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Relationship between room shape and acoustics of rectangular concert halls

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Extensive acoustics computer simulations have been made using Odeon computer simulation software. In 24 rectangular rooms representing “shoe-box” type concert halls with volumes of 8 000 m^3, 12 000 m^3 and 16 000 m^3 from 300 to 850 measurements positions have been analysed. Only room averaged objective measures are considered here, in particular Clarity (C_{80}), Strength (G) and Early Lateral Energy Fraction (LF_{80}). Results from simulations have been compared with regression models created based on real hall measurements. In general, simulated results of C_{80} and G are found to be in good agreement with regression models. Divergences are found in LF_{80} behaviour; these have been associated with the influence of proportions of rectangular halls. Updated formula for predicting of LF_{80} in rectangular halls has been proposed, which takes into account both width and length of hall.

1 Introduction

Computer simulation has been used to predict acoustics of concert halls for quite a long time now [1]. This method is especially valuable, when predicting the influence of hall geometry on the sound field, as changes in geometry are easily made. It can be also utilized when a large number of sources and/or receiving positions are to be analyzed. Modern computer simulation software like Odeon [2] offer a reliable level of prediction, which - to some extent – can substitute real hall measurements [3]. It is however not without risk – as results from simulations are realistic only, if the hall geometry, absorption, diffusion and also other factors in the computer model reflect those of the real hall. The risk is even greater, because as for now, none of the programs mentioned above take care of wave effects like interference and diffraction. It is then recommended to compare results from simulation with real hall measurements, whenever possible.

In the 80s several authors [4, 5, 6] started making systematic measurements surveys in real concert halls, by measuring objective parameters specified in ISO 3382 standard. Results from those measurements, combined with halls geometrical data were used for creation of simple design/acoustic relationships [7, 8, 9]. Those relationships were presented as linear regression models, from which the acoustic effect of changes in certain design variables can be easily calculated.

This paper presents results from computer simulations made in 24 models representing rectangular concert halls [10]. In those simulations audience and stage area was kept constant, but room proportions were gradually changed from square to elongate rectangular. Simulations were repeated in three different room volumes to allow for the results to be valid for a larger range of halls. This paper also compares the hall-average results from simulations with the ones calculated for the same room geometry, but according to linear regression models discussed above. Three parameters given in ISO 3382 have been discussed: Clarity (C_{80}), Strength (G) and Early Lateral Energy Fraction (LF_{80}).

2 Method

2.1 Odeon simulations

Simple models of concert halls, rectangular in plan, have been modelled in Odeon version 8. Three examples are shown in Fig 1. In those models only two variables were changed: volume (V) and length-to-width ratio (L/W). Three volumes were analyzed: 8 000 m^3, 12 000 m^3 and 16 000 m^3, each in eight length-to-width ratios (L/W=1.10; 1.43; 1.77; 2.10; 2.43; 2.77; 3.10; 3.43). Room plans for all 24 created models are shown in Fig 2.

All simulations were made with the following assumptions:
- for models in one volume floor area was constant;
- stage area was 190 m^2 in all models;
- audience area equals floor area minus stage area;
- audience floor was horizontal in all models;
- stage height was 1.0 meter.

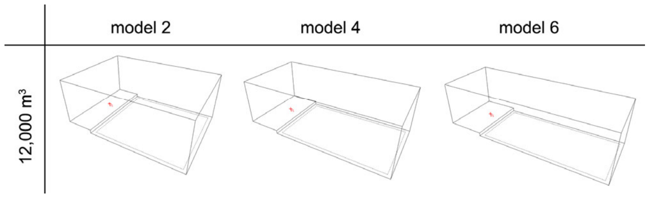

Fig.1 Three examples of simulated “shoe-box” halls in one of the analyzed volumes (V=12 000 m^3). L/W ratio equals 1.43 (model 2); 2.10 (model 4); 2.77 (model 6).

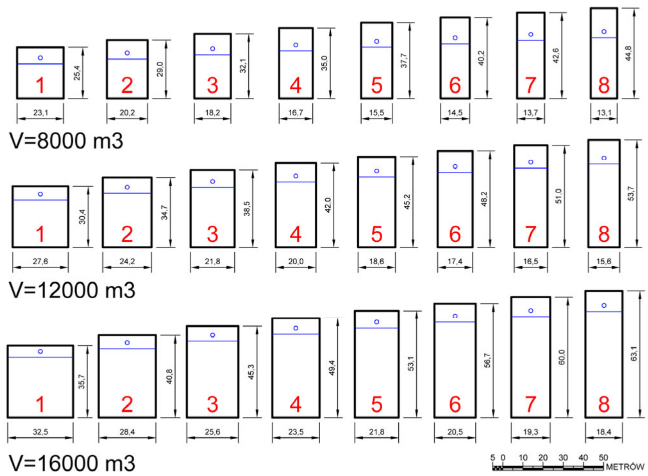

Fig.2 Room plans of all analyzed models.
Model 1 has L/W ratio=1.10. Model 8 has L/W ratio=3.43

For all models, realistic figures of absorption and diffusion were used. Audience was simulated as fully occupied with Odeon material n°. 907 (“Audience, heavily upholstered seats”). Stage was modelled with orchestra by using Odeon material n°. 900 (“Orchestra with instruments on podium, 1.5 sq.m per person”). For walls and ceiling the Odeon material n°. 2354 was used (“Walls, average total residual absorption of 15 halls”). No other materials were used.

Scattering coefficient of 0.65 was used for audience and stage area in all frequencies 125~4000 Hz. For walls and ceiling scattering coefficients were frequency dependent and set as 0.30 for key diffraction frequency 707 Hz [2]. Such a high value was chosen based on suggestion of positive correlation between preference and high level of diffusity of room boundaries [11]. This was also consulted with the Odeon developers.

Room height for all models was 14 meters, which according to simple Kosten [12] formula should result in reverberation time of approx. 2.0 sec. This formula is widely used for preliminary room dimensioning during early design phase, so it was chosen as a reference for models height.

Omnidirectional source was positioned centrally, 1.2 m. over stage, 3 m. away from stage front. Source overall gain was set at 31dB to allow Strength (G) calculations.

In each model a grid of receivers was created 1.2 m. over audience area, based on 1x1 meter grid. Depending on volume, 300 to 850 receivers were created in models. No receivers were less than 1.0 from walls/stage front.

Most important Odeon calculation parameters (in "Room Setup") were set as following: number of rays was 50 000, transition order was 2, desired late reflection density (in grid response) was 999999/ms, impulse response resolution was 1ms and angular absorption was set to "all materials". Temperature was set at 20°, relative humidity at 50%.

For all receiving positions in all 24 models, eight objective parameters have been calculated, namely Reverberation Time (T_{30}), Early Decay Time (EDT), Clarity (C_{80}), Strength (G, G_{early}, G_{late}), Early Lateral Energy Fraction (LF_{80}) and Late Lateral Strength (G_{LL}). Only 3 parameters mentioned in ISO 3382 are discussed here - Clarity (C_{80}), Strength (G) and Early Lateral Energy Fraction (LF_{80}).

2.2 Regression models

Based on measurements in 53 concert halls simple relations between room geometry and objective acoustical parameters have been found [8, 9] and presented in the form of linear regression models. Regression models used in this paper for comparison with simulation results are shown in Table 1.

Room acoustical parameter	**Regression model: F (theory, geometry)**	**Correlation coefficient**	**% of variance**	**STD residuals**
Clarity C_{80} [dB]	$-1.7 + 1.1C_{exp} + 0{,}065$ W	0.84	70%	0.9 dB
Strength G [dB]	$-0.56 + 0.84\ G_{rev}$	0.91	83%	1.0 dB
Early Lateral Energy Fraction LF_{80}	$0.39 - 0.0061$ W	0.70	49%	0.05

Table.1 Linear regression models used in this paper for comparison with simulation, where: ***W*** – hall width; $\mathbf{C_{exp}}$ = expected seat average Clarity based on Sabine diffuse theory; $\mathbf{G_{rev}}$ – expected seat average values of Strength based on Barron revised theory.

In regression models, for calculation of expected values of C_{exp} and G_{rev}, room-averaged simulated Reverberation Time (T_{30}) was used. For G_{rev} calculation, room averaged source-receiver distance was used.

All regression models were made based on measurements in empty halls, while simulations were made based on fully occupied audience - this should be noted while comparing both, particularly in case of Clarity and Strength.

3 Results

To simplify the presentation of simulation results, they were averaged over individual frequency range, as recommended in [13]. Results of Clarity (C_{80}) and Strength (G) are average of 500Hz, 1000Hz and 2000Hz. Results of Early Lateral Energy Fraction (LF_{80}) are average of 125Hz, 250Hz, 500Hz and 1000Hz. For all results, only receivers positioned more than 10m from source are included.

3.1 Reverberation Time (T_{30})

Relation between shape and Reverberation Time is not within the scope of this paper, but a few observations should be noted.

Theoretical mid-frequency Reverberation Time calculated for all three analyzed volumes according to Kosten [12] formula should be 2.06 seconds (± 0.01).

Simulated T_{30} averaged as recommended in [14] over frequency range 125~2000Hz was close to 2.0 seconds for V=8 000 m^3 and was slightly increasing with volume, up to 2.17 seconds for V=16 000 m^3.

Reverberation Time (T_{30}) for all analyzed models is shown in Fig.3, with mean values, +/- Standard Deviation and 1st, 5th, 95th and 99th percentile.

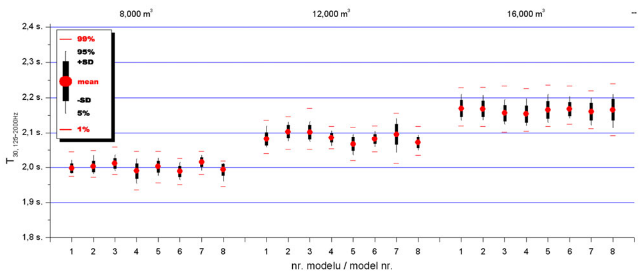

Fig.3 Room-averaged Reverberation Time $T_{30,\ 125\sim2000Hz}$ calculated by Odeon (grid response) in all analyzed volumes and models. Models N°. – see Fig.2.

3.2 Clarity C_{80}

Results from simulation shows (Fig.4) that room-averaged Clarity (C_{80}), is between 0 to -1 dB. In rooms close to square in shape, (model 1) Clarity is close to 0dB, and it decrease to approx. -1 dB with elongation of the room. For rooms with plan close to square, especially in smallest volume (8 000 m^3), deviation of C_{80} values from mean is small with Standard Deviation (SD) equal to 0.3 dB. In other shapes uniformity of Clarity distribution decreases with increase of volume and elongation of shape. Maximum SD was found in model 8 from volume 16 000 m^3 - 1,1dB. For comparison, SD for Clarity given in [15] for three best classical "shoe-box" type concert halls is 1,5 dB. As programs like Odeon will not reproduce the wave effects and can therefore be expected to give smaller values for the SD, also for Clarity [16].

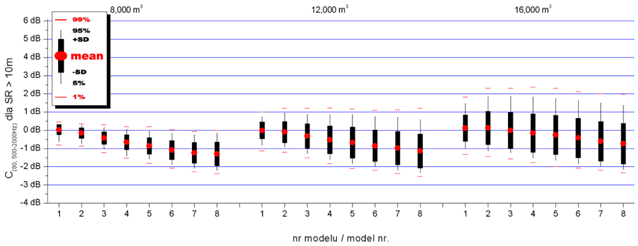

Fig.4 Comparison of room-averaged Clarity $C_{80,\ 500\sim2000Hz}$ calculated by Odeon (grid response) in all analyzed volumes and models. Models N°. – see Fig.2.

Comparison of simulation results and figures calculated based on Clarity regression model is shown in Fig.5. As regression models were created based on measurements in empty rooms, simulation results need to be corrected for lack of audience. To do this, simulations were repeated for several models with absorption of audience changed to ‘empty well upholstered chairs’, and absorption of stage changed into ‘parquet on counter floor’. Clarity simulated in empty conditions was approx. 1.3 dB lower, than in fully occupied state, so results from simulations shown in Fig 5 were lowered by approx. 1.3 dB, to allow direct comparison with regression model.

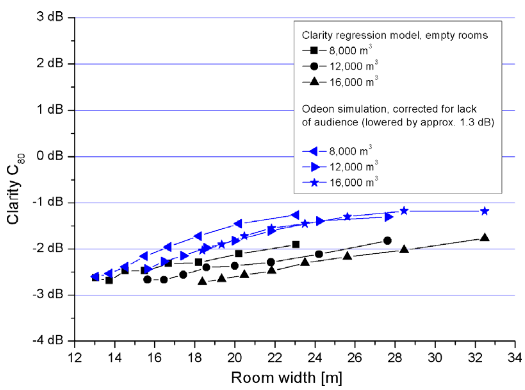

Fig.5 Relation between Clarity and room width shown for Odeon simulation (corrected for lack of audience) and for Clarity regression model from Table.1 (empty rooms)

Simulation and regression model results agree quite well. Clarity is increasing with room width both in simulation and regression model. Simulation results show, that for rooms wider than 26 meters this increase is becoming marginal. Also difference between two largest analyzed volumes is almost not visible in simulation, while it is visible in calculation of Clarity based on regression model.

3.3 Strength G

Simulation results show, that room-averaged Strength (G), is between 2 dB for 16 000 m^3 models to 5.5 dB for 8 000 m^3 models. Within one volume, mean Strength slightly decrease with elongation of a room. Increase in room volume by 50% make Strength to decrease by approx. 1.5 dB. This was shown in Fig.6.

For rooms with plan close to square, deviation of G values from mean is small, with Standard Deviation equal to 0.3~0.6 dB. In other shapes uniformity of Strength distribution decreases with increase of volume and elongation of shape. Maximum SD was found in model 8 from volume 16 000 m^3 - 1,5 dB. For comparison, SD for Strength given in [15] for three best classical “shoe-box” type concert halls is 1~1,5 dB.

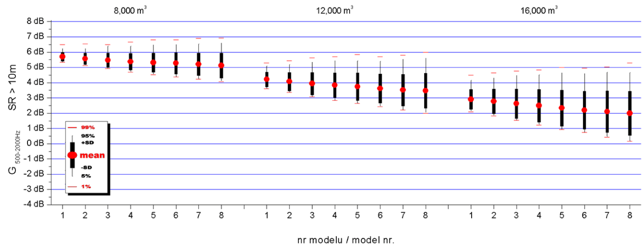

Fig.6 Comparison of room-averaged Strength $G_{500\sim2000Hz}$ calculated by Odeon (grid response) in all analyzed volumes and models. Models N°. – see Fig.2.

Comparison of simulation results and figures calculated based on Strength regression model is shown in Fig.7. For the same reasons as in Clarity comparison, simulation results need to be corrected for lack of audience. This was accomplished in the same way, as described earlier. Strength simulated in empty conditions was approx. 1.0 dB higher than in fully occupied conditions, so results from simulations shown in Fig 7 were increased by that figure, to allow direct comparison with regression model.

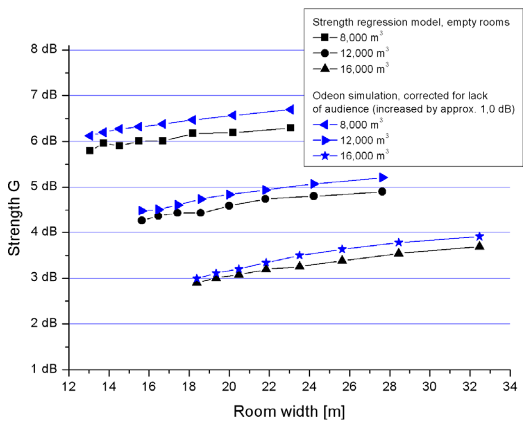

Fig.7 Relation between Strength and room width shown for Odeon simulation (corrected for lack of audience) and for Strength regression model from Table.1 (empty rooms)

Simulation and regression model results agree very well. Strength is increasing with room width both in simulation and regression model. It is probably due to fact, that in more square rooms, audience is seating closer to source, than in long rooms, so room-average Source-Receiver distance is smaller.

3.4 Early Lateral Energy Fraction LF_{80}

Simulation results show, that in analyzed models room-averaged Early Lateral Energy Fraction is between 0.20 to 0.25. In rooms with shape close to square (model 1), room-average LF_{80} is close to 0.25, and decrease to 0.20 with elongation of room. This is shown in Fig.8.

Standard deviation is rather small in all models (0.03 ~0.04), compared to measurements in real halls [15], where SD is typically in range 0.05 to 0.10. This is due to lack of wave effects in computer simulations [16]. On the other hand within-hall variations of LF are huge, reaching 50% in some models. This makes traditional room-average values of little use, if they are not supplemented with additional information, like histograms or percentage of seats falling into particular range.

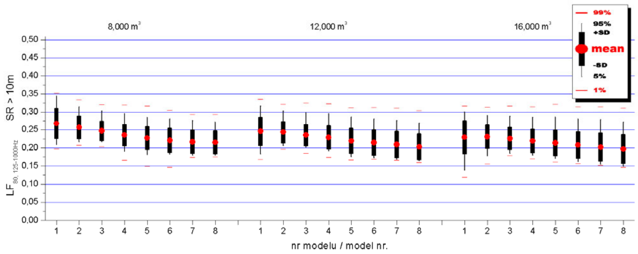

Fig.8 Comparison of room-averaged Early Lateral Energy Fraction $LF_{80,\ 125\sim1000Hz}$ in all analyzed volumes and models. Models N°. – see Fig.2.

Outcome from comparison of simulation results and figures calculated based on LF regression model is shown in Fig.9. Additionally to linear regression from Table 1, in Fig.9 second regression was added, given in [17]. When simulation results are grouped by volume, it is clearly visible, that the relation between LF and room width is not as expected. Simulation results show LF increase with width, while both regression models predict the opposite! There are several possible explanations of this:

a). strong linking of the geometrical variables in models used in simulations: with the room height and volume kept constant, the length of the hall is rapidly changing from long to short with the increase in width; this may lead to unnatural shape ratios that could cause other factors than the width to dominate in the results;

b). by changing length-to-width ratio, the receiver positions are stretched to the sides along with stretching the hall width; so the hall becomes very short at the same time, and as receivers are always pointing towards the source, it may be that it actually turn the hall around the receiver into becoming a "narrow" hall again (now determined by the front and back walls) while the receiver "turns" its head orientation towards 90 degrees (to be parallel with the seat row instead of normal to it); that would happen with measurements as well!

c). Odeon is erroneous in calculation of LF or scattering coefficients used in simulation are not realistic;

d). width is not the only one factor to influence the LF in concert halls.

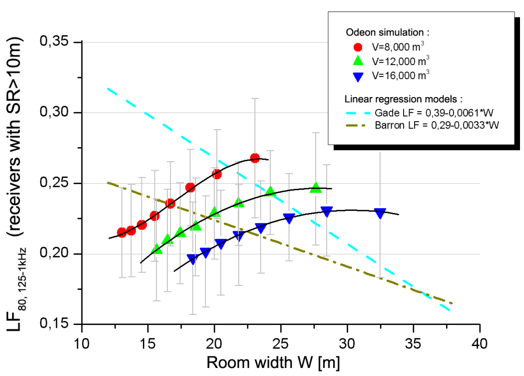

Fig.9 Relation between LF_{80} and room width shown for Odeon simulation and for two regression models (by Gade and Barron) grouped by models volume.

To investigate this surprising result, an additional simulation was performed on one selected model (Model 6, volume 12 000 m^3). Starting from this model, seven additional models were created, with width gradually increased by 4 meters. Results of room-averaged LF_{80} for this additional simulation are shown in Fig.10. It shows, that even if only width is increased, LF do not follow the regression models very well. The decrease in LF values starts to be seen from width of approx. 30 meters.

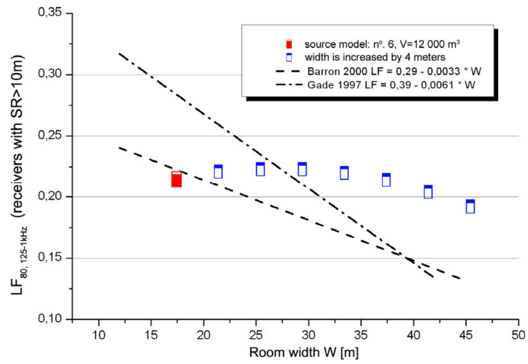

Fig.10 Relation between LF_{80} and room width shown for one model (Model 6) with varied width

As mentioned earlier, one possible explanation for the relation shown in Fig.9 is, that width is not the only geometrical parameter influencing LF in concert halls. Changes in height are known to have rather low influence on LF [18], assuming the ceiling is not too low. So other parameter left is the length. Small concert halls are narrow in general, while large ones are wide, so maybe a width and length are both responsible for changes in magnitude of Early Lateral Energy Fraction in concert halls. To prove it, a different presentation of results from Fig.9 is shown in Fig.11.

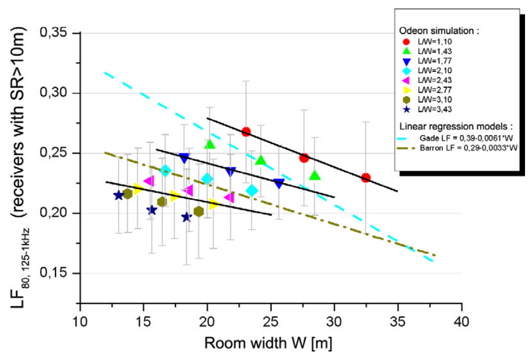

Fig.11 Relation between LF_{80} and room width shown for Odeon simulation and for two regression models (by Gade and Barron), grouped by models length-to-width ratio.

This time results from simulation were grouped not by volume, but by length-to-width ratio of analyzed models. The decrease in LF with width is clearly visible now (marked in Fig.11 with three black lines representing best fit linear regression for L/W ratio of 1.1, 1.77 and 2.77), and its slope is similar to both linear regression models. But it is also clearly seen, that increase in width always lowers LF only in rooms with similar L/W ratio. It also explains, why rooms with same width can have much different LF values, and also, why rooms with different width (like Amsterdam Concertgebouw and Vienna Gr. Musikvereinssaal) can have similar LF.

The relationship between room length-to-width ratio and Early Lateral Energy Fraction LF_{80}, shown in Fig.11 can be presented in numerical form, as equation, having room width (W) and room length (L) as variables. It is shown below as Eq.(1) [10]:

$$LF_{80} = 0.22395 + 0.39148 * e^{\frac{-L}{W*1.03755}} - W * \left(0.00193 + 0.01081 * e^{\frac{-L}{W*0.6763}}\right) \quad (1)$$

where: **W** - room width in meters; **L** – room length in meters.

Equation Eq.(1), together with two linear regression models shown in Fig.9 were used to calculate expected values of LF_{80} in 16 existing rectangular concert halls with volume 4 000~20 000 m^3, where also LF measurement data exist [7, 9, 19]. For each of three best classical concert halls [15] both measured values, given in [19] were used. Differences between predicted and measured values were compared, and shown in Table.2 as mean prediction error.

prediction model	mean error	Std. Dev.
Eq.(1)	0,035	0,028
0.39-0.0061*W (Gade)	0,046	0,029
0.29-0.0033*W (Barron)	0,039	0,031

Table.2 Comparison of 3 prediction models expressed as mean error between predicted and measured values of $LF_{80,\ 125\text{-}1kHz}$ for 16 rectangular concert halls.

4 Conclusion

The results of this paper permit conclusion concerning strong influence of room shape on acoustics of “shoe-box” type concert halls. This paper confirm that in rectangular concert halls having identical volume and absorption/diffusion characteristic, room shape is an important factor influencing acoustics. Even without changing Reverberation Time, other acoustical parameters, like Clarity (C_{80}), Strength (G) and Early Lateral Energy Fraction (LF_{80}) are sensitive to changes in room geometry.

Results from simulation shows, that with the exception of Reverberation Time, values of all analyzed parameters vary greatly depending on receiver position. This information is lost, if only room-averaged values are used to describe the acoustic of particular concert hall. It is then recommended to describe concert hall acoustics with more information, than just mean values. Histograms or stating percentage of seats falling into particular range could be useful.

In the case of Clarity and Strength results from simulation matches linear regression models quite well, reconfirming the regression models and proving the quality of simulation method.

In the case of Early Lateral Energy Fraction, the hall width only was found to be insufficient to describe the LF_{80} behavior in simulated rooms. An updated formula for predicting of LF_{80} in rectangular halls has been proposed, which takes into the account both width and length of hall.

Acknowledgments

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