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Early Design Criteria for Small Multipurpose Cultural Houses

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The article discusses early design criteria for typical multipurpose halls for music in light of measured data from a series of Norwegian cultural venues. Acoustical design guidelines given by The Council for Music Organizations in Norway (CMON) are under revision. Unfortunately, proper acoustical measurements of halls in cultural venues are rare. The necessary feedback for control of these requirements, as well as the results, has thus been somewhat limited. There is need for a proper verification of the recommendations given by CMON and we should share data in a common effort to do so. Basic early basic design criteria are related to the type of cultural events the venue should house, how many seats are wanted and what dimensions and volume is needed to be able to fulfill good acoustical conditions for the purpose of the venue. Data on room and stage volumes, ceiling heights, number of seats, reverberation times and background absorption areas are assessed up against CMON's design criteria as well as those given in NBI Håndbok 20 and Beraneks classic book on concert halls. We suggest recommendations for early design criteria based on our measurements and experiences from about 20 cultural venues around in Norway.

1 Introduction

Most Norwegian acousticians are familiar with Svein Strøms well written "NBI Anvisning 20" with its checklist for projecting acoustics for rooms of different use, advice for achieving acceptable acoustics as well as an extensive collection of laboratory measured absorption data [1]. Early design criteria for Norwegian halls for music, dance and speech, is probably based on the simple rules of thumb, like volume per seat and sizes, mainly from that publication. A set of guidelines and basic acoustical understanding are also available in the SINTEF Byggforsk knowledge series written by J.H. Rindel [2, 3]. The rules of thumb and requirements here are basically congruent with those given in NBI Handbook 20.

The *Council for Musical Organizations in Norway* (CMON) has about 140000 members direct or through 33 democratic member organisations. They have local councils in some 150 communities [4]. CMON represent both the volunteer and professional music life, e.g. they have the main music labour union (MFO) and the Network of Cultural Houses as members. CMON has recently revised and published their acoustical recommendations for halls for music [5]. Until 2010 CMON served as a body entitled to comment for the Ministry of Culture in affairs regarding regional cultural houses. From 2010 the distribution of governmental financial support (typically some 30%) for building and running regional cultural houses, as well as any "process control routines" at will, has been delegated to the County Councils [6]. The support is financed through governmental lotteries.

2 Theory

We are able to assess the acoustics of halls based on semi empirical theories like the works by Barron using his *revised theory* for the room acoustical parameters based on the volume and reverberation times [22]. Anders C Gade made simple regression formulae for the room acoustic parameters based on room dimensions and other features in his extensive measurement experiences from concert halls in Denmark and internationally [7, 8, 11].

However, usually the early design phase is done based on the key numbers as given in NBI 20 and former experience. Often the last two or three projects become the basis for the next, only extending what could be improved from the last if the cooperation with the architect and contractor works well and have the sufficient finance to back this up.

Sabines semi-empirical formula RT = 0.163*V/A is helpful in the early assessments as well as the diffuse field strength formula G (10m) = 10*log(RT/V)+ 45 dB (-2dB for empirical correction) can be useful. Gades semiempirical formula on the stage support: $ST_{Early} \approx - 7.65*\log(V_{Stage}) + 12$ dB is useful for assessments of the loudness at the stage.

When the initial phase of discussions on the volume and placement of rooms has been done and the physical limits and gross designs more or less are fixed, the project is left over to the room acoustical calculations using a ray tracing software like Odeon. The basic acoustic properties of the halls are probably already largely determined at that stage.

If we are lucky, we may be able to have an influence on the chosen seats and Stage textiles and that we get the concrete surfaces covered with something useful acoustically. Often variable absorption is included in the projects.

Can we get some information from our measurements that can be useful in this process?

3 Method

Our room acoustical measurements was conducted according to ISO 3382 using source and receiver position following the concept used by Anders C. Gade in his studies of about 25 Danish- and 11 international concert halls [7,8]. Three source and receiver positions on the stage, three or four up to 10 receiver position in the halls are used. Typically nine to 12 impulse responses are measured for the hall and nine at the stage plus the tree stage support measurements 1m from each source position (S1-S3) at the stage. We also usually measure the sound engineers position.

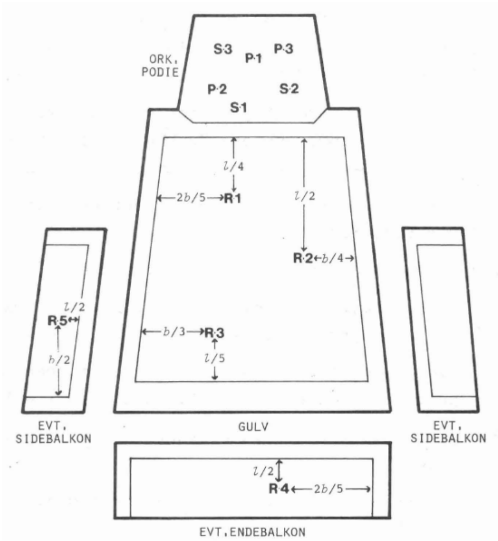

Figure 1: Source (S1-S3) and receiver positions (R1-R5) and P1-P3 at the stage, from Gade [7].

Averages of the measured room acoustical parameters: Reverberation time, T30 [s], Early decay time, EDT [s], Clarity, C_{80} [dB], Sound strength, G [dB] and Early Stage support value, ST_{Early} [dB] has been extracted from the measurement sets. Late strength G_{Late} [dB] has been calculated assumed to be based on Barrons Revised Theory or based on measured $C_{80,\ 3B}$ [dB] and G_M [dB] values, if they have been available. The formulas included in the spreadsheets from Jens Jørgen Dammeruds PhD homepage has been used [9]. Background noise levels have been omitted in this study.

The basic idea has been to compare our measurements to data from the study conducted by Hidaka and Nishihara on European and contemporary Japanese chamber music concert halls [10]. Their seat number and volume compare to our typical multipurpose halls and a reference to available information in the literature is useful.

3.1 The measurement instrumentation

Instrumentation has been WinMLS 2000 using the MLS technique and after 2007 the 2004 version, using sine sweeps. A Digigram VX pocket PCMCIA soundcard in a laptaop computer, a B&K "studio" condenser microphone as well as a LAB 300 amplifier with an omnidirectional loudspeaker is the measurement system. There are a battery powered phantom supply and a home made microphone amplifier in the set. The measurement chain was calibrated for G factor measurements in an echo free room at NTNU in 2001 by L. H. Morset the developer of the system. The G-calibration was transferred from WinMLS 2000 to the WinMLS 2004 system on a new laptop computer by an iterative trial and error in a small room until identical results were achieved by the systems.

A few of the included rooms are measured using gunshots (or balloon bursts for an American auditorium) and a Norsonic or B&K 1/3rd octave band analyzers (N830, N118 and B&K 2260 Investigator). One of the auditoria is measured by A. C. Gade using his measurement system in 1996 [NRK Store Studio].

3.2 The measured auditoria

Data from measurements conducted in the following multipurpose auditoria are included in the study:

- Ten main multipurpose concert halls in cultural houses
- Four rehearsal spaces and concert halls, two for medium sized symphony orchestras and two for a 50 member brass and woodwind orchestra
- Three theatre spaces, including a somewhat large "blackbox"
- A multipurpose medium sized concert hall at a well known north American musical academy

The halls have mainly been measured in a reverberant and a dry condition, so they count up to 33 data entries while writing. 7 of these are measured by others than the author. These are projects that either have been references for later ones included in the study, are well known from computer simulations or other personal experiences with them.

3.3 Statistical study

Our measured room acoustical data (n = 33) has been added into a spreadsheet in three sets. One separate, one with the data from the 18 chamber music halls Hidaka et al reported on (n = 51), and finally one also containing data from the 85 concert halls in Beraneks book (n = 137) [11]. There is also a single set containing only the Hidaka chamber halls.

3.4 Inputs

The data inputs follow basically Hidaka and Nishiharas work on chamber halls + a few from Beraneks work, as well as some combined values of special interest like the Sabine absorption area, A. The data entries are:

Hall volumes, **V [m3]**, number of seats, **N**, seated area **Sa [m^2]**, volume per seat, **V/N [m^3]**, volume per seated area, **V/Sa [m^2]**, occupied and unoccupied mid frequency reverberation times, **RT_M [s]**, unoccupied mid frequency **EDT_{Unocc} [s]**, bass ratio **BR [1]**, three band Clarity, **$C_{80, 3B}$ [dB]** (3B=0.5-2kHz), low frequency strength **G_L [dB]** (L=average 125-250Hz), mid frequency strength **G_M [dB]** (M=0.5-1kHz), seated area per seat, **Sa/N [m^2]**, unoccupied absorption area **A, [m^2 Sabine]**, absorption area per seat, **A/N [m^2 Sabine]**, late strength **G_{late} [dB]**, hall dimensions: length (audience area), **L**, width **W**, height, **H [m]**, aspect ratio length / width **L/W** [1], distance between seat rows [mm], distance between chairs [mm], **seating rake [1]**, **stage area [m2]**, **stage volume [m3]**, **stage ceiling height [m]**, **stage depth [m]**, **stage width [m]**, **ratio of stage height over width [1]**, stage floor height [mm], **early stage support $ST_{Early\ 4B}$ [dB]** (4B=0.25-2kHz), ratio between low and mid range strength, **G_L/G_M [1]**, average source receiver distance [m], Beranek/Hidakas "strength determination" factor **10^6*$EDT_{M,unocc}$/V [s/m^3]** as well as information on seat type (L, M, H upholstered), if there is a pipe organ present, the plan shape of the room (Fan, Rectangular, Oval, Wineyard, Moderate Fan) and where any balconies are if any (Front, Side or Stage).

Our halls are measured unoccupied. The occupied RT values are calculated using Hidaka and Nishiharas octave band regression between occupied and unoccupied RT values from four chamber music, two large concert halls and an opera hall [13]. The lowest and highest $RT_{unocc, M}$ was 1,26sand 3,05s respectively, so the correction might work best for more reverberant spaces.

3.5 Significance tests for the correlations

A correlation coefficient matrix was made between each of the values containing numbers. The significance of the correlations was calculated the t-number and p-values with two alpha borders based on the Boneferroni correction for significance, alpha/n, where n is the “number of independent entries”, here conservatively set to be 40 (The input columns are up to 39, but many of these inputs are dependant on each other) [14]. Correlations having p-values between 0.001 and 0.00025 (significant on the 5% level) was marked in bold green and correlations with p-values below 0.00025 (significant on the 1% level) were set to be bold black, see example in Figure 2.

This method can be looked at as a sort of an simple “data mining technique” and is a fast overlook method for finding linear correlation in the data. The most interesting correlations were graphed up in xy-plots and best fitted regression lines were calculated and included.

	N	V/S_A	V/N [m^3/#]	$RT_{occ,M}$	$RT_{unocc,M}$	$EDT_{Unocc,M}$	BR_{Occ}	$C80_{3B}$	G_L [dB]	G_M [dB]	S_A [m^2]	S_A/N [#/m^2]	A_{Unocc} [m^2 Sabine]	A/N [m^2 Sabine/#]	G_{Late} [dB]	H [m]	W [m]	L [m]
V [m3]	**0.81**	-0.04	-0.11	0.14	0.07	-0.02	-0.08	0.20	**-0.78**	**-0.80**	**0.77**	-0.19	**0.76**	-0.04	**-0.56**	**0.89**	**0.72**	**0.63**
N		-0.37	-0.53	0.11	0.14	-0.11	0.05	0.16	**-0.83**	**-0.75**	**0.89**	0.01	**0.53**	-0.40	-0.28	**0.59**	**0.76**	**0.64**
V/S_A	-0.37		**0.97**	-0.09	-0.22	0.02	0.09	-0.06	0.09	-0.02	**-0.54**	-0.50	0.15	**0.73**	-0.20	0.19	-0.43	0.00
V/N	**-0.53**	**0.97**		-0.07	-0.18	0.04	-0.01	-0.06	0.23	0.07	**-0.56**	-0.28	0.08	**0.74**	-0.19	0.15	-0.46	-0.12
$RT_{occ,M}$	0.11	-0.09	-0.07		**0.98**	**0.94**	-0.50	**-0.73**	0.26	0.37	0.22	0.05	-0.32	**-0.56**	**0.53**	0.13	0.19	-0.09
$RT_{unocc,M}$	0.14	-0.22	-0.18	**0.98**		**0.95**	-0.40	**-0.80**	0.39	0.49	0.28	0.19	-0.49	**-0.65**	**0.62**	0.11	0.12	-0.08
$EDT_{Unocc,M}$	-0.11	0.02	0.04	**0.94**	**0.95**		-0.44	**-0.85**	0.42	0.55	-0.03	-0.18	-0.48	-0.54	**0.68**	0.03	-0.11	0.02
BR_{Occ}	0.05	0.09	-0.01	-0.50	-0.40	-0.44		0.04	0.13	-0.04	0.00	-0.14	0.07	0.14	-0.10	-0.10	-0.25	0.22
$C80_{3B}$	0.16	-0.06	-0.06	**-0.73**	**-0.80**	**-0.85**	0.04		-0.59	**-0.68**	0.15	0.24	**0.72**	**0.65**	**-0.89**	0.08	0.34	-0.04
GL [dB]	**-0.83**	0.09	0.23	0.26	0.39	0.42	0.13	-0.59		**0.95**	**-0.70**	0.09	**-0.83**	-0.14	**0.85**	**-0.65**	**-0.82**	-0.44
GM [dB]	**-0.75**	-0.02	0.07	0.37	0.49	0.55	-0.04	**-0.68**	**0.95**		**-0.70**	0.18	**-0.88**	-0.31	**0.94**	**-0.71**	**-0.74**	-0.48
S_A [m2]	**0.89**	**-0.54**	**-0.56**	0.22	0.28	-0.03	0.00	0.15	**-0.70**	**-0.70**		0.25	0.44	-0.42	-0.19	**0.55**	**0.76**	**0.57**
S_A/N [#/m_2]	0.01	-0.50	-0.28	0.05	0.19	-0.18	-0.14	0.24	0.09	0.18	0.25		-0.24	-0.24	0.12	-0.22	0.11	-0.25
A [m_2 Sabine]	**0.53**	0.15	0.08	-0.32	-0.49	-0.48	0.07	**0.72**	**-0.83**	**-0.88**	0.44	-0.24		0.49	**-0.86**	**0.64**	**0.52**	**0.52**
A/N [m_2 Sabine/#]	-0.40	**0.73**	**0.74**	**-0.56**	**-0.65**	-0.54	0.14	**0.65**	-0.14	-0.31	-0.42	-0.24	0.49		**-0.58**	0.07	-0.29	-0.05
G_Late [dB]	-0.28	-0.20	-0.19	0.53	**0.62**	**0.68**	-0.10	**-0.89**	**0.85**	**0.94**	-0.19	0.12	**-0.86**	**-0.58**		**-0.55**	-0.33	-0.24
H [m]	**0.59**	0.19	0.15	0.13	0.11	0.03	-0.10	0.08	**-0.65**	**-0.71**	**0.55**	-0.22	**0.64**	0.07	**-0.55**		0.50	0.44
W [m]	**0.76**	-0.43	-0.46	0.19	0.12	-0.11	-0.25	0.34	**-0.82**	**-0.74**	**0.76**	0.11	0.52	-0.29	-0.33	0.50		0.45
L [m]	**0.64**	0.00	-0.12	-0.09	-0.08	0.02	0.22	-0.04	-0.44	-0.48	**0.57**	-0.25	0.52	-0.05	-0.24	0.44	0.45	
Aspect ratio L/W	-0.06	0.44	0.35	-0.21	-0.15	0.12	0.45	-0.35	0.33	0.23	-0.14	-0.38	0.02	0.23	0.12	-0.04	-0.47	**0.56**

Figure 2: Extract of the correlation matrix for our 33 data entries. Bold black numbers are significant on the 1% level, the green bold numbers are significant on the 5% level. The matrix is symmetric across the diagonal line.

4 Results

4.1 Comparisons with chamber and concert halls

We compare averages and standard deviations of room dimensions, number of seats, the room acoustical data and some key parameters for design between our and the chamber and concert halls in Hidaka and Beraneks works [10,13].

Table 1: Measured hall data and standard deviations compared to chamber and concert halls.
RT_{occ} values for our contemporary halls has been corrected using a method from Hidaka and Nishihara [13]

Type hall	**V [m^3]**	**N**	**V/N [m^3]**	**$RT_{occ, M}$ [s]**	**$RT_{unocc, M}$ [s]**	**$EDT_{unocc, M}$ [s]**	**BR**
Contemporary multipurpose halls (“2n”=33)	4872 ± 2066	362 ± 198	14.1 ± 4.7	1.22 ± 0.31	1.41± 0.35	1.22 ± 0.32	1.2± 0.4
Hidaka and Nishihara Chamber halls (n=18)	4096 ± 1993	531 ± 192	7.7 ± 2.5	1.51 ± 0.30	1.79± 0.41	1.79 ± 0.43	1.1± 0.1
Beraneks concert halls (n = 85)	20451 ± 9559	2174 ± 751	9.5 ± 2.4	1.85 ± 0.30	2.20± 0.37	2.15 ± 0.39	-

From Table 1 we see that in spite of significantly larger volume per seat, the reverberation times of our halls are lower than the chamber and concert halls. We have included the Stage volume in the calculations. If we only include 50% of the stage volume along with the audience area volume in our halls, the number becomes 12m^3 per seat, still higher by 56% and 26% respectively than the chamber and concert halls and still they have a more moderate reverberation.

The EDT is lower by about 47% and 76% respectively but the difference is a little smaller for the RT values by 27% and 56%. Some of this difference is due to the variable absorption and that there is some theatre spaces included. Excluding the dry versions and omitting the theatre data, we get an average EDT of 1,37s which is still substantially lower.

Table 2: Measured hall data and standard deviations compared to chamber and concert halls.

Type hall	**$C_{80, 3B}$ [dB]**	**G_{Low} [dB]**	**G_M [dB]**	**S_A [m^2]**	**S_A/N [m^2]**	**$A_{unocc, M}$ [m^2 Sabine]**	**$A_{unocc, M}$/N [m^2 Sabine]**
Contemporary multipurpose halls (“2n”=33)	3.0 ± 2.8	6.2 ± 3.2	6.5 ± 2.9	231 ± 114	0.61 ± 0.06	612 ± 344	**1.82 ± 1.08**
Hidaka and Nishihara Chamber halls (n=18)	-0.2 ± 1.9	10.5 ± 2.9	11.2 ± 1.8	330 ± 126	0.62 ± 0.09	399 ± 169	0.77 ± 0.22
Beraneks concert halls (n = 85)	-0.9 ± 1.6	3.1 ± 2.3	3.5 ± 2.0	1318 ± 473	0.61 ± 0.08	1534 ± 580	0.71 ± 0.18

In Table 2 we see further that our halls objectively have a clearer sound, as expected by the lower reverberation times. We also see that the strength is moderate in comparison to the chamber halls but still about 3dB higher than the average of the concert halls. The seat area per seat (including a 0.5m stripe around the aisles), S_A/N [m^2], is comparable, so we can’t say that the seats are larger in our halls than in the classical chamber or concert halls.

But the overall absorption per seat is more than double of what we see for the chamber and concert halls. Excluding the dry versions of the halls and the theatres we get 1.57 m^2 Sabine per seat versus the 0.77 and 0.71, respectively, for the chamber- and concert halls.

We do have data from halls with comparable absorption per seat to the chamber- and concert halls, One is a small concert hall (Lidmansalen at the Norwegian Academy of Music) where there is no stage textiles at 0.81 m^2 Sabine per seat. A refurbished hall (Eidsvoll kulturhus) with a small stage, eccovelour on the stage and leather upholstered seats is at 0.67 m^2 Sabine per seat. A medium size (634 seats) concert hall at the Music Concervatory at Oberlin, Ohio, USA, has variable absorption, but no stage textiles at 0.81 m^2 Sabine per seat. Also Maihaugsalen has a moderate number (0.93 m^2) assumed to me measured with an orchestra shell and the stage textiles up in the flytower.

A hypothesis for the higher absorption per seat in out halls is the stage textiles and possibly ground absorption from the variable absorbers in the retracted position.

Table 3: Measured hall data compared to chamber and concert halls. For the concert halls from Beranek only hall dimensions, stage volumes and areas where Early stage support, ST_{Early} [dB], is measured is included (n=23).

Type hall	**G_{Late} [dB]**	**ST_{Early} [dB]**	**H [m]**	**W [m]**	**L [m]**	**S_{Stage} [m^2]**	**V_{Stage} [m^3]**	**Stage H/W**
Contemporary multipurpose halls ("2n"=33)	2.4 ± 4.3	-12.8 ± 3.0	10.9 ± 2.9	17.6 ± 2.6	18.4 ± 3.3	194 ± 65	2256 ± 1378	0.69 ± 0.09
Hidaka and Nishihara Chamber halls (n=18)	8.2 ± 2.3	-9.1 ± 2.9	10.6 ± 2.5	14.0 ± 3.1	25.2 ± 4.4	79 ± 31	803 ± 435	0.75 ± 0.13
Beraneks concert halls (n = 85)	1.3 ± 2.0	-15.1 ± 1.9	17.8 ± 4.5	30.4 ± 8.7	31.8 ± 6.4	205 ± 49	2556 ± 892	0.67 ± 0.18

We see that the late strength, G_{Late}, and early stage support is stronger for the chamber halls than our and Beraneks concert halls. The chamber hall stage volumes and areas are smaller, while our stages are similar to the concert halls. The chamber halls also differ by being narrower and longer giving a higher aspect ratio between the width and length of the audience area, 1,8 versus close to 1 for both our and Beraneks concert halls. The narrower and longer design and the small stages of the chamber halls may contribute to the louder reverberant field in these halls.

Late strength G_{Late} has appeared to be a promising candidate for symphonic musicians overall acoustical impression of a hall from subjective assessments [19, 20]. Further the geometrical aspect ratio between the stage height and with, H/W_{Stage} also share that property, and it should be above some 0.58 [19, 20]. We see that the hall averages for the H/W_{Stage} seems to be in that range for all three hall groups.

Our halls also seem to be within the preferred G_{Late} values, 1-3dB as given in Dammeruds work, but with a larger spread than found in the other halls. The stage support, ST_{Early}, follow the values of the G_{Late}. They also correlate significantly in the statistics tests, correlation coefficient, r = 0.74. The correlation between stage support, $ST_{Early,}$ and the overall mid frequency strength, $G_{M,}$ is 0.81 in the larger data set. The trend is the same in all sets, so we may conclude that the early sound a musician hear at stage, or we hear by clapping our hands, to some extent should give information on how loud the room is as well as the level of the reverberation. This is also in agreement with Dammeruds findings in his study of stage conditions for symphony orchestra musicians [12].

4.2 Linear regression results

Somewhat surprisingly the RT does not seem to correlate significantly with the room volume and dimensions as we would have expected from the theory. Only in the large set containing the 85 concert halls (total n=137) we see moderate significant correlations between RT and the volume, r= 0.61. The key parameter volume per seat, V/N, does not correlate significantly with the RT in any of the sets, but the volume correlate with the seat count. We may assume that this origins from using V/N as a key design figure.

However, the strength, G, show significant negative correlations with the seat count, volume, height and width, as well as the amount of absorption in our halls, see Figure 2. The strength also shows negative correlations with the stage volume, which explain the former addresses correlation between strength G_M and stage support ST_{Early}.

The strength factor thus seems to be predicted more reliable by the room volume and seat count than the RT. As figure 3 shows, the strength G_M follow the absorption area in a logarithmic trend as predicted by theory.

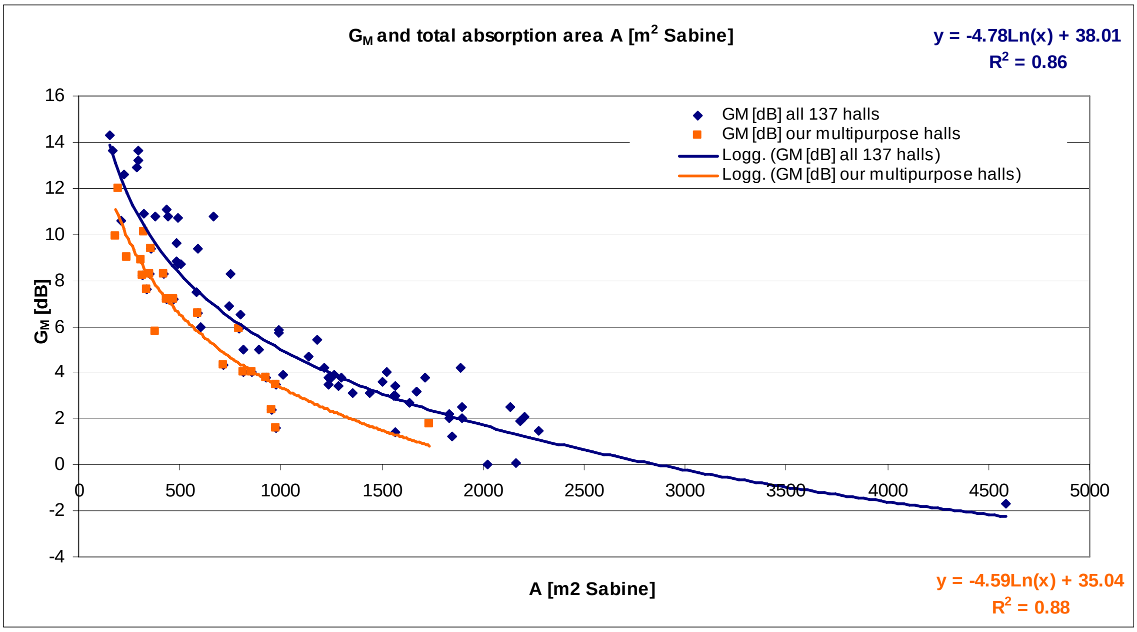

Figure 3: Measured mid frequency strength G_M [dB] versus absorption area for our multipurpose halls Hidakas and Nishiharas chamber and Beraneks concert halls. Average source receiver distance in our measurements is 13.5 m.

When we know the absorption area of a hall we can, within certain limits, predict the average sound level of the room. The measured G fall below the diffuse field value G = 10log(T/V) + 45 dB by about 2dB as seen in Figure 2.

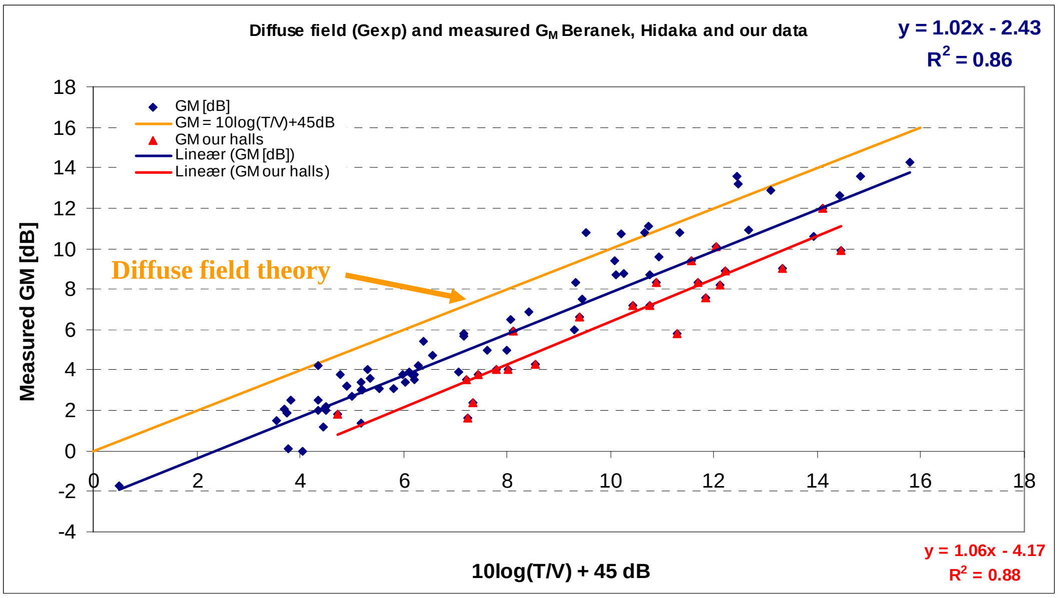

Figure 4: Measured mid frequency strength G_M [dB] versus the expected Gexp from diffuse sound theory for our multipurpose halls, Hidakas and Nishiharas chamber and Beraneks concert halls. Average source receiver distance in our measurements is 13.5 m.

Our data is below the average trend line by about 1dB. That may be due to a longer average source receiver distance (we have not corrected the data to 10m which give a 1.3dB in free field conditions).

Our halls may also be less loud due to the stage configuration with theatre textiles, and variable absorption distributed in the halls giving a faster reduction of the sound level with distance than the more reverberant, often flatter floor designed and hard stage concert and chamber halls. These factors are subjects for further study.

4.3 Comparisons to the CMON requirements

CMON's requirements are mainly given on as recommended RTs for loud and more moderate instrument groups as well as for amplified music. In Figure 4 we show the measured unoccupied RTs from our halls plotted in CMON's recommendations.

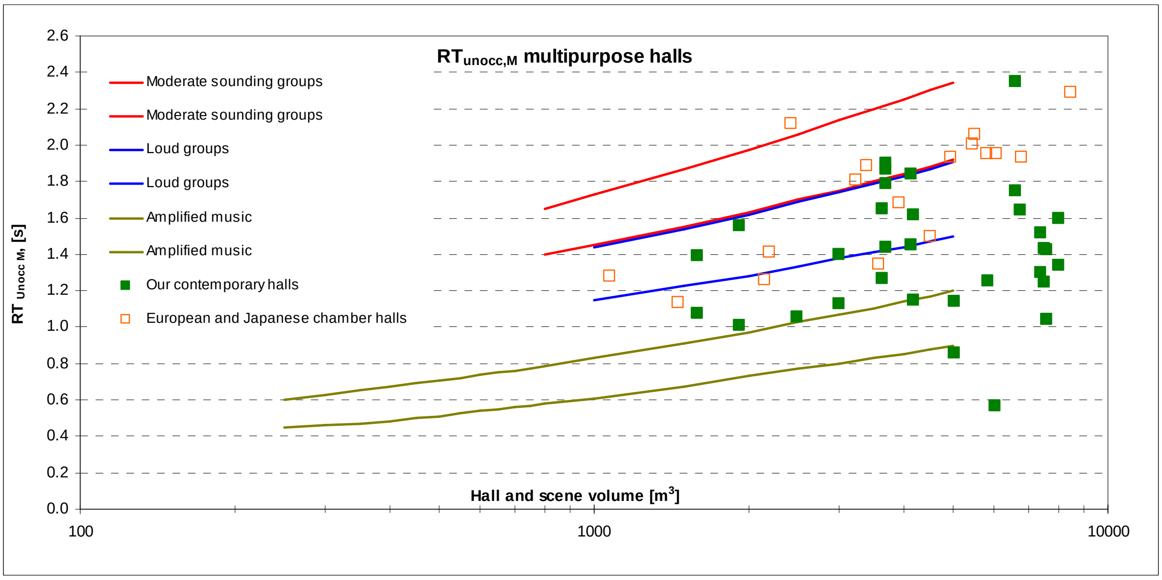

Figure 4: Measured mid frequency RT for our multipurpose and Hidakas and Nishiharas chamber halls plotted in CMONS recommendatations for different instrument groups.

In general our halls seem to fall in the region for loud instrument groups, some in the "nowhere land" between loud instrument groups and amplified music. A few seem to fall within the borders given for amplified music.

A small group of the chamber halls seem to meet the criterion for moderately loud sounding instruments. The upper 'outlier' in our data is the live version of the American 635 seat multipurpose concert hall at a musical academy (Oberlin, Ohio), assumed to be designed for organ music.

We may assume that the loud small stage designed chamber halls are designed for weak and moderately loud sounding instruments. Given the CMON recommendations and the measured data given here, we may speculate if the recommendations are somewhat out of proportions for the weaker sounding instruments.

CMON write that the recommendations are not made for the large hall in the cultural house, but for any room used for musical rehearsal and performances [5]. In many communities the churches may fall in that group as they have a relatively generous volume and acoustics. Unfortunately we do not have included these in our study here. But we know that CMON does collect data with their own measurement system.

As we have seen form the comparisons of hall groups, the chamber halls are also louder than the other two groups in spite of a comparable volume to our multipurpose halls. That higher loudness may come from their lower overall absorption.

Our experience with professional symphony and brass orchestras indicate that the loudness of the rooms seem to be of major concern. We do not have systematic studies to support our experience, but halls with a G_M higher than say 8-10dB seems to be considered to be too loud for these strong groups.

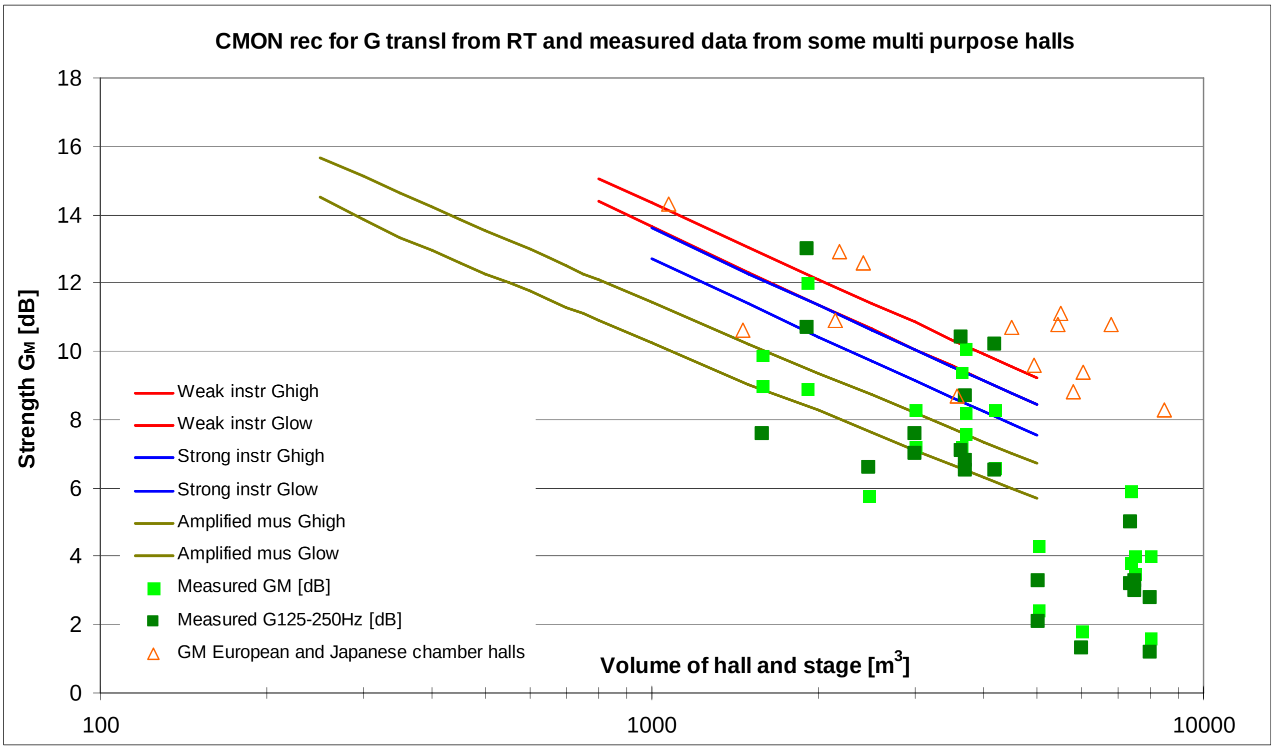

Figure 5: CMON's RT requirements translated to *expected measured* mid frequency strength, G_M. Our measured values for mid frequency and low frequency strength (green squares) as well as data from Hidakas and Nishiharas chamber halls (open triangles) are plotted in for reference.

The chamber halls in figure 5 are likely to be too loud for the strong instrument groups as the blue lines do indicate. However, CMON's lines extend beyond our measured data for smaller volumes. More measured data supporting the recommendations would be beneficial. We may also benefit from more systematic subjective studies of how well the multipurpose halls function for the users.

The weakest room in the study is a relatively large, but heavily damped, theatre hall that formerly was a TV studio. This hall is liked by the sound technicians, but it seems to be too dead and weak for the performers and listeners, especially those at rear seats. Rooms certainly can become too dead. Studies by Barron have indicated that listeners expect a certain sound level at a certain distance [Barron IOA 2008].

4.4 Comparisons to Adelman Larsens criteria for Rock and Pop music

The multipurpose halls around in the Norwegian cultural houses are probably used mainly for amplified performances, speech, or music. Halls for rock and popular music has recently been studied by Adelman-Larsen et al in a subjective study of 20 rock music venues in Denmark [15]. He found that he low frequency reverberation and clarity was of importance for the sound engineers and to some extent for the musicians.

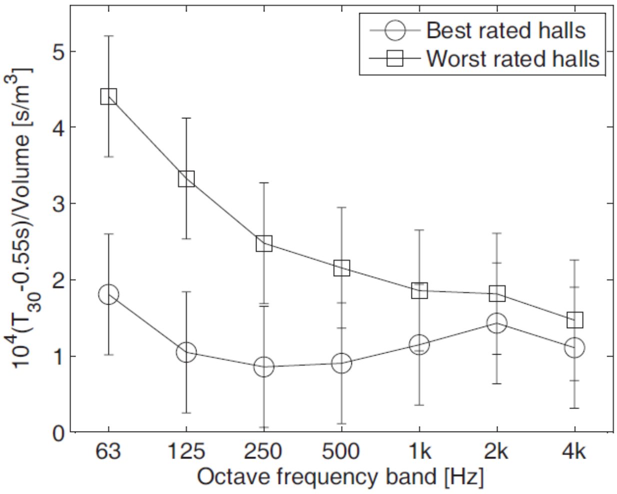

Figure 6: Adelman-Larsens linearly transformed T30 values for good versus bad rated halls for rock and pop music with 95% confidence intervals included, from [15].

From about 500Hz and up the curves tend to overlap as seen in Figure 6. These curves are extracted from a regression formula that can be translated to requirements for low frequency reverberation times as given in the following plot:

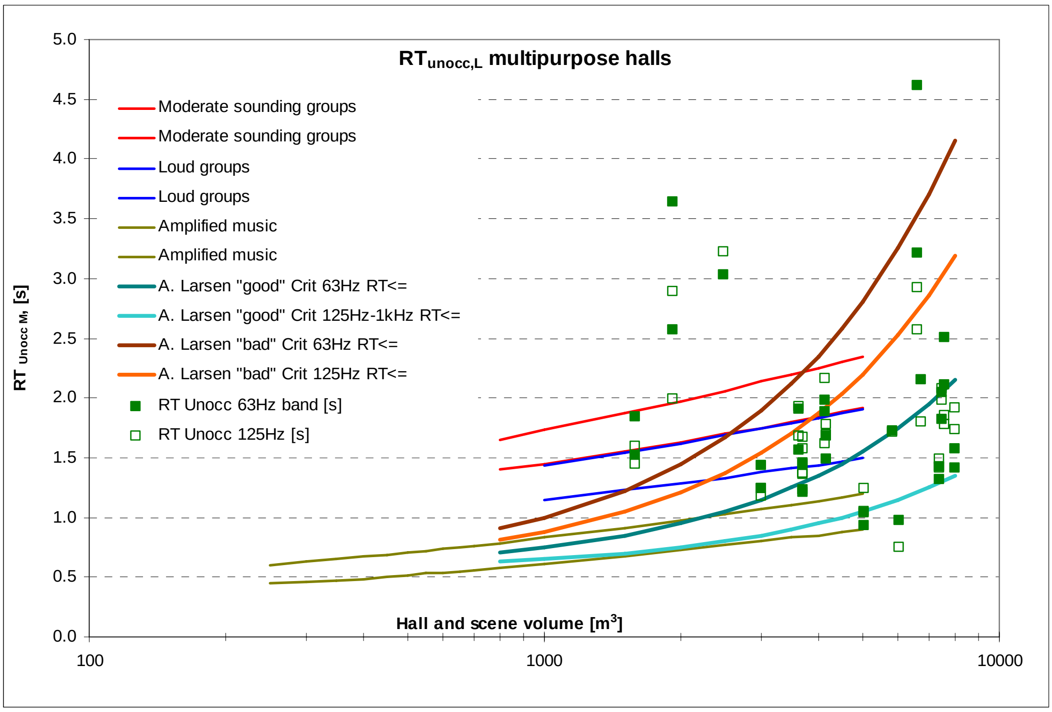

Figure 7: CMONS RT requirements plotted with Adelman-Larsens rock and pop music requirement along with measured RT values for the 63Hz and 125Hz bands from our halls.

The region of "good" hall RT data from Adelman Larsens study seem to fall within CMONS requirements for amplified music up to a certain hall volume. The bigger halls seem to work with somewhat larger reverberation times than the CMON requrements are indicating. The largest hall in A. Larsens study was 7000m^3, we have extrapolated the lines an extra 1000m^3.

Some of our halls seem to fall within the "good" lines for rock and pop. However we have not measured all halls with a flat floor, a condition many such concerts may be held at. However some pilot measurements seem to indicate that removable bleachers are not very absorptive at low frequencies. We may need more field data on the absorptive effect of seats in bleachers to confirm that.

We also see that some of the halls do have low frequency RT outside any limits. Two of these are theatres, one with variable absorption (two measurement points per octave band). These are either all concrete plus curtains (except the hard theatre floor and seats), or the stage house and hall ceiling is bare concrete. The users did not complain about it for the main hall, but they did for the smaller black box. Halls for speech may have less demanding requirements for low frequency reverberation, but music is usually part of any performance, so we do not recommend the solution. The 4,5s outlier at 63Hz is from the American concert hall measurement using balloons, possibly a measurement inaccuracy.

4.5 How much absorption?

We have seen that the size and amount of absorption in the halls affect the overall loudness of the rooms. The RT is by theory highly dependant on the amount of absorption in the halls according to Sabines simple empirical and statistical diffuse field theory. (The absorption area is calculated using the reverberation time as input to the Sabine equation).

Now how much absorption do we need in a room to fulfil CMONs and Adelman Larsens requirements?

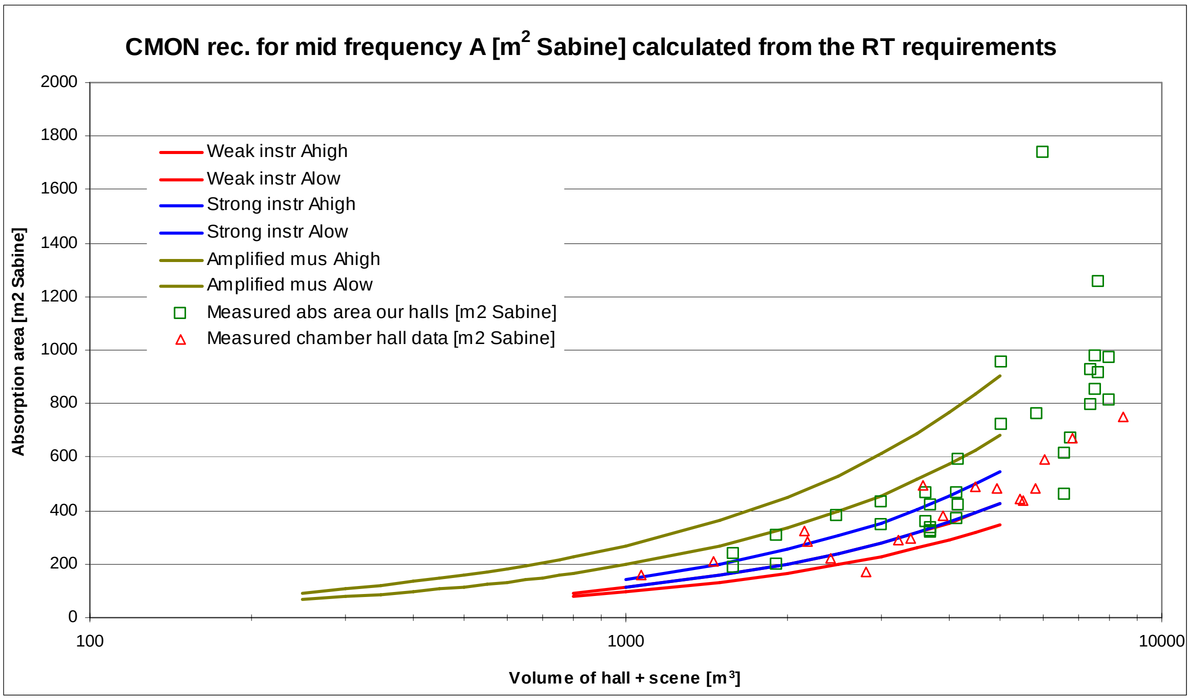

Figure 8: CMON's RT requirements recalculated as absorption areas. We have also plotted our and Hidakas chamber hall absorption areas.

How much absorption is needed to fulfil the easily achievable 0.5 second variation in reverberation time as claimed in CMONs recommendations?

We see that none of our largest halls in the study has mid frequency absorption areas less than 800m^2. The exceptions are halls without stage textiles. If we want to change the reverberation time say 0,5s in these large halls e.g. 33% from 1,5s to 1s, we would need the equivalent absorption area of 400m^2 Sabine.

If we use heavy curtains at an absorption factor of say 0.6 as variable absorbers, we would need 666m^2 of it in that 7000m^3 hall, which amounts to more than the overall wall surfaces. Of practical reasons one cannot cover all surfaces with absorbers.

The green squares in Figure 8 do show some data straight above each other. These are likely to be the same halls in "wet" and "dry" conditions, respectively. The largest gap is about 340m^2 Sabine, but more usual is around 150m^2. That is also about the effect of a 300seat bleacher. We have 250m^2 in a hall with absorbers all around including the stage tower sides and 7 stripes 1,5m high wool curtains across the ceiling in the audience side of the hall.

How much absorption can we expect in the stage region in the cultural houses?

We may use the average absorption area per seat at about 1.6m^2 Sabine for our halls with stage textiles. The lowest absorption area per seat in halls without stage textiles is about 0.8 m^2 Sabine, which includes the residual absorption in these halls. Assuming 350 seats in the hall, the stage textiles, and possibly the retracted variable absorption, amount to about 280m^2 Sabine alone. If the hall has 500 seats the number becomes 400m^2 Sabine. Even in halls with legs, "light shades" and other stage cover drapes (sceneindekning) of sound reflecting textiles, the absorption area per seat is still in the 1,3-1,5m^2 Sabine range. These reflective stage textile halls also tend to have reverberation coming form the stage house, so the balance here should be done carefully.

But nonetheless, one cannot exclude these amounts of absorption from the calculations and requirements. The extra absorption in the stage and variable absorption textiles may help the halls to be less loud and may, in sin spite of somewhat limited reverberance, have a favourable level of that reverberation at least for orchestral musicians. The stage dimensions also seem to be in the right ballpark.

How about the bass absorption and Adelman Larsen?

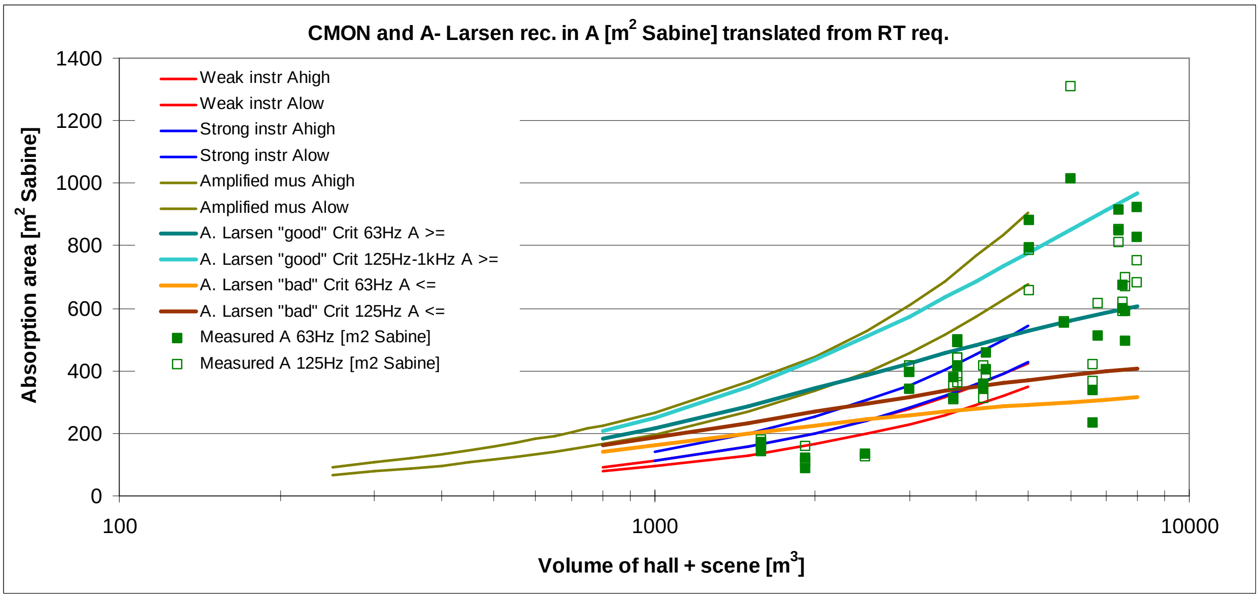

Figure 9: Adelman-Larsens RT requirements recalculated as absorption areas with CMON's rec. as a reference. We have also plotted our measured absorption areas for the 63Hz and 125Hz bands.

Our bigger and later halls seem to be in the right region for the low frequency absorption. Some are still in an unfavourable region, among these are the concrete stage house halls. The needed bass absorption in the halls to have good conditions for rock and pop music is about 600-800m^2 Sabine for the bigger halls and in the range of 430-600m^2 for the medium sized halls (4000m^3 including the stage volume). This is hypotheses until we are able to establish sufficient subjective evaluation data for our type of halls and use.

We may also see from comparing our interpretation of Adelman-Larsens requirements with those from CMON that if the reverberation curve is more or less flat in the frequency response, we may see from Figure 9 and 7 that it will be difficult both to achieve good conditions for weaker instrument groups and rock and pop music in the same room. Either probably has to have an own venue.

For the bigger halls above some 6000m^3, however, there seem to be possible to achieve favourable conditions both for the louder instrument groups and amplified music like rock and pop.

We have measured data for halls in a range larger than the CMON recommendations span. It would and should be possible to extend these based on experiences from these halls. We look forward to CMON's results of their measurements and would be glad to share data with them if that can be used in a common effort to improve the conditions for music and performing art life in Norway.

5 Discussion

The most common RT requirements to use in Norwegian auditoria are those from NBI Handbook 20, also given in Rindels “Building sheets” (Byggdetaljdatablad) [1,2,3]. In Figure 10 we have plotted these recommendation regions for music and speech as given in these publications in the same plot as those from CMON.

We see that the region recommended for music extends beyond CMON’s data, but seem to fall quite well together with the region given for loud instrument groups in CMON’s curves.

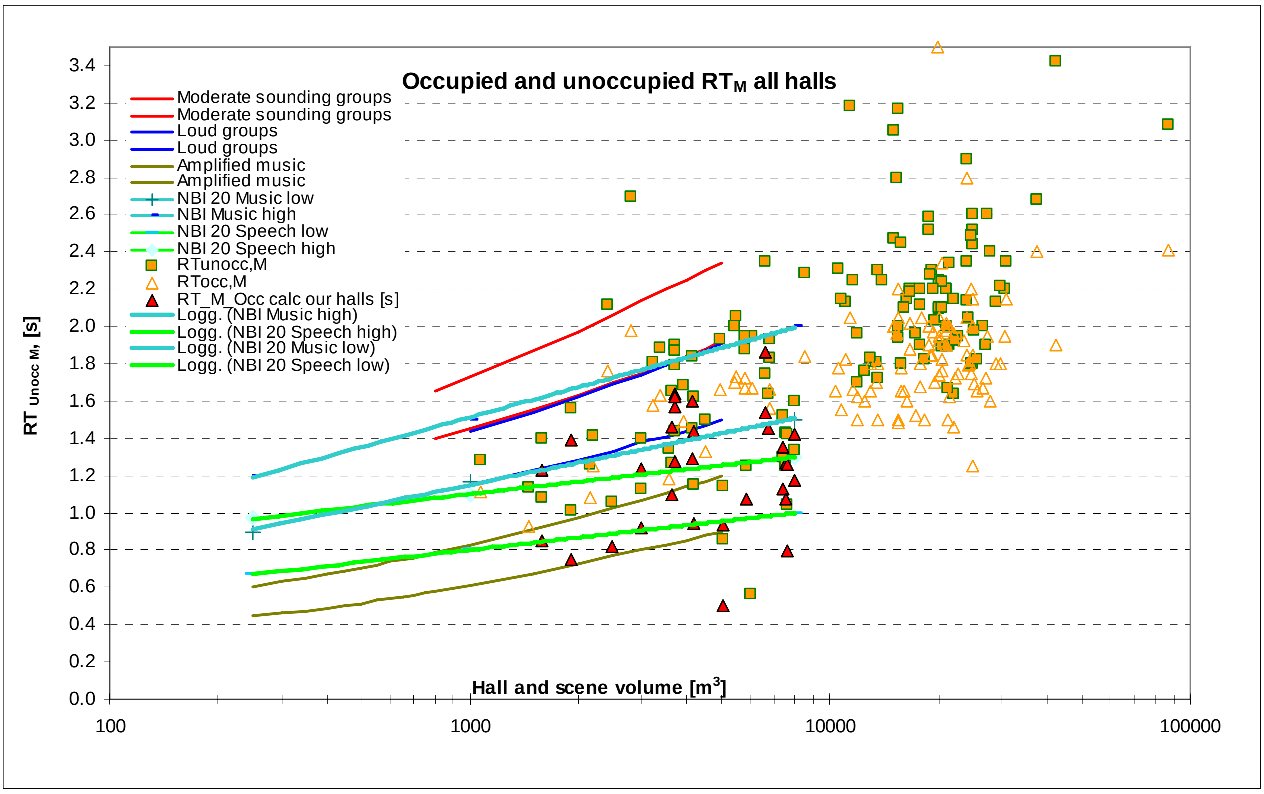

Figure 10: CMON’s and NBI handbook 20 as reference and all RT data occupied and unoccupied. Our occupied data have been calculated using Hidaka and Nishiharas regression formulas from [13]. This correction may work better for the more reverberant rooms we have, but may exaggerate the effect of the audience some 10% too much for the less live rooms.

We have also plotted the unoccupied and occupied RT data for all the 137 data entries from Berneks 85 concert halls, Hidaka and Nishiharas 18 chamber halls and our 33 multipurpose halls. The data curves for NBI 20’s recommendations for music seem to fit well with the occupied RT values if extended to larger volumes. Also many of the chamber halls and some of ours also fall in here, while the majority of our multipurpose halls seem to fall outside the region for music. The data points may look a bit worse than it is, as the effect of the audience on the lower reverberation times probably is a bit exaggerated.

Many of these multipurpose halls are also used for amplified music and (amplified) speech, so from this plot we may assume that quite a few of them may function well for that purpose e.g. in their damped versions.

By watching these curves one may speculate if what is meant by the conditions for weak sounding instruments might be special designs of halls we have not included in our study like churches and musical spaces for special genres. The halls that seem to fit in here are the *“Schuberthall im Konzerhaus”* in Vienna and the *“Martinic hall”* in Prague, both small volume European classic chamber halls [10].

We have not included reverberation times for music practice rooms in schools etc in this study. These are under regulation by the building standard NS 8175 that regulates architectural acoustics conditions in Norwegian buildings like schools, offices, hotels, building for humans and institutions. If we were to follow CMONs recommendations for the weak and strong instrument groups we would probably have to violate that standard.

It is easy to fall into the ditch believing that reverberation is the most important factor for room acoustics experiences as found in studies of large concert halls [12]. Smaller and reverberant halls will be louder than the bigger and less live ones. We have experienced that for loud groups like symphony orchestras and brass and woodwind bands the loudness of the halls seem to be more important than the reverberation. Halls with strength G_M higher than, say, 8-10dB does not seem to be suitable for these groups. They also may be more interested in critical listening and thus prefer somewhat higher clarity which comes with lower RT's. We will need to assess if this holds true also for amateur musicians that does not have the hall as their main occupation rehearsal space and maybe they benefit from more 'blend' in the sound? However the ears can be exposed to strong sound levels form some instruments, and a tinnitus is severe to anyone, not only professional musicians.

We may assume that smaller and louder rooms might lead to larger problems for the users than the bigger ones. Thorough studies on that subject have still to be accomplished. CMON is doing a great work participating in the "Grenser for lyd" project aimed at artists, concert providers and audiences addressing the risk of hearing damages in loud musical environments [21]. It shows that the music industry and community is taking that risk seriously.

We also would benefit from a more elaborate and systematic study of how well the multipurpose halls function for the users. Maybe they work pretty well, in spite of somewhat moderate reverberation- and strength values. Some may also work well for amplified music, maybe especially our later and somewhat bigger halls.

6 Conclusion

We have collected average room acoustical data (n=33) according to ISO 3382 in some 18 multipurpose halls for music and speech and compared the data and room dimensions to data from 18 chamber halls published by Hidaka and Nishahara. We have also collected and compared our values to similar data from Beraneks book on 100 concert halls and opera houses, containing data from some 85 concert halls.

The aim has been to "mine" for the typical traits of our halls. What parameters and properties can be predicted from the early key design criteria and how does the measured and literature data compare to the requirements usually used in the design of multipurpose halls in Norway?

We discuss CMON's requirements up against those given in NBI 20's as well as those from Adelman-Larsens work on halls for rock and pop music. And we assess these requirements up against our measured data and vice versa.

From the studies we have following conclusions:

- The sound strength G_M is easier to predict from the key input parameters, like Volume per seat, than the RT.
- The late strength G_{Late} and mid frequency strength G_M and the Early Stage support, $ST_{Early,}$ correlate significantly. The conditions for mutual hearing at the stages of our halls are directly related to how loud the halls are. This may come from the fact that the stages volume and dimensions correlate well with the dimensions and volume of the audience part of the halls. What we hear while clapping out hands or shouting at the stage may respond the necessary information in assessing the loudness of a hall. This confirms the considerations we experienced from the Norwegian Opera Orchestra during the projecting and experience from the new halls regarding this issue.
- The average absorption area per seat for our multipurpose halls is some 1,6 m^2 which is about the double of what we find in the chamber and concert halls with no stage flight-towers and textiles. This is supposed to origin in the stage textiles and possibly the absorption in the variable absorption being retracted, but still to some extent present in the rooms.
- The key values for volume per seat ($\geq$ 10m^3 seat) and ceiling heights, $\geq$ 10m and 6m, respectively, given in NBI Handbook 20 and CMON, does not ensure the sufficient reverberation time resource if there is stage textiles present of any form.
- Average stage textile absorption in a 350 seat hall is loosely calculated to be about 280m^2 Sabine which is comparable to the seat absorption.
- The stage textile absorption contributes to a moderate sound strength of our multipurpose halls. Some have G_{late} values believed to be quite favourable for orchestral music, in spite of rather moderate reverberation in these halls.
- The necessary absorption in the bass bands 63Hz and 125Hz should exceed some 600-800m^2 in bigger halls around 7000m^3 and some 430-600m2 for the medium sized halls at some 4000m^3, including the stage volume, if they are expected to work well for pop and rock performances.

- Multipurpose halls can't be made with substantial areas of bare concrete if they are expected to work well for rock and pop performances or any amplified music. This also probably holds true for any type of multipurpose use including halls mainly for speech, as amplified music is involved anyway.

Finally some recommendations:

- Follow the checklist in NBI Hanbook 20 in the projecting process.
- If the hall is expected to contain stage textiles, take account for that in your volume per seat assessment. $20m^3$ per seat and ceiling heights above 13m might be a good start.
- Do not promise to make long RT's and large variations in the RT in agreements!
- If you haven't stated yet, start measuring the G-values in your halls, and share the data at some point.
- Personally I will try to achieve G_{Late} values in the range 1-3dB in occupied halls where orchestral music is prioritized and maybe let the reverberation time be somewhat moderate if that is needed for the compromise.
- We should start assessing our halls subjectively either in a larger questionaire studies or at least just by attending concerts and getting closer in contact with the users. Talking to sound engineers might be essential in that process.
- Use the strength as a guide in your projecting of halls.
- Make sure the halls have sufficient bass absorption.
- Measure the background noise levels (we have omitted them here due to time restrictions)
- Share your measurement data and experiences in some form, we will all benefit from it!

7 Further work

- Include the measured noise data
- Extend the data entries form Beraneks halls as well as Gades measurements as well as data from other Scandinavian halls in the literature which may be more similar to ours
- Look closer at how the data are distributed in the halls and listen to aurlalisations of impulse responses from them.
- Initiate and cooperate in possible listener- and user assessments.

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The opinions and conclusions in this article do not necessarily reflect our company's standards on the subject, if there are any.

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