future.

- Voice ergonomics relate either indoor air quality or acoustics – or both [31]
- Insufficient air condition in over 80 % of schools [31]
- Mold problems in over 50 % of schools [31]

- Voice tiring as voice disorder weekly 40 % of teachers [31]
- Noise level in classroom around 69 dB. [32].

In case of new school buildings there may not occur instantly humidity or air conditioning problems but voice disorders and high noise levels and still occur depending on room acoustics and sound insulation.

3 Research methods

3.1 Room acoustic modelling

Room acoustic modelling was used to evaluate and study different space dividers such as screens, curtains and bookshelves. As variables there was height of the space, height of divider, width of divider, sound level of sound masking system and distance to the space divider. Sound insulation of Bookshelf can though vary a lot depending on the load and possible doors. Room models were created in SketchUp and room acoustic calculations were performed in Odeon. In table 1 there is presented used masking sound spectrums and source signal spectrum. Masking sound spectrum itself presents the most neutral and less distracting noise [33]. Signal spectrum presents normal speech spectrum [30].

Table 1: Used masking sound spectrums. Values as decibels.

Frequency band [Hz]	63	125	250	500	1000	2000	4000	8000
$L_{A,eq}$ = 30 dB	42,7	37,7	32,7	27,7	22,7	17,7	12,7	7,7
$L_{A,eq}$ = 40 dB	52,7	47,7	42,7	37,7	32,7	27,7	22,7	17,7
$L_{w,s,\text{ Normal Speech}}$	-	60,9	65,3	69,0	63,0	55,8	49,8	44,5

Side walls of the room acoustic models were modelled 100 % sound absorbing. This how it was possible to analyse only straight sound and reflected waves from floor and roof surface. Absorption values of used materials are presented in table 2.

Table 2: Absorption coefficients of used materials

	Absorption coefficient α per frequency band							
Material	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Floor	0,0	0,0	0,02	0,04	0,09	0,22	0,25	-
Ceiling	0,1	0,5	0,85	0,95	0,85	0,95	0,85	0,9
Curtain	0,05	0,05	0,35	0,85	0,9	0,78	0,85	0,9
Screen	-	0,07	0,29	0,58	0,66	0,63	0,63	-

Used materials were matched good quality already existing materials. Purpose of this was to provide results, that could be used in room acoustic designing as a reference. Screen and curtain had also sound insulating properties, which are presented in table 3.

Table 3: Sound insulation values of the screen and curtain per third octave band

	Sound insulation value R per third octave band							
Low bands	*50*	*63*	*80*	*100*	*125*	*160*	*200*	*250*
Screen	8,0	8,0	8,0	8,0	8,0	8,0	9,9	9,9
Curtain	5,0	5,0	5,0	5,0	5,0	7,5	7,3	6,4
Mid bands	*315*	*400*	*500*	*630*	*800*	*1000*	*1250*	*1600*
Screen	9,9	12,2	12,2	12,2	14,8	14,8	14,8	17,6
Curtain	7,5	8,0	7,7	8,7	10,3	12,5	14,5	16,3
High bands	*2000*	*2500*	*3150*	*4000*	*5000*	*6300*	*8000*	*10000*
Screen	17,6	17,6	20,4	20,4	20,4	20,4	20,4	20,4
Curtain	19,0	22,4	24,0	26,0	26,0	26,0	26,0	26,0

Screens and curtains were placed room wide middle of the modelling space to eliminate side diffractions. With curtains there was also circle shaped bases, which modelled learning spaces. With this kind of models there were two learning spaces with two different radiuses – three and six meters. Distance between learning spaces varied between 0,1 m and 6,0 m. Shape of the room acoustic model and the different modelling situations presented in figure 1.

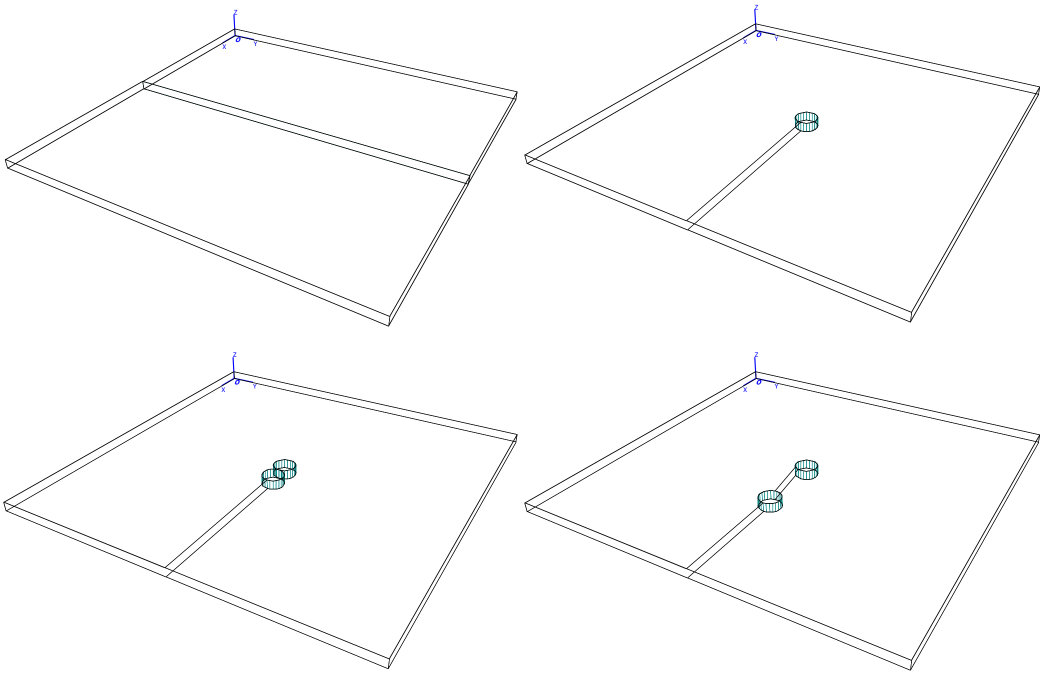

Figure 1: Shape of used room acoustic model and different modelling situations

3.2 Field measurements

To evaluate the current stand of Finnish open-plan schools there was performed room acoustic measurements to three different newly built open-plan school. Selected learning spaces were fully open-plan and their floor area varied from 177 m^2 to 230 m^2. Room heights varied form 2,5 m to 3,1 m. Every learning space had acoustical ceiling. One of these four spaces included movable walls and three of these included sound absorption curtains. One of four spaces included fully covered floor area of pile carpet. Example photo of a learning space is presented in figure 2. Age of the pupils in these four learning spaces varied from eight to twelve.

Figure 2: Preview from learning space number one. This learning space included movable walls.

Field measurements were carried out following room acoustic measurement standard of open-plan offices (ISO 3382-3). Measuring method was though applied a bit in way, that it was possible to get meaningful results between two different learning areas. Learning area in this context means an individual learning unit inside the learning space. As measuring gear there was omnidirectional loud speaker, signal generator, microphone with preamplifier, calibrator and sound analyser. Distances between measurement points per measurement lines were measured with a laser distance meter. Example distances between measurement points are presented in table 4. Corresponding graphical presentation for those lines is in figure 3. Expression LX in table 4 means measurement line x and MPX means measurement point x on current measurement line. Distances are presented in meters.

Table 4: Example distances between measurement points on measurement lines. Distances in meters.

	MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8
L3	2,0	3,0	3,7	6,5	10,0	12,4	13,8	15,0
L2	2,0	6,7	-	-	-	-	-	-
L3	2,0	4,0	6,5	8,0	9,0	12,0	14,4	-
L4	3,5	4,0	6,2	7,0		-	-	-
L5	2,0	3,3	4,0	5,8	-	-	-	-

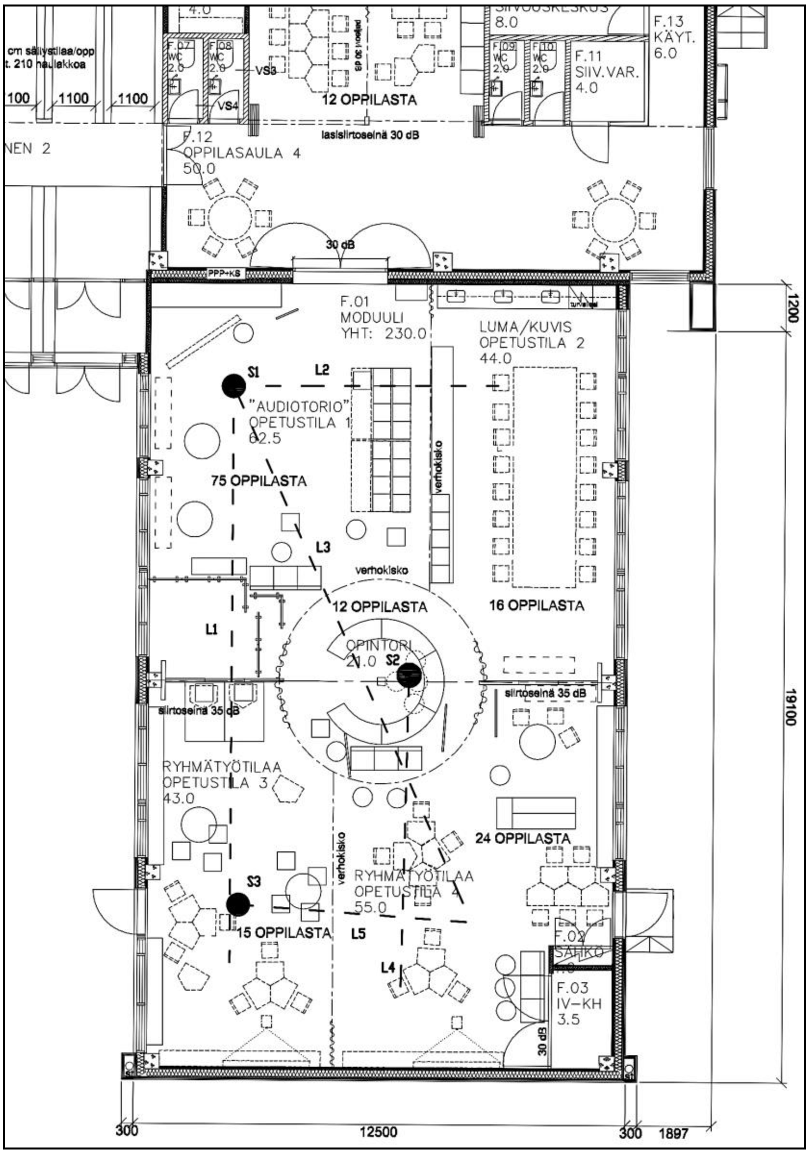

Figure 3: Example of measurement lines from learning space number one

3.3 Survey to teachers

Web based survey was formed for teachers, who were teaching in field measured open-plan schools. The survey consisted of five different sections, which were:

- Transition to open-plan school
- Open-plan school in view of teaching
- Voice ergonomics of teachers in previous and current teaching environment
- Learning process of pupils in view of teachers
- Improvement suggestions for open-plan learning spaces.

In part one (transition) teachers were asked if they had previous experience about open-plan teaching environments. They were also asked if they were orientated to their new teaching environments or if they had planned any methods or rules how to use their new teaching environments.

In part two teachers were asked do they find open-plan learning environments improving learning experience of pupils. They were also asked if they had noticed any chances in sound environment between their previous teaching environment and present teaching environment. Finally, they were asked to evaluate how far can they hear their co-teachers voice clearly.

Part three was a section about voice ergonomics and it was presented on general level including questions for example did teachers have any voice disorders in their previous teaching environment or in present teaching environment.

In part four teachers were asked how well they think their pupils perform in open-plan learning environment. They were also asked how they think different individual factors such as low noise level or freedom in space usage affecting on their pupils.

In part five teachers were asked that how do their new learning environments perform in view of their prejudices. They were also asked that how they would improve their new learning environments if there is something to improve.

4 Results

4.1 Room acoustic modelling

One of the key results of the room acoustic modelling was, that sound masking of $L_{A,eq}$ = 40 dB is highly recommendable for open-plan classrooms. The second key result was, that increasing room height shortens privacy distance, which is of course logical. Different room height and space divider height combinations did though behave unexpectable for example results with divider height of 2,0 m and room height of 2,5 m were steadier than with divider height of 2,5 m and room height of 4,5 m. Example of this behavior in figure 4. Bolded lines present curtains and white ball sound source position. Height of the sound source and curtains in figure 4 are only for visualizing. Real scale heights are presented in figure 5.

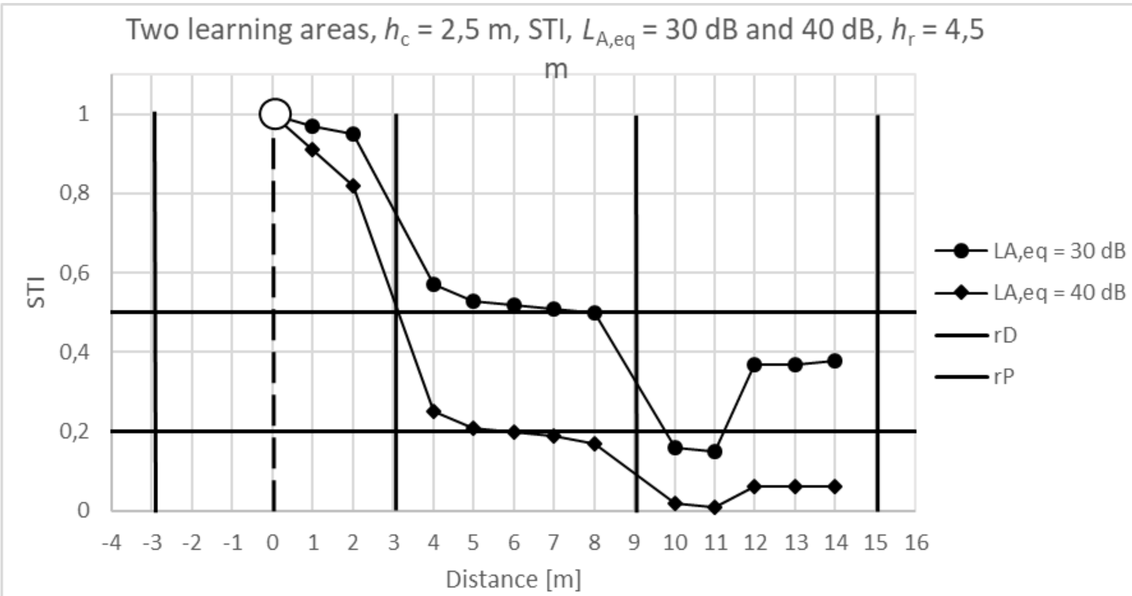

Figure 4: Nonlinear STI progression between two learning areas

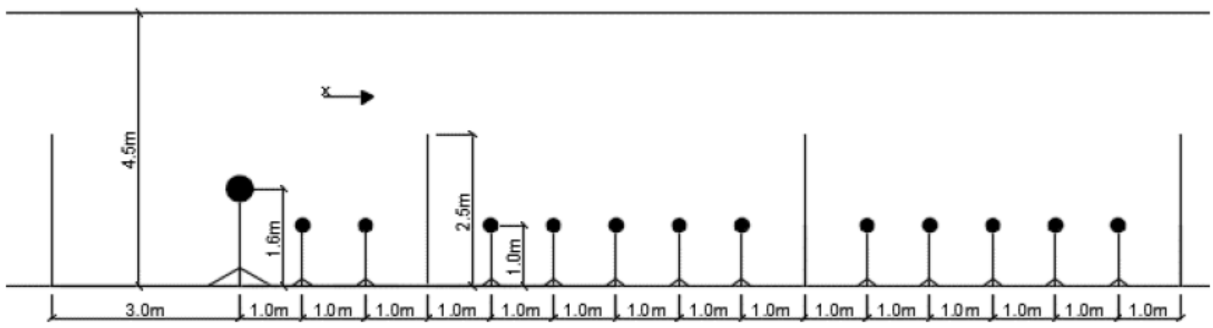

Figure 5: Real scale heights of results in figure 4

With screen height of 1,7 m (source height 1,6 m, receiver height 1,0 m), room height of 3,5 m and masking sound level of $L_{A,eq}$ = 40 dB, privacy distance was reached 8,0 m behind the screen (r_D = 9,0 m) when source position locates 1,0 m another side of the screen. If source position distance to the screen is 3,0 m, privacy distance will be reached at 6,0 m other side of the screen (r_P = 9,0 m). If screen height is 2,0 m, privacy distances for the same situations will be 6,0 m (r_P = 7,0 m) and 5,0 m (r_P = 8,0 m). Screens lower than source height do not have much effect.

With one layer of curtain, if curtain height is 2,5 m, masking sound level $L_{A,eq}$ = 40 dB and room height 3,5 m, if source position is 1,0 m behind the curtain will privacy distance be reached at 4,0 m other side of the curtain (r_P = 5,0 m).

With two curtain surrounded learning areas, when curtain height is 2,5 m, room height is 3,5, masking sound level is $L_{A,eq}$ = 40 dB, radius of one area is 3,0 m and loud speaker is in the center of the first learning area, privacy radius r_P will be around 3,9 m. This means, that another layer will lower privacy radius only 1,1 m.

4.2 Field measurements

Open-plan learning space number 1 yielded shortest privacy radius results of the four measured learning spaces; with curtains closed and with calculated masking sound level of $L_{A,eq}$ = 40 dB privacy distance was 10,6 m for L1, 7,6 m for L2, 10,8 m for L3, 14,9 m for L4 and 9,9 m for L5, when there were also movable walls as a partial obstacle. Line number two though has only two measuring points, which is too little according to ISO 3382-3. Reverberation time in every learning space was below 0,5 s. Speech intelligibility in learning area was above STI = 0,6 in every learning space. Speech intelligibility in the most of learning areas were though above STI = 0,7. Privacy radius in other learning spaces was between 10,1 m and 20,2 m. Generally, there seems to be enough absorption materials in open-plan learning space to provide good sound intelligibility in learning area but there is yet not enough space dividers such as sound insulating curtains or acoustic screens to provide acoustic privacy between different learning groups and areas. None of the measured open-plan learning spaces included sound masking system. Original privacy radius values with original back ground noise levels (between 25 dB and 35 dB) were far too long for every space (11,8 m – 48,6 m).

4.3 Survey to teachers

Only 16 teachers answered to the survey and therefore the results are not comprehensive. Though it is possible to form a limited conclusion.

In general teachers were satisfied with their new teaching environments. Teachers had though recognized elements insufficient acoustic privacy and as improving points many of them had more space dividers or more silent areas for concentration requiring tasks. 26,7 % of teachers had some kind of voice disorder in their previous teaching environment. On 26,7 % of teachers voice disorders has decreased in the new teaching environment.

5 Discussion and summary

According to literature research, open-plan school as a term seems to be as much an ideology as a physical building. Ideology behind open-plan schools is nearly 90 years old, though it had developed during the decades. Within the term of open-plan school information transferring and communication is desired to be open, movement is wanted to be free and progressive teaching meant to be more effective than traditional teaching. To support these points school buildings have become more open, where open-plan teaching and learning have been chosen as ideology. Partition walls have been replaced by open space or screens and another lighter dividing structures. Around 1970s some open-plan schools and classrooms were transformed back to traditional schools and classrooms with partition walls. Main issues back then were high noise levels in open-plan classrooms and lack of acoustical privacy. At 21th century there is once again a movement towards open-plan ideology. As a difference, countries such as United Kingdom and Nordic countries except Finland have now different acoustical regulations specifically designed for open-plan schools to reduce the original acoustical problems. Purpose of the study for master thesis was to examine already existing solutions for open-plan schools, inspect the current state of open-plan schools in Finland and to be the first step on acoustic surveys of open-plan schools in Finland.

So, what would be good parameters to guide designing acoustics in open-plan schools? Based on literature research, field measures and the survey - speech transmission index, reverberation time and spatial decay of sound level. STI values contain information about sound source's sound level, general noise level and reverberation time. STI value 0,2 is probably enough good criteria between two different learning spaces as far as the value itself presents noise without information content. Minimum criteria for STI inside a learning space could be somewhere between 0,6 and 0,8; some studies point out that young children require higher speech intelligibility value for understanding that older children. Minimum STI criteria could therefore be scaling linearly starting from 0,8 and lowering to 0,6, where 0,8 would be for children at the age of seven and 0,6 children at age of fifteen. STI value 0,8 refers also to the top class designing criteria for traditional classrooms in Finland. Good STI values require short reverberation time below 0,5 s or 0,4 s, which will probably require fully acoustical ceiling and extra absorption as curtains and furniture. This will though require more researches on subject to evaluate the exact values.

Privacy radius and distraction radius can prove themselves useful in acoustic designing. They do not have only information of wanted speech intelligibility value but also the distance where that will be reached. Especially privacy radius can be a useful tool when evaluating screens and such between two different learning areas within one larger open-plan classroom. Distraction radius and therefore speech intelligibility value 0,5 does not seem to have much usage in open-plan classrooms because the idea is to lose information content of speech. Thought it could be used as criteria between group working stations which do not generate confidential information.

Sound masking system proved to be an efficient way to shorten acoustical privacy radius. $L_{A,eq}$ = 40 dB with the least distraction spectrum was the more efficient than $L_{A,eq}$ = 30 dB one; spectrums presented in table 1. This would mean that more gained sound masking with this particular spectrum provides shorter privacy distances. $L_{A,eq}$ = 40 dB maybe still safe to use in schools, but higher level sound masking may need some voice ergonomics researches mainly because of long term stress to hearing. Another occurring event above $L_{A,eq}$ = 40 dB will be Lombard's effect, which encourages voice usage by five decibel for every ten decibel raise in noise level [32].

Acoustics of a large open-plan school area which has different designed activities at the same time, may be wise to design computer assisted. If there is be gaps between walls and dividing structures or ceiling and dividing structures, sound decaying can get unpredictable with larger distances. This was a minor found in the room acoustic modelling part of this study. Self-standing separating structures such as screens and bookshelves are easy to move and are therefore usable in open-plan schools. To prevent unpredictable sound decaying with low height separating structures, it could be possible to hang lids from ceiling where needed. Those lids should though have at least sound insulating properties.

If acoustic designing bases on room acoustic modelling the height of source position and height of receiving points do matter. If open-plan space would include only sitting activities and teaching from sitting position, it might not be necessary to design 2,0 m high separating structures. In this study though the main situation was to evaluate situation, where teacher is teaching standing and pupils are sitting on their benches; evaluated source position height was 1,6 m and receiving point height 1,0 m. For older pupils it may be wise to set receiving height to 1,1 m or 1,2 m. Modelling spectrum for sound source was selected optimistically as normal speech. In real open-plan space room acoustic modelling it may be though wise to at least check the results also with raised voice spectrum, which can simulate some situations more accurate.

Base guide line of open-plan office measurement standard ISO 3382-3 proved to be useful with clearly separated learning areas. Precisely reported measurement points provide an easy access to remeasuring. Precisely reported measurement points and therefore the measurement results are also easy to compare with a room acoustic model. If the open-plan space is large and includes great diversity in activities and learning areas, it may get challenging to evaluate the most critical lines to measure.

To improve the chance of successful acoustics and space usage in open-plan classroom, it is necessary to orientate teachers to their new teaching space. Though this is not purely acoustics, it will have an impact to outcome. If teachers internalize open-plan methods, they will be able to get the most of the designed room acoustics and in other hand, designed room acoustics will support them the most. A successful outcome may though require cooperation between teachers, principal, architect, acousticians, structure engineers and other specialised designers at the early stages of the construction process while compromises will be reality with this kind of spaces.

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