SOUND STRENGTH IN SMALL HALLS

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1. INTRODUCTION

A major acoustical challenge in designing large concert halls has been to create a large room that nevertheless sounds acoustically "intimate" and in essence for it to sound smaller than it physically is. Research over the past several decades has indeed been aimed at determining what factors relate to Acoustical Intimacy[1,2] and to finding architectural correlates which provide adequate loudness, reverberance, and spatial impression in large occupancy halls.

The subject of this paper turns the large hall problem upside-down. Here, we analyze the situation of a low occupancy concert hall which must accommodate a full orchestra, perhaps even with choir. Such a space for the purposes of this discussion is less than 1,000 seats, down to as low as around 400 seats. The acoustical challenge is to take a "small hall" and make it sound like a large one. While such a space might be termed a "chamber hall," it will nevertheless require extraordinary physical solutions when it presents a full orchestra, e.g. playing Bruckner or Mahler.

In summary, the acoustical success of large concert halls hinges on the ability to provide intimate sound, with the impulse response of a smaller space, including adequate sound strength. The success of a small occupancy hall for the same large orchestral source requires making the hall sound appropriate to the nature of the source, which in part means that it not be too loud while at the same time preserving the reverberation characteristics know to be preferred.

2. ACOUSTICAL COMPARISON OF LARGE AND SMALL CONCERT HALLS

Of the orthogonal objective factors believed important in concert hall acoustics, this paper will center its analysis on the factors of Sound Strength (G) and Reverberation Time (T), with a brief mention of the Clarity Index (C_{80}). [In this discussion, the objective factors for mid-frequency values averaged over the space in question (i.e., G = G_{mid}(ave), T = T_{mid}(ave)).]

In comparing the impulse response or large and small halls, the major features of comparison are as follows: a) level of the direct sound, b) level of the early reflections, c) the time density of the early reflections, d) total early reflection energy (@ 80 msec), e) directional character of the early reflections, f) level of the reverberant or "late" field energy, g) total sound strength, and h) the decay rate of the reverberant field.

A comparison of each of these acoustical issues essentially shows that all the acoustical attributes are greater in value for the smaller, lower seat-count performing space. It will be shown later in the this paper how these attributes are dealt with to reduce their value to more resemble a larger hall with a sound field more appropriate to a large orchestra performance. The technical work given in this paper deals with the issues of balancing sound strength and reverberation decay characteristics in small occupancy halls, and on how quick calculations of these factors can be made early in the design process.

3. CRITERIA FOR SOUND STRENGTH (G) IN CONCERT HALLS

The range of desired and maximum values of G in the case of concert halls has not been widely discussed in the literature. Before computer-driven calibrated measurement technology quite common by 1990, the issue of "loudness" in a hall was essentially connected to the measurement of Reverberation Time (T) in that they are both dependent (inversely) on the total sound power absorption (A) in the room. Nevertheless, in the 100 years time over which T has been measured, the positive relationship between T and the "loudness" has indirectly included Sound Strength as a quality criterion[3], with the general trend being that the more popular halls were also the more reverberant. This therefore translated to the notion that more "loudness" was generally better, and for large halls desirable, as opposed to them being more "quiet."

In the past fifteen years, the measurement of G in empty large and small halls has been commonly accessible, and with this information has come a correlation with preferred values in actual spaces under performance conditions. The convention has been to measure and report average G values for empty halls (G_o). Barron[4], noting the significant variation in G versus distance in large halls, has recently proposed a distance related criterion with a minimum value set at $G_{o(min)}$ = 0 dB at a distance of 40 m. The reasoning for this is that subjective loudness in halls is found to be positively correlated with source-receiver distance[1,,2,5]. This puts the average for such large halls at around $G_{o(min.\text{-}ave)}$ = +2 dB. Earlier, Lehmann and Wilkens[6] have proposed a minimum value of $G_{o(min)}$ = +3 dB. Based upon correlating measurement and listening experience, Hyde[7] has proposed a maximum average value of G_o = +4 dB.

Since these earlier proposals, we now have had the advantage of a great deal of data, for spaces that acousticians have known well. For instance, the Musikverein in Vienna, with N_T = 1,680 seats, measures G_o > +6 dB. According to Beranek[8], the conductor von Karajan has said that the hall is too loud for a full orchestra, and Beranek agrees with him. Other smaller halls of similar quality such as the Stadt-Casino in Basel (N_T = 1,448, G_o = +6.9 dB) and the Grosser Tonhalle in Zurich (N_T = 1,546, G_o = +7.2 dB) are considered to be too loud for full orchestra. Note that these three halls have an average capacity of around 1,560 seats. Beranek[8] has recently suggested a maximum value of G_o = 5 dB (for large symphonic performances). A preferred range for average G, in the case of performing large orchestral works, is therefore suggested as +3 dB ≤ G ≤ +5 dB.

Restraint on the part of the orchestra may be an option allowing for a value for G in smaller venues to be perhaps a few decibels greater than a large hall maximum criterion, and it will be seen later in this paper that in the case of quite small rooms, say at N_T < 800 seats, every extra decibel can be quite important. Providing good musician ensemble conditions with a high level of reflected energy can assist musicians in not playing to loudly. In the case of touring orchestras, there may be difficulty in immediately adjusting to a smaller "loud" hall, whereas a resident orchestra can become used to the space and may be able to make adjustments on effort and sound power output without seriously compromising the quality of the music played.

4. "THUMB-NAIL" APPROACH TO ESTIMATES OF VOLUME AND REVERBERATION TIME VERSUS OCCUPANCY

Early conceptual design work often requires the ability to make quick judgments about room size, and to be able to quickly adjust factors such as seating size, volume, and floor area to understand the order of magnitude of the acoustical changes. Often, these judgments take place before an architectural plan is developed, and early input can help direct the design team as to scale, room form, building massing, and degree of acoustical variability as a function of room presentation use and audience size. As the design is developed, simple computer models can be used to quickly (on the order of less than a day, perhaps) validate the initial design, followed by more detailed computer modeling, (and in the case of high profile, high budget projects, 1/10th scale physical models can be built and tested).

The first round of "thumb-nail" calculations can be quickly done making well established assumptions about typical "lumped" absorption values[9] (i.e. for empty and occupied seats, and for all other "lumped" hard surfaces) and with the use of empirical relationships derived from nearly two decades of acoustical measurements[10] in small and large performing spaces. Quick calculations of T_{occ}, Volume (V) and Strength G_o require, on the first order approach, knowledge of the basic surface areas involved, those being the seating area, aisle area, and all other hard areas, here referred to as "lumped" areas. In order to perform "quick-calcs," the authors have developed these area relationships as a function of room design type, and have then applied them to empirically derived relationships, primarily for those of T_{occ} versus V and A, and for G_o versus occupancy N_T.

The approach is to define a value "beta" as being the ratio of all hard "lumped" areas (S_L) to the sum of the seat (S_s) and aisle (S_a) areas. Thus our hall design type parameter (β) is defined as $\beta = S_L / (S_s + S_a)$. For typical large and medium size concert halls, using balconies and a proscenium style stage performance end, β ≈ 3.4. Also included in this design class are older halls with densely packed seating areas (e.g. the Musikvereinsaal, Vienna, β = 3.8, T_{occ}= 2.0 sec.). The other basic hall type reported here is for typical European style chamber and concert halls as follows: These have a) the volume at full height above the stage end, and b) a stage of at least 150 m^2 capable of accommodating a large orchestra. Such rooms which have modest balconies and shallow boxes have a value of β ≈ 5.5; smaller rooms with no balconies and little or no shallow boxes have a value around β ≈ 7.0.

Borrowing from the work of Beranek[11] the relationship between T_{occ} and the room absorption quotient of V/S_T can be plotted where S_T is defined as the sum of all major absorptive areas including the seating area S_s, a seating "edge" correction, and the orchestra. Figure 1 shows the generalized relationships for T_{occ} versus V/S_T, and shows the typical values derived for the three hall design type values (β).

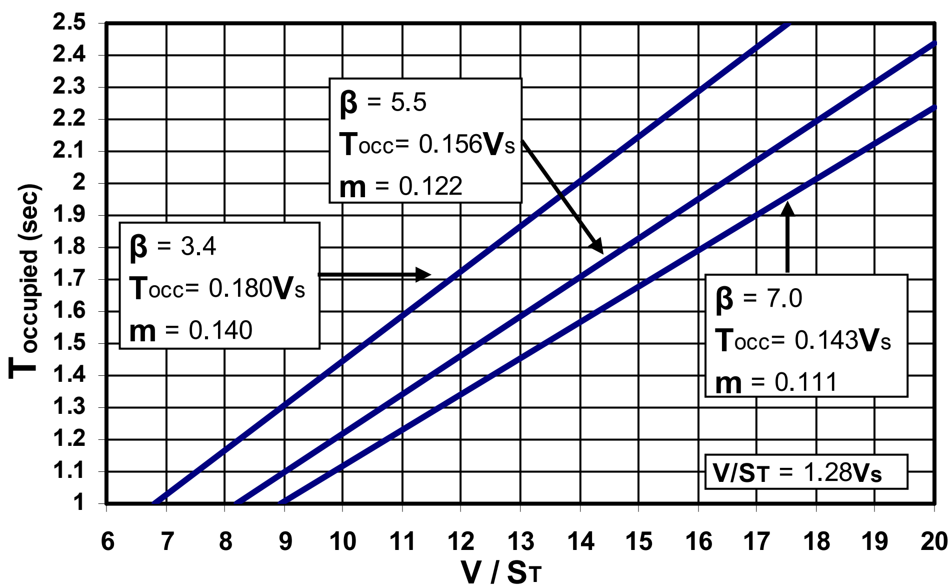


Figure 1 – T_{occ} versus V/S_T as a function of room design parameter β

[Note: The values indicated assume a seating edge correction of 14% of the seating area, and the number of musicians being 1/10th the number of seats, up to a total of 100. The equations for T_{occ} and V/S_T in Fig. 1 assume no added absorption and no carpet in the aisles. In this case, then, $S_T = 0.78 \cdot N_T$, yielding the relationship of $V/S_T = 1.28 \cdot V_s$ where V_s is the Volume per seat, V/N_T. "m" indicates the slope.]

An example of the use of Fig. 1 is to apply the typical “small” European hall type of β ≈ 5.5, where in this case we choose the criterion of T_{occ} = 2.1 sec. From the figure, V/S_T = 17.25 m, and for $S_T = 0.78 \cdot N_T$ as discussed above, $V = 13.45 \cdot N_T$. For an 800 seat hall, therefore, we estimate a volume of V = 10,760 m^3 will yield T_{occ} = 2.1 sec. At this point, no added absorption is considered to be in the space. The design guides of Fig. 1, therefore, present a quick way to determine the minimum Volume of the hall, based upon the approximate hall “design type” β, number of seats N_T, and the criterion for T_{occ}. Note that as β increases, the reverberation efficiency of the space decreases

The next task is to apply the newly derived Volume to the empty hall and determine the value of Sound Strength G_o. If additional absorption is required to reduce G_o, the volume will need to be increased to attain the chosen criterion for T_{occ}.

5. SOUND STRENGTH (G) VERSUS OCCUPANCY (N_T)

G in an enclosure involves the summation of the direct, early reflected and late reflected reverberant energy. It is also correct to say that G is simply inversely proportional to the sound power absorption (A) of the space. Defining G_{exp} as the value of G for all reflected energy based on statistical theory, we have $G_{exp} = 10 \cdot \text{Log}(40^2\pi/A)$. Many measurements of G have been made in concert and chamber halls in which the sound power absorption A has been determined through the measurement of T and knowledge of the Volume of each space. From these, an empirically derived regression is attained showing a linear (logarithmic) inverse relationship between G and A, and with the slope of the regression line indicating the predicted 3 dB drop in G for a doubling of A. In rooms below 1000 seats, the generalized value for G in an empty hall is found to be:

$$\mathbf{G_o = -1.2\ dB + 0.94 \cdot G_{exp} = (\,33.6 - 9.4\ Log\ A_o)\ dB}\ [12] \qquad \mathbf{(1)}$$

where A_o is the power absorption value for the empty room. Using the same “lumped” surface analysis discussed in Section 4, the following values for A_o can be derived for the three hall design types as follows (assuming the empty seat absorption coefficient as α = 0.68): [β ≈ 3.4, $A_o = 0.67 \cdot N_T$], [β ≈ 5.5, $A_o = 0.80 \cdot N_T$], [β ≈ 7.0, $A_o = 0.90 \cdot N_T$]. These values assume a “modern” seating density of 0.56 m^2/seat. Substituting into Eq. (1) above yields a theoretical family of curves which defines the approximate number of seats as a function of G_o as shown in Fig. 2.

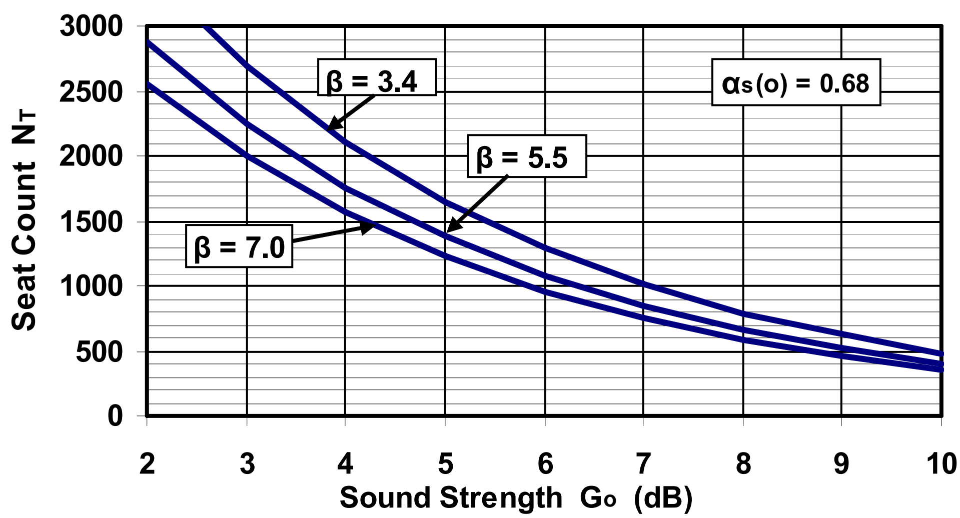


Figure 2 – Sound Strength G_o(empty) vs. seat count N_T and design type β

It can be seen from Fig. 2 that small halls around 500 seats will have G_o ≈ +9 to 10 dB which may be preferred for chamber music and recitals, but be considered too loud for larger sources for which variable absorption would need to be added.

If the number of proposed seats for a project is less than that determined for a given G_o criterion in Fig. 2, absorption must be added to make up the difference. In a typical chamber hall design of $\beta \approx 5.5$, $A_o \approx 0.80\ N_T$, the amount of added absorption required, expressed in metric Sabines, is $\Delta A(m^2) = A_{max} - 0.80 \bullet N_T$ where A_{max} is calculated from Eq. (1) for a given G_o criterion. This relationship is shown in Fig. 3 where the intersection of constant G values with the abscissa indicates the maximum number of seats shown in Fig. 2 for $\beta \approx 5.5$.

To use Fig. 3, choose the proposed number of seats and the maximum value for G which would best match the use of the hall per the discussion in Section 3. Where the number of seats intersects vertically with the chosen value of G, the approximate amount of absorption (metric Sabines) required to be added is found on the ordinate. To cover the broad range of performance size, from soloist to full symphonic, it is presumed that a good deal of this added absorption would be variable in nature.

It should be emphasized here that these are general design guidelines derived through "thumb-nail" calculations, very early in the design process. They are based upon average mid-frequency behavior, averaged over many halls. For instance, a desirable goal might be to achieve G=+4dB, and based upon averages, Fig. 3 would indicate that there can't be more than around 1800 seats (for $\beta \approx 5.5$). There are other aspects of the design, however, such as increasing reverberation efficiency, and providing significant early reflections which increase the value of G away from the regression average. Doing so would increase the number of allowable seats.

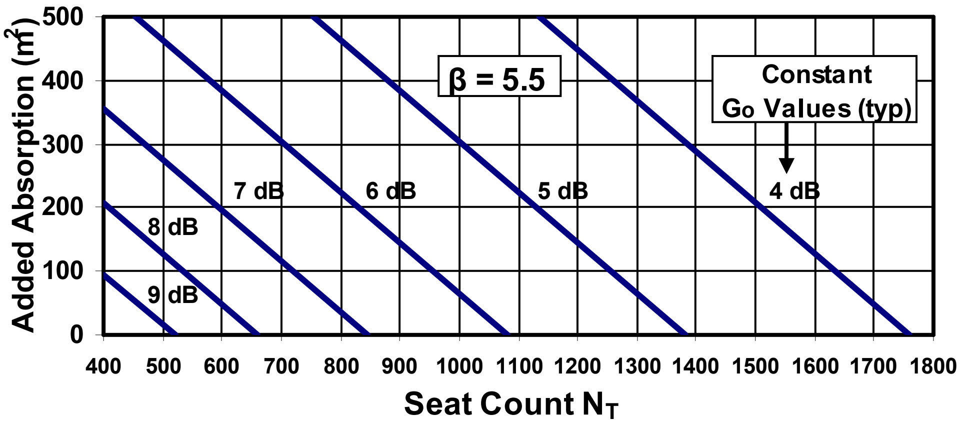


Figure 3 – Seat count versus added absorption for constant G_o (β = 5.5)

This paper, however, is about the lower end of occupancy, where the issue at hand is potentially one of too much Sound Strength from a large symphonic source. In this case, in addition to increasing inherent room absorption, the design might also increase the seating area, and selectively absorb early first order reflections which significantly contribute to G.

<u>A note on Clarity Index (C_{80})</u>: Quick estimates of the relationship between C_{80} and the factors A and room volume (V) can be made using the statistically derived formula for the Clarity Index of $C_{80} = 10 \bullet \text{Log}\ [\ \exp(7A/V) - 1\ ]$ dB. The preferred value for this objective factor is in the range of from -1 dB to + 2 dB for symphonic music.

6. GENERAL DESIGN CONSIDERATIONS FOR SMALL HALLS

In most cases the small halls described in this paper are located in small cities, typically with less than 100,000 inhabitants. Normally these locations can only accommodate one multipurpose hall. This means that the hall also has to provide a rich variety of performance types, apart from acoustic music. Typically the specifications for these halls are, in order of priority:

- Classical music (acoustic music, from large symphony to recital)
- Conference
- Reinforced music, including “rock” and popular music
- Music theatre and opera
- Drama theatre
- Others shows and community uses, such as circus, banquets, etc.

Examples of these types of halls are common at least in the Nordic countries, typically represented by the majority of the halls in Finland[14, 15]. In a way this priority list of course is contrary to the fact that the major income for these halls is from conferences and popular (reinforced music) concerts. As the halls are normally operated by the local government however, the design brief is done as part of a political process, and thus classical music normally ends up with the highest priority. From the standpoint of design input requirements, this priority would seem justified.

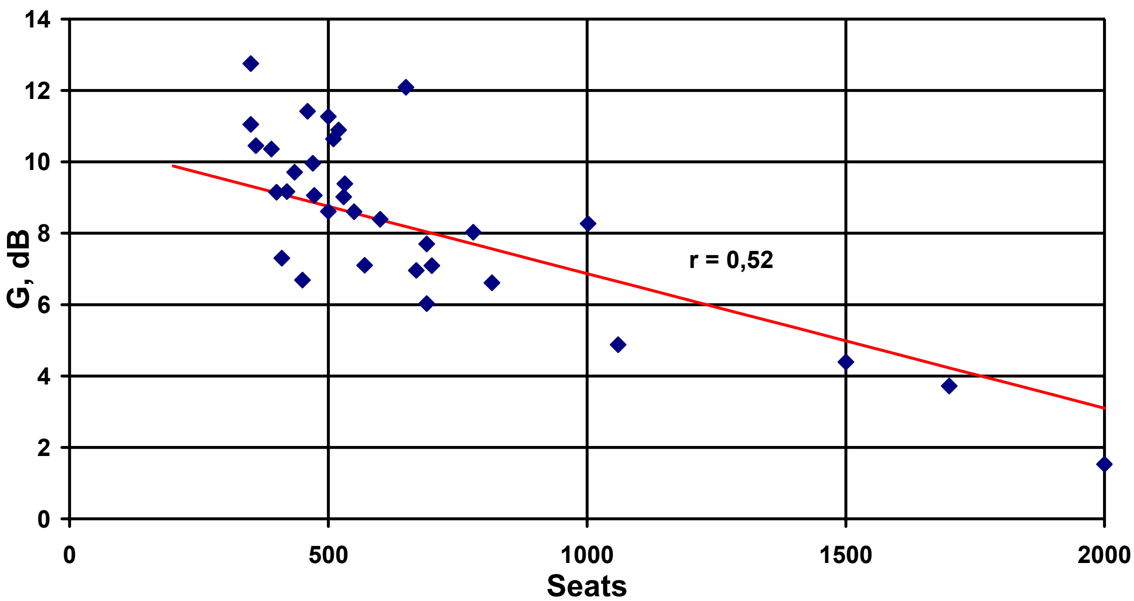


Figure 4 – Measured G_o in Finnish halls as a function of seat count N_T [15]

From a design point of view, the above specifications imply:

- Variable acoustics,
- Well functioning stage mechanics and AV-systems
- Variable seating layout

In most cases the main limitation of the architectural design will normally be the basic “foot-print” of the hall. Also the width is determined both by the requirements for lateral efficiency, as well as by stage conditions. Thus the necessary volume is achieved through choosing the height of the hall.

The secondary advantage of extra height is that when additional damping is needed, this can done by drapes or panels applied in the ceiling area, in other words by acoustically reducing the volume instead of changing the acoustic properties of important reflection surfaces. In the case of large symphonic presentations, however, even some early first order reflections may also need to be attenuated to assist in controlling G as well as image shifting. These changes in the reverberant, Sound Strength and early reflection conditions are the basic tool in helping a small occupancy hall sound appropriate for the larger symphonic presentations.

As stated earlier, full height above the stage is assumed. From a performance space design point of view, this has the advantage that it is possible to achieve a “semi” fly tower for theater productions.

Given a minimum height above the stage of 16 m, a “proscenium” opening height of about 5 m can be achieved for theater-type presentations, which with an opening width of about 12 m is acceptable. This obviously also implies that the acoustic reflectors or canopy can be removed or at least moved out of the way.

7. VERKATEHDAS HALL, HAMEENLINNA, FINLAND: A CASE IN POINT

7.1 Project Outline and Design Brief

The genesis of looking at the “large orchestra in a small hall” concept was the new, yet to be built concert hall for the city of Hämeenlinna, Finland. Here, the design programme included the ability to present a full 100 piece orchestra in a hall seating less than 750.

The project was started by an architectural competition in 2003. In the architectural brief for the competition, a shoebox-style concert space with one or two side balconies was called for. The brief also called for a width of 17-19 m and a minimum height of 16 m., with full height in the whole space.

Use of the hall is as the list presented above, however the priorities were not as strict as normally seen. In this case it was decided that acoustics of the hall should be designed for a full orchestra as long as it did not jeopardize the other uses. It should be noted the city of Hämeenlinna only has a small city orchestra so the full size orchestra comes from a wish to accommodate visiting orchestras. In general the brief called for the “next generation” Finnish Cultural Center.

The architectural competition was won by JKMM Architects from Helsinki and the design was begun in 2004 and the complex is to be completed by June 2007.

7.2 Preliminary “Thumb-nail” Acoustical Results

From the design brief of approximately 750 seats plus the dimensions listed, an approximate room length of 35 m was estimated, along with the room having a maximum volume in the range of from 9,500 m^3 up to around 11,500 m^3. This range was based upon the knowledge that a larger than normal volume would be needed to allow for attaining the balance between T_{occ} and G_o, achieved, essentially, by a ceiling height approaching 18 m. Taking into account the existence of a rear balcony and two shallow side box balconies, the first calculations used V = 10,000 m^3 which for 750 seats is V_s = 13.3 m^3/seat, normally considered to be a high value.

Another reason for using this volume was based upon the design philosophy of Kahle, a collaborator on this project, and the choice of a minimum volume depending upon the size of the largest acoustic performance, in this case being a 100 musician orchestra. The theory applied here suggests a minimum volume of 10 m^3/musician, where the assumption is that in smaller rooms, there would be at least 10 patrons/musician, and each patron would require a minimum of 10 m^3.

The design parameter β for this type of hall (see Section 4) is known to be in the range of $\beta = 5.5$. The preliminary acoustical criteria were chosen as T_{occ} = 2.0 sec, $G_o \leq +6$ dB. Consulting Fig. 1, the value V_s = 13.3 yields T_{occ} = 2.07 sec. and V/S_T = 17.0. Using $A_o = 0.80 \cdot N_T$, T_o = 2.7 sec. is found for the empty room. From the information given in Section 5, and from Fig. 2, N_T = 750 yields a value of G_o = 7.5 dB, for $\beta = 5.5$. From the data in Fig. 3, reducing G_o to +6 dB would require the addition of approximately 270 m^2 (metric Sabines) of absorption to the space. Adding this absorption to the full occupancy condition yields a revised T_{occ} = 1.56 sec. which is significantly lower than accepted reverberation criteria for symphonic uses.

Analysis of these data indicates that either the volume may need to be increased, or the criteria reevaluated. This is an example, however, of the early "thumb-nail" calculation process, allowing for making quick adjustments of variables in the beginning stages of a design, before the architectural details of the room are developed.

7.3 Design Development and the Results of Computer Modeling

The winning entry from the architect competition had a basic shoebox layout, with a width of 17 m and 3 levels of side balconies. The design was investigated by computer modeling [ODEON] with the following principal results:

- The overall width of the hall should be increased to about 18 m, both for stage acoustic reasons but also for better balance of the early reflections.
- A two side balcony layout was acoustically favorable compared to a three level side balcony layout, because the height between the balconies could be increased, thus minimizing shadow effects and as the width was increased, more seating could be achieved. Also the modeling showed that the lateral efficiency and early reflection pattern would still be appropriate.
- The modeling clearly showed the need to acoustically narrow the hall near the ceiling.
- Some (variable) absorption would be necessary to reduce early reflections from the lower parts of the side wall for some circumstances.
- The model also indicated that it would be desirable to add (variable) absorption around the orchestra in some cases.

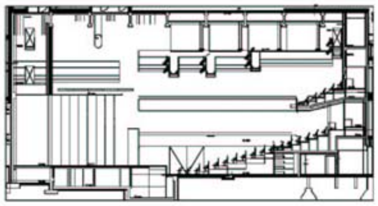
After several iterations of drawings were completed, the hall volume became $V \approx 9{,}500\ m^3$, $\beta \approx 5.6$, and the number of seats totaled $N_T = 715$. Using the design figures above, $V_s = 13.29\ m^3$, $V/S_T = 17.0$ m, and $T_{occ} = 2.07$ sec., with $T_o = 2.67$ sec. Figure 2 and Eq. (1) indicate an approximate $G_o = +7.7$ dB. Fig. 3 indicates that approximately 100 m^2 absorption would reduce G_o to +7.0 dB and 280 m^2 total for Go = +6 dB. Note that Fig. 4 predicts (based upon averages) $G_o = +8.0$ dB for $N_T = 715$ seats.

Modelling by ODEON indicated that the empty hall, with "medium" upholstered seats will have a reverberation time of 2.7 s and $G_o = +6.6$ dB. The model also gives $T_{occ} = 2.1$ sec. (including orchestra) and a corresponding $G_{occ} = +4.7$ dB. Different combinations of curtains and acoustical panels can vary T from $T_o = 2.3$ sec. to $T_{occ} = 1.6$ sec. and take G down to $G_o \approx +4$ dB.

The model results appear to agree well with the "thumb-nail" calculations for T but seem to significantly under-predict the inherent value for G_o. Since there is a good deal of variable absorption provided because of the need for amplified music, there is enough to reduce G if necessary, without critically affecting T_{occ}. The addition of 100 m^2 as noted above would result in $T_{occ} = 1.82$ sec. which is still within acceptable limits for symphonic works.

7.4 Acoustical Design of Verkatehdas Hall

Figure 5 – Plans of the Verkatehdas Hall, first and second floor



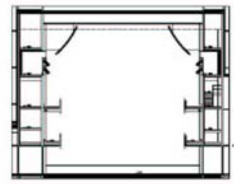


Figure 6 - Length and cross section of the Verkatehdas Hall

The hall is basically a shoe-box with two side box balconies and rear-balcony. Furthermore there is a third technical balcony. The length of the hall is approx 34 m, the width 18 m and the height 18 m above front floor, (17 m above the stage). The stage is in normal setting 18 m wide and 9 m deep (162 m^2) and can be extended by a further 4 m into the audience. The orchestral pit is 4 m deep and 14 m wide and has a nominal depth 1.4 m below the front floor.

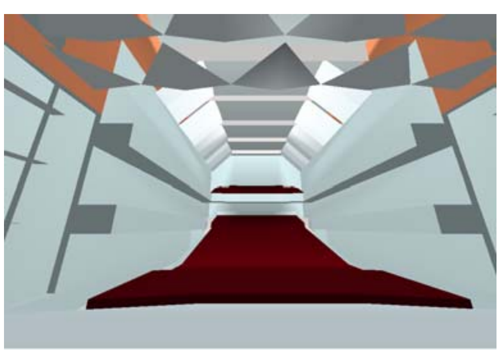
The seating consists of 416 on the main floor with movable risers, a fixed back floor with 140 seats, four side box balconies, with 16 seats on the lower and 17 seats on the upper balconies, and a rear upper balcony with 125 seats, yielding a total count of 715 seats.

The lower front floor riser can be configured to an extension for the upper floor seating, as is shown in the length section in Fig. 6, it can be configured to give a "half" rise with wider platforms for raised table seating, or it can be retracted to give a flat floor for banquets etc.

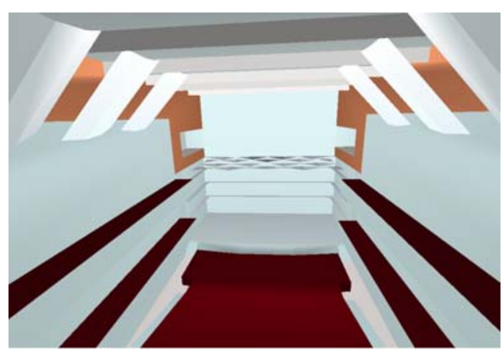
Both side and back wall are covered with "acoustic detailing" varying in depth from about 300 mm in the front of the hall to about 150 mm in the back. The variable acoustics are implemented by curtains. The main curtains are four double curtains which extend from the ceiling 3 m down over the whole width of the hall. It is intended that these curtains will be the primary tools of adapting the acoustic of the hall to different performances as well as to add additional damping for rehearsals.

Furthermore there are curtains which can cover most of the side walls. These curtains are rolled down approx 200 mm in front of the wall surface and are retracted into the balcony construction when not used. The curtains will be individually operated, which for instance will make it possible to use the lower front curtains to reduce the strength of the first reflections of the orchestra.

The stage has a reflector cloud and areas with variable absorption, both on the stage side walls and back wall. Furthermore the side wall elements can be moved to "vent" the stage or in other words provide more absorption on the stage.



From stage towards audience



From rear balcony towards stage

Figure 7 – 3D view of Verkatehdas Hall with the ODEON program.

8. DISCUSSION AND CONCLUSIONS

This paper demonstrates an alternative view on design of small rooms for full orchestras. The principles have been implemented in the design for the new Verkatehdas Hall in the City of Hämeenlinna in Finland. The principle presented here states that the minimum volume of a hall should be determined in part by the maximum size of the orchestra intended to play in the hall. The final volume is then determined by balancing the applicable criteria for G_o and T_{occ} through the application of absorption to simulate the "missing seats".

The principles shown in this paper do not give solutions to the problems of "loudness saturation" in cases where the volume of the room is locked by traditional design criteria. However, the methods presented indicate an alternative of how to make small rooms considerably better without requiring the extra seats.

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9. REFERENCES

1. J.R. Hyde, Acoustical intimacy in concert halls: Does visual input affect the aural experience?, Proc. Institute of Acoustics, Vol. 24, Pt. 4, (July 2002).
2. M.F.E. Barron, Intimacy, loudness and sound level in concert halls, Proc. 12th ICA, Toronto, Paper E4-3, (1986).
3. J.R. Hyde, Development of "modern" room acoustic parameters from Sabine's reverberation theory, Proc. Wallace Clement Sabine Centennial Symposium, Paper 2aAAa4, (June 1994).
4. M.F.E. Barron, Using the standard on objective measures for concert auditoria, ISO3382, to give reliable results, Jour. Acoustical Science and Technology (Japan), V.26, 162-169, (2005).
5. M.F.E. Barron, Loudness in concert halls, Acustica, V. 82, S21-29, (1996).
6. P. Lehman and H. Wilkens, Zusammenhang subjektiver Beurteilungen von Konzertsälen mit raumakustischen Kriterien, Acustica, 45, 256-268, (1967).
7. J.R. Hyde, Segerstrom Hall in Orange County – Design, measurements and results after a year of operation, Proc. Inst. of Acoustics, Vol. 10, Part 2, (1988).
8. L.L. Beranek, Personal communication, (March 2006).
9. L.L. Beranek, and T. Hidaka, Sound absorption in concert halls by seats occupied and unoccupied, and by the hall's interior surfaces, JASA, Vol. 104(6), 3169, (1989).
10. A.C. Gade, The influence of basic design variables on the acoustics of concert halls: New results derived from analyzing a large number of existing halls, Proc. Inst. of Acoustics, Vol. 19, Part 3, (1997).
11. L.L. Beranek, *Concert Halls and Opera Houses*, 2nd Edition, Springer, 2004, Fig. A3.1.
12. J. R. Hyde, developed on the basis of work by A.C. Gade[10] and L.L. Beranek.[13]
13. Ref. 11, Fig. 4.9.
14. H Möller, T. Lahti, and A. Ruusuvuori, New design of medium-sized concert halls, Auditoria: The legacy of the 20th Century and beyond 2000, Manchester 22-24.10.1999, Proceedings Institute of Acoustics Volume 21 Pt 6 (1999), 117-122
15. H Möller, T. Lahti, and A. Ruusuvuori, The acoustic conditions in Finnish concert spaces, 17th International Congress on Acoustics, Rome, 2-7.9.2001, CD-ROM proceedings paper 3C.10.04