

FROM MEASUREMENTS, THROUGH COMPUTER MODELLING, DESIGN AND CONSTRUCTION, BACK TO MEASUREMENTS: ACOUSTICAL MODERNIZATION OF 800 PUPILS PRIMARY SCHOOL IN WARSAW, POLAND

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This paper discusses the design, realisation and acoustical performance of the newly modernised (2018) primary school SP340 at Lokajskiego street (classes' I-VI) located in Warsaw, Poland. Four types of rooms are discussed: classrooms, corridors, canteen and a sports hall. Pre-modernisation acoustical measurements showed long reverberation times, high sound pressure levels and low speech intelligibility in all rooms, which confirmed complains from teachers, parents and pupils and resulted in a decision to retrofit sound absorbing elements in all rooms just 5 years after the school was commissioned (2012). Due to restrictions in possible reduction of classrooms height and area of retrofitted materials, acoustical and architectural designs were focused on minimising the thickness and required area of newly installed sound absorbing materials, while still achieving the required reverberation time ($RT \leq 0,6$ s.) and Speech Transmission Index ($STI \geq 0,6$). Use of measurements for proper calibration of computer models are described, followed by the acoustical performance and subjective evaluation of the finished rooms. Aspects deserving special mentioning were: the possible use of materials only on walls in sports hall; negative effect of parallel smooth painted walls in acoustically damped corridors causing flutter echoes; the effect of low thickness of sound absorbing material on it's performance in low frequencies; construction details of interior materials and technical installations.

Keywords: reverberation time, speech transmission index, speech intelligibility, classroom acoustics, noise reduction

1. Introduction

In July 2012 a new primary school SP340 complex was constructed at Lokajskiego street in Warsaw, Poland. This three levels building, with usage area of 8200 m², included 29 classrooms, 4 common rooms for Grade I-III, 4 language rooms, 4 corridors at each level, a canteen, an auditorium and a large gym (44x24x11m). School was planned for 800 pupils, but finally almost 1200 pupils study here. After school opening parents and teachers started to report problems with excessive noise and lack of speech intelligibility [1,2,3]. Acoustical measurements [4,5] confirmed those findings. Five

years after school opening, City of Warsaw decided to perform an acoustical modernization of all rooms. Author was the General Designer of that project.

2. Aim, scope and constrains of the design

The main aim of the design was to achieve in all rooms the acoustical requirements of new Polish Standard PN-B 02151-4:2015 [6] introduced in 2015, which become obligatory for all new buildings from January 2018. The Standard specifies either maximum allowable reverberation times or minimum required equivalent sound absorption area. Additionally, for rooms for speech (classrooms, auditoriums, lecture rooms, etc), the standard specifies also a minimum required Speech Transmission Index (STI). Required values depend on room type (ie. classrooms, canteens, gyms, sports halls, swimming pools, corridors, offices, museums, etc), room volume or height. Standard requirements are mostly referring to typically furnished rooms without presence of people. Typical classroom, with volume between 120-250 m³ should have an average reverberation time below 0,6 seconds (250-8000Hz) and below 0,78 seconds (125Hz) when measured according to ISO 3382 part 1 or 2 [7,8], and average speech transmission index STI above 0,6 (with minimum value above 0,55) when measured with artificial mouth [9] with realistic background noise level (typically 35dBA) according to EN ISO 60286-16 [10].

The design process of acoustical modernization was including both pre- and post-completion acoustical measurements, detailed interior design of all acoustical (mostly sound absorbing) elements, electrical design for repositioning of electrical installations (mostly lamps), structural, fire and sanitary approvals, as well as cost estimate and detailed materials specification.

The following constrains applied by the user, local sanitary regulations and structural engineers impacted greatly the design process:

- Total cost of acoustical adaptation works was limited to 200,000 euro (+VAT), implying the use of low cost sound absorbing materials, limiting their area and wastes to a possible minimum;
- The height of all existing classrooms (3,0m) could not be further decreased so it was not possible to use traditional sound absorbing suspended ceilings;
- The use of sound absorbing materials in classrooms was limited by official sanitary and epidemiologic control to max. 40~50% of ceiling with the aim to use as thin layer of sound absorbing material on ceiling as practically possible
- A maximum possible number of existing lamps should not be relocated, so the cost of electrical works can be minimized;
- In sports hall, finishing materials could be fixed only to walls (roof was not strong enough from structural point of view);
- In most rooms and corridors, finishing materials could be fixed to walls only above 2m over floor level, allowing to use existing furniture's and hard wall surfaces for hanging educational materials;

Due to constrains listed above, it was agreed with the school management, that exact fulfilment of reverberation time in all rooms should not be treated as mandatory, but rather as a design goal.

3. Method

The combined process of architectural and acoustical design was started with detailed inventory of room interiors, including furniture's. Rooms were divided into groups with comparable size, function and finishing materials. Then acoustical measurements were performed. Impulse responses were recorded in all rooms with balloon and pistol shots, and basic ISO 3382 parameters were calculated (mainly T₂₀/T₃₀/EDT) using Dirac (v.6) software [11]. Additionally, STI was measured in selected rooms for speech using NRC SPMSOft [12]. Then 1-2 rooms from each group were modelled in Odeon

(v14) software [12]. For each room model a calibration procedure was implemented, to match measured reverberation time and STI to ones simulated in the models. Then absorbing materials were added to models. Type, location and area of sound absorbing materials were minimized in that way, that requirements for reverberation time were fulfilled with minimum safety margins. In rooms for speech fulfilments of requirements for STI were also verified in the computer models. Examples of Odeon room models are shown on Fig.1.

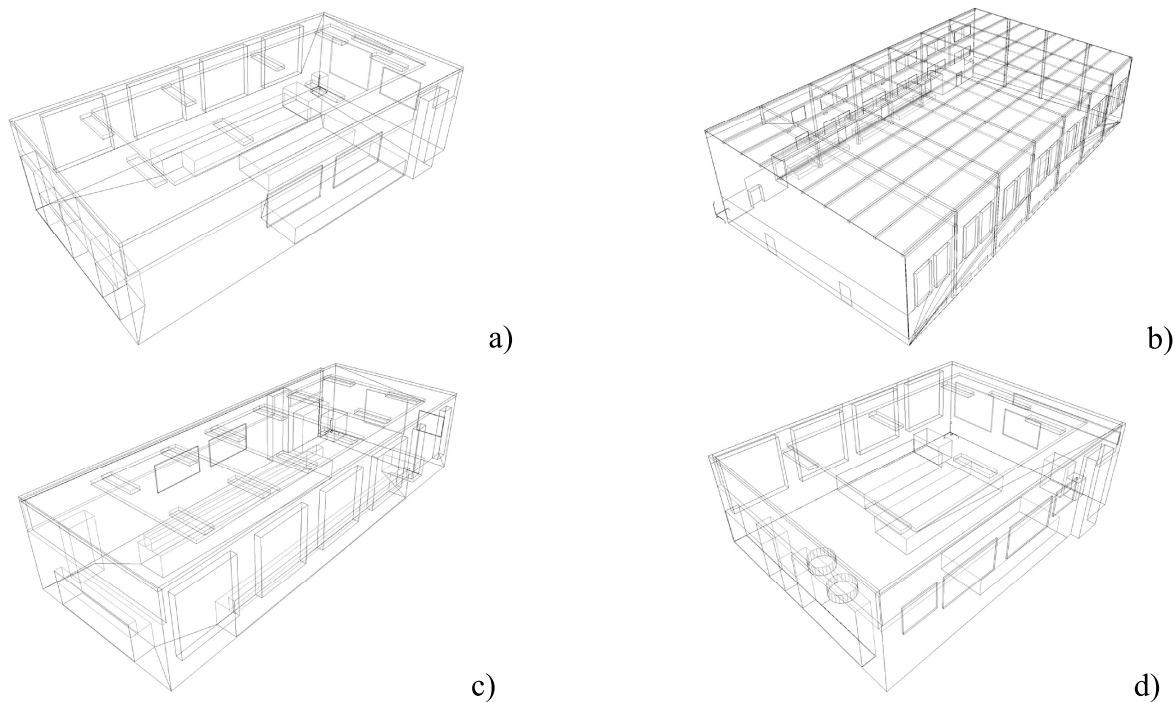


Figure 1: Acoustical Odeon scale models for selected rooms: polish language room no. 116 (a); sports hall no. 68 (b); computer room no. 215 (c); primary education classroom Grades 1-3 no. 137 (d) (room size on figure do not reflect real differences in sizes between rooms).

Based on Odeon simulation final architectural design was formulated for all room types.

4. Design and results

In Classrooms with room height limited to 3,0m, to fulfil the Polish Standard requirements ($RT_{250-8kHz} \leq 0,6$ / $RT_{125Hz} \leq 0,78$ and $STI \geq 0,6$) as a general rule, the sound absorbing material was placed on outer parts of ceiling, covering from 45-50% of total ceiling area, leaving inner ceiling area finished with lime-cement plaster (fully reflecting). Additionally, a 1m high strip of sound absorbing material was placed on back wall and on wall opposite to windows, so the whole wall area from floor level up to 2m above was fully available for users. In all classrooms the total area covered with sound absorbing material (on ceiling, and upper part of 2 walls) was only 66~73% of room floor area. As reverberation time requirements in Polish Standard includes octave frequency bands of 125Hz and 250Hz, the sound absorbing material had to offer some absorption also at those frequencies. To achieve that, and at the same time to minimize the material thickness, 100mm mineral wool sound absorbers were used both on ceiling and on walls. When commercially available product was only available with smaller thickness (i.e. 40mm), an additional layer of mineral wool (i.e. 60mm) with similar density as commercial product was placed behind. Those design principles were typically enough to reduce reverberation time from typically ~2,0 seconds before modernization down to 0,6 seconds at 125Hz up in all classrooms. Speech intelligibility in classrooms was also greatly improved, with Speech

Transmission Index being typically 0,45~0,50 before modernization up to at least 0,7 after modernization. Typical 3,0 m high classroom, with floor area of 64,4 m², before and after acoustical modernization and as Odeon room model is shown on Fig.2.

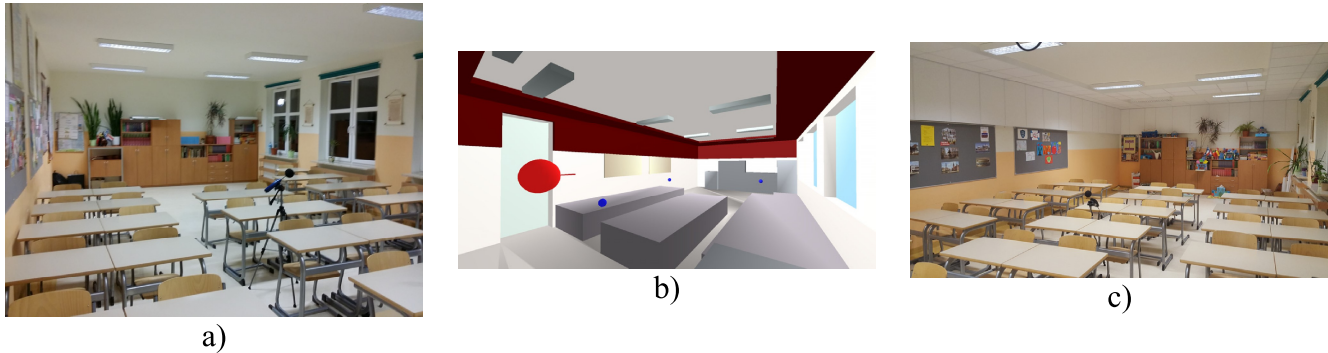


Figure 2: Typical classroom (N°116): before modernization (a), as Odeon model (b) after modernization (c).

In common rooms with room height of 3,3m, to fulfil the Polish Standard requirements ($RT_{250-4kHz} \leq 0,6$) as a general rule, the sound absorbing material was placed on the whole ceiling. Additionally, similarly as in the classrooms, a 1m high strip of sound absorbing material was placed on back wall and on wall opposite to windows. In all common rooms the total area covered with sound absorbing material (on ceiling, and upper part of 2 walls) was 122% of room floor area. To achieve efficient sound absorption from at least 250Hz, 15mm thick ceiling mineral tiles were suspended 200mm below structural floor. At the same time thickness of absorbing material on wall were reduced, compared to classrooms, to only 40mm mineral wool. Those design principle were typically enough to reduce reverberation time from typically ~1,5 seconds before modernization, down to 0,4 seconds at 500Hz up, and down to 0,5 seconds at 250Hz in all common rooms. It is worth mentioning, that post-modernization reverberation time at 125Hz in common rooms ($RT_{125Hz, common rooms} \sim 0,75sec$), is much higher than in classrooms ($RT_{125Hz, classrooms} \sim 0,55sec$), possibly due to 100mm thick sound absorbers being more efficient than a combination of 200mm suspended 15mm boards and 40mm wall absorbers. A slightly larger room volume and smaller number of pupils tables/desks could influence that also, but measurements of pre-modernization reverberation time were actually higher in classrooms then in common rooms, which contradicts that. Typical 3,3 m high common room, with floor area of 65 m², before and after acoustical modernization and as Odeon room model is shown on Fig.3.

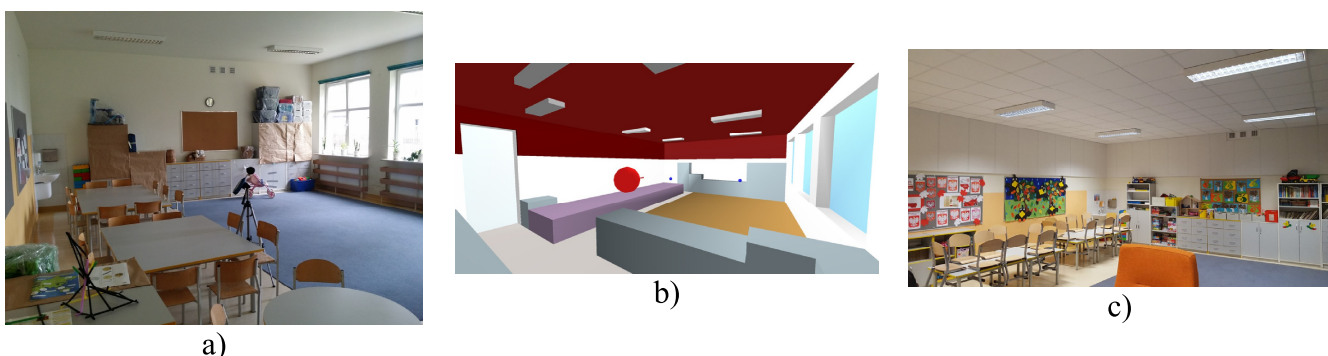


Figure 3: Typical common room (N°41): before modernization (a), as Odeon model (b) after modernization (c).

In Gym with room height of 9,5~11,0m, to fulfil the Polish Standard requirements ($RT_{250-4kHz} \leq 1,8s$), the sound absorbing material was placed only on all four walls, as the loading capability of the roof was too weak to place additional materials there. Fortunately, this was possible, as the Gym roof was sloping in one direction, eliminating the typical risk of flutter echo between acoustically hard floor

and parallel hard ceiling. To achieve efficient sound absorption from at least 250Hz, materials covering walls above 2,5m level were constructed as 40mm mineral wool sound absorbers with impact resistant glass woven surface, placed on top of medium density mineral wool, with air flow resistance not higher than $10 \text{ kPa} \cdot \text{s/m}^2$. This assured that sound absorption coefficient at low frequencies will be relatively high. Sound absorbing materials on walls below 2,5m level were only 40mm thick, as impact resistance was here more important than in upper parts of walls. A small area of 40mm thick mineral wool panels were also fixed to ceiling over audience niche on one of longer walls. Those design principles allowed to reduce reverberation time from more than 6,0 seconds down to 1,75 seconds at 250Hz up, and achieve an decent 1,88 seconds also at 125Hz band. A Gym, with floor area of 1068 m^2 , before and after acoustical modernization and as Odeon room model is shown on Fig.4.

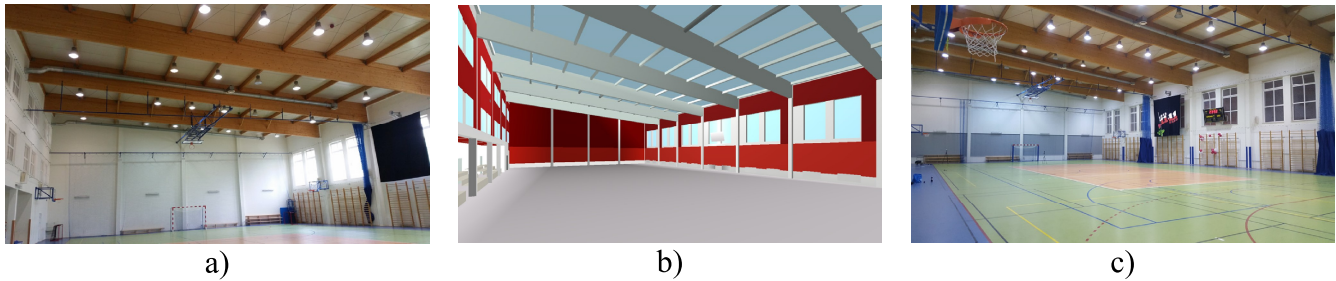


Figure 4: Gym (N°68): before modernization (a), as Odeon model (b) after modernization (c).

In Corridors with height of 3,0m, to fulfil the Polish Standard requirements (equivalent absorption area A at 500-2kHz $\geq 1 \text{ m}^2$ of A per each 1 m^2 of floor area, calculated based on declared sound absorption coefficients), the sound absorbing material was placed on almost the whole ceiling and in upper part of walls, where it was practically possible. To achieve a required equivalent absorption area, 15mm thick mineral wool tile was suspended 200mm from soffit, and additionally walls above 2,5m level were covered with 40mm mineral wool sound absorbers. Those design principles allowed to reduce Early Decay Time in corridors from more than 2,5 seconds down to 0,50 seconds at mid frequencies. Typical noise level in corridors before modernization was measured at $L_{Aeq}=88\text{dB}$. This was greatly reduced after modernization. A Corridor 1A, with floor area of 216 m^2 , before and after acoustical modernization and as detailed design drawing is shown on Fig.5. In this corridor 202 m^2 of sound absorbing material was installed on ceiling, and 28 m^2 on walls.

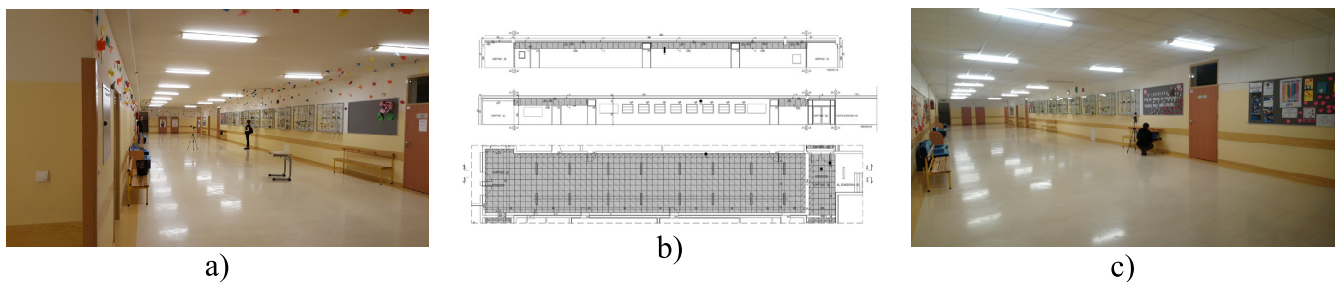


Figure 5: Typical corridors: before modernization (a), design (b) after modernization (c).

5. Comparison of pre- and post-modernization measurements

A comparison of Reverberation Time (T_{30}) before and after acoustical modernization in three types of rooms (6x Common rooms with height of 3,3m, 7x Classrooms with height of 3,0m and a Gym) is shown on Fig.5. It is clearly visible, that thicker sound absorption materials mounted directly (100/100mm) are more efficient in reducing of reverberation time in low frequencies, then thinner ones

with larger mounting depth (15/200mm). It can be also seen, that placement of materials on three main room directions resulted in quite low standard deviation in acoustically modernized rooms.

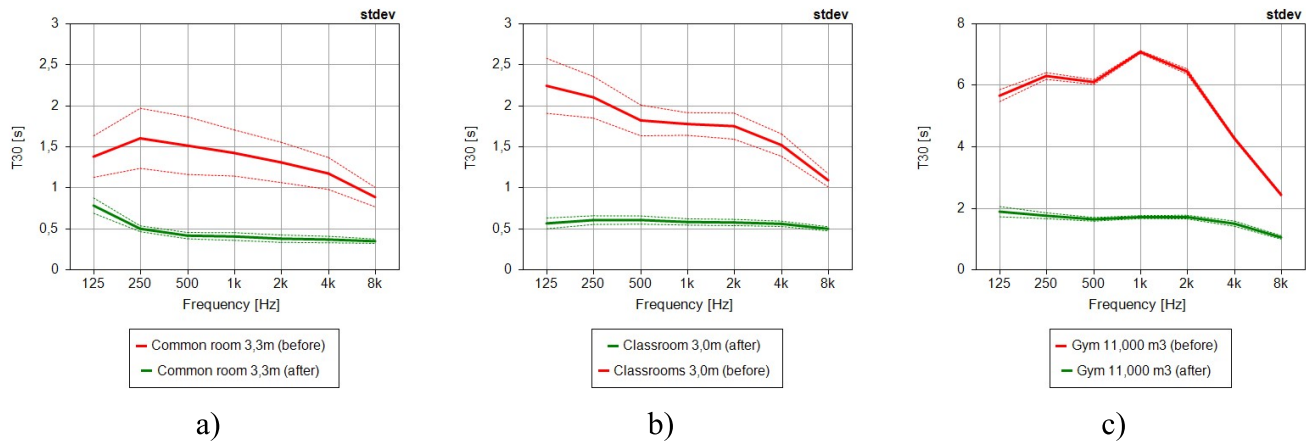


Figure 6: Comparison of Reverberation Time T_{30} before (red) and after (green) acoustical modernization for 6x Common rooms 3,3m high (a), 7x Classrooms 3,0m high (b); Gym (c). (Solid line – room average, dashed lines – Standard Deviation)

The influence of placement of sound absorbing material in corridors is shown on Fig.6. Reduction in A-Weighted Sound Pressure Level was measured before and after acoustical modernization in one of the corridors. It is clearly visible, that reduction of SPL(A) with distance is much larger after modernization, stabilizing at approx. 8-9dB(A) at 20m from source. However, due to very weak diffusion on lower part of corridor walls, in empty corridors a weak flutter echo can be heard. This flutter echo also makes results of T_{20}/T_{30} measurements longer then EDT. A better solution for corridors from purely acoustical point of view, seems to be to cover (additionally to the ceiling) one long and one short wall with impact resistant sound absorbing material. Then two other walls can be left hard and reflecting. But it is unlikely, that users will easily accept such a solution.

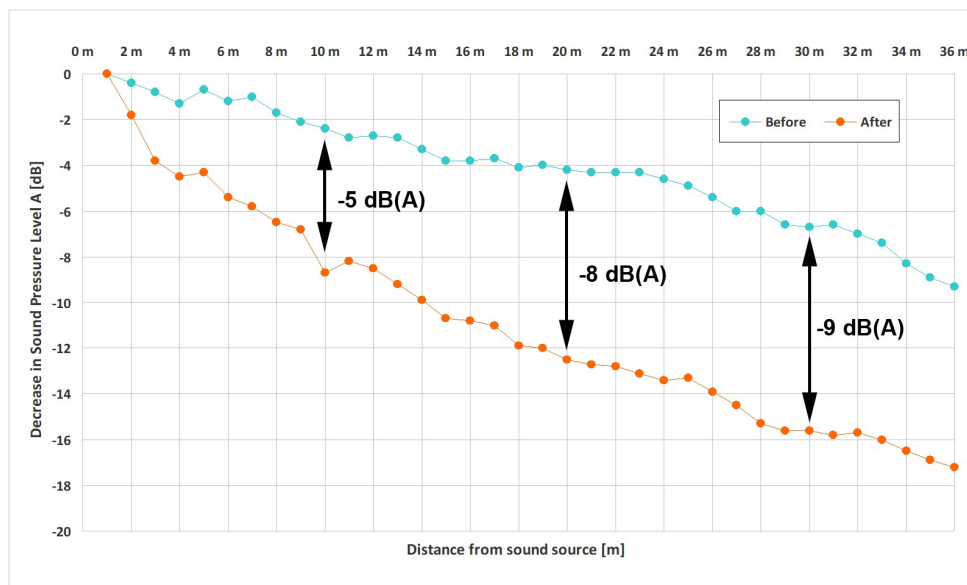


Figure 7: Decrease of A-Weighted Sound Pressure Level with distance from sound source, before (blue) and after (red) acoustical modernization for typical corridor.

6. Summary

Both the school management, teachers and pupils are happy with the acoustics of the SP340 primary school after it's acoustical modernization. Teachers mention large reduction in noise at corridors during breaks and at Gym, much improved speech intelligibility in classrooms and also in Gym. Pupils are also recognizing the change in noise levels, and describe it as "rooms are quieter now". Besides this positive feedback, the authors experienced the following: 1) in typical classrooms with normal furnishing achieving of reverberation time as low as 0,6 seconds even at low frequencies (125-250Hz) can be made with careful placement of limited areas of sound absorption on outer part of ceilings and on upper part of walls; 2) in large Gyms, if it is possible not to place any sound absorption on ceiling, almost all remaining walls have to be covered with thick porous absorbers to achieve reverberation time below 1,8s; 3) calibration of acoustical calculation models with RT measured in existing rooms is crucial for minimizing errors in predictions; 4) reduction of reverberation time in low frequencies (125-250Hz) can be achieved with 100mm thick mineral wool absorbers placed directly on walls, and 5) in rooms with absorption concentrated in upper part of room height, reflecting parallel surfaces located in lower part of rooms can create audible flatter echoes when rooms are empty.

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