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Early reflection surfaces in Concert Halls - a new quantitative criterion

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A new acoustic parameter has been defined for the acoustic brief of the Philharmonie de Paris Concert Hall. With a seating capacity of 2400 and the audience enveloping the performers on all sides, the new hall will be at the upper limit of the ideal range for symphonic music, and an efficient acoustic design was called for. In order to relate architectural design to acoustic efficiency, and based on quantitative study of existing halls, an *early efficiency parameter* was developed. For the Paris Philharmonie the brief requested a total area of 1400 m² of surfaces being able to create early reflections, with 500 m² being less than 15 meters from the stage. Another, more accurate definition expresses the early efficiency parameter in terms of the solid angle for a source on stage, allowing generalization of the new criterion for all hall sizes.

1 Definition of an architectural criterion for *early efficiency*

1.1 Why would we need an architectural criterion for *early efficiency*?

For the new Philharmonie de Paris concert hall, the client's brief asked for a 2400-seat concert hall with excellent acoustics for the symphonic repertoire, and an innovative acoustical and architectural concept. For the Acoustic Brief of this competition, Kahle Acoustics wanted to guide the pre-selected architects and their teams while allowing the development of a completely new design that would fulfil the specific requirements for a quite challengingly large concert hall. Instead of specifying a precise architectural form, it was decided to explain the architectural implications of each acoustic requirement in terms that could also be understood by architects, so that acoustics would not be a limiting factor to architectural creativity but a well-defined constraint stimulating new architectural concepts.

In such a large concert hall, a very efficient acoustic design in terms of early reflections is essential to ensure that adequate clarity and "presence of the sources" is achieved even in the huge volume required for adequate reverberance. This is what will be referred to as "early efficiency" in the context of this paper. Recent studies in psychoacoustics have demonstrated that the human ear – and the brain – differentiates the audio information into two different "data streams". One is related to the perception of the source while the other one is related to the perception of the space [1, 2, 3]. As a consequence, the design of a large concert hall should not only optimise the global loudness of the room, but should also aim to optimise separately the early response (early efficiency, providing *source presence*) and the late response (responsible for *room presence*).

Which architectural criterion should be used to quantify this acoustic early efficiency? The traditional dimensions (width, height, length) can give some information, but are probably too limited and better adapted to shoe-box designs. Adequate acoustic efficiency requires that within the volume of the hall, a sufficient surface area of reflectors (or other reflective surfaces that are part of the architecture) is located close to the orchestra and each part of the audience and oriented to create early reflections. From a 1600-seat to a 2400-seat design, keeping a good presence of the sources involves that the larger volume required for reverberance be created while keeping a sufficient amount of acoustically efficient surfaces close to the performers and members of the audience. Following these considerations can lead to "vineyard" designs, "reverberation chamber" designs or other designs in which reflectors are included in the total acoustic volume of the hall.

The acoustic brief for the Philharmonie de Paris concert hall defines other important subjective and objective parameters as well as architectural criterions, and guidelines are provided to address each of the major challenges [4, 5]. Early efficiency is only one aspect of the many acoustic requirements for the design of a large concert hall and the study presented in this paper concentrates on this aspect.

1.2 S_{EE}: Acoustically efficient surfaces

A new architectural criterion was thus developed, aiming at correlating an architectural shape to its acoustic efficiency in terms of early reflections. It can be determined directly from the plans and sections and is simply defined as S_{EE}, the total surface area of all "acoustically efficient surfaces" S_i (i = 1..N) in the room:

$$S_{EE}[m^2] = \sum_{i=1}^{N} S_i \tag{1}$$

Acoustically efficient surfaces are defined as those reflective surfaces located less than 15 m from the source(s) and/or from the audience and the orientation of which creates reflections towards the audience or back to the musicians. It is understood that these reflections can be of 1st order or of higher order.

When calculating the early efficiency parameter, the following surfaces should be considered:

- The acoustic reflectors suspended from the ceiling above the stage, or within the volume of the room.
- The balcony fronts, as long as they are efficient in the way explained above.
- The portions of the walls being acoustically efficient. Those located behind an audience are not to be considered.
- The balcony soffits, when they generate early reflections towards the stage or the audience. These reflections may be of first order or of second order.
- The ceiling of the room when part of the audience is less than 15 meters from the ceiling, and only the part of it that is efficient in the meaning defined earlier.

Obviously, this simple "total surface area"-based early efficiency parameter has some limitations. First, the 15m limit may seem arbitrary. Then, an appropriate value of S_{EE} for a given concert hall will probably depend on the size of the hall and its seat count. It may also depend on the type of music played: for example, chamber music would most likely need more "efficiency" than late romantic symphonies. In addition, the parameter defined does not estimate the uniformity of the early energy coverage, and it is up to the designers to make sure that each part of the audience and the musicians on stage are properly covered. Finally, all surfaces are not equally efficient depending on their distance to the sources and receivers and their absorption, diffusion and scattering characteristics (curvature, edge diffraction…). However, we should keep in mind that this early efficiency parameter has to be as easy to handle as possible, so that architects are able to take its requirements into account during the early development of their design.

1.3 Ω_{EE}: a refinement based on solid angles

Another definition of the early efficiency parameter has also been developed in order to take into account the amount of energy effectively reaching each of the acoustically efficient surfaces. From a geometrical point of view, the amount of energy emitted by an omnidirectional source and received by a given surface is proportional to the solid angle Ω_i of this surface measured from the source point.

For each of the acoustically efficient surfaces defined above, the fraction of energy produced by the omnidirectional source that is reaching the surface is given by:

$$\Omega'_i[\%] = \frac{\Omega_i}{4\pi} \tag{2}$$

The sum over all acoustically efficient surfaces is consequently representative of the percentage of emitted sound energy that is reflected towards the audience or back to the stage and that will contribute to early energy.

However, solid angles are very complicated to measure from plans and sections, and some simplifications are needed. For a plane surface S located relatively far from the source ($S << d^2$ where d is the distance from the centre of the surface to a source in the middle of the stage) and with a normal similar in direction to the incident sound wave, the following approximation is valid:

$$\Omega'_i[\%] \approx \frac{S_i}{4.\pi.d_i^2} \tag{3}$$

Please note that this approximation differs from the one previously defined in the acoustic brief and [4] by a $\pi/4$ factor. The impact on the results of this study and the validity of the parameters is not significant though.

The $S << d^2$ approximation generally creates a slight overestimate for large surfaces, with an error inferior to 10% until $S < 0.40d^2$. The error becomes superior to 50% when $S > 2.13d^2$ which may then create serious imprecision in the calculation: large surfaces near the stage should be divided into several smaller ones at different distances, or the parameter will be artificially overestimated. In order to guarantee an error < 10%, an appropriate division should limit the factor $S_i / (4\pi d_i^2)$ to a maximum of 3% for each individual surface.

For larger surfaces, using a peak value of 3% instead of $S_i / (4\pi d_i^2)$ leads to an underestimate which is generally less severe than the overestimate caused by the use of $S_i / (4\pi d_i^2)$. Consequently, a reasonable alternative and simplification to the calculation consists in setting for each individual surface a peak value of 3% for the factor $S_i / (4\pi d_i^2)$. This will prevent the need of dividing large surfaces in many smaller ones and make the calculation easier.

The individual solid angle fractions obtained are also overestimated each time the surface is not normal to the incident direction, which is actually the case most of the time in reality. However, a possible refinement to take into account this effect was not pursued as it would make the calculation considerably more complicated.

Finally, the mathematical definition of the "solid angle"-based early efficiency parameter is the following:

$$\Omega_{EE}[\%] \approx \sum_{i=1}^{N} \max\left(\frac{S_i}{4\pi.d_i^2};\ 3\%\right) \tag{4}$$

2 Quantitative study of early efficiency parameters in several existing concert halls

2.1 The choice of reference concert halls

The two early efficiency parameters having been defined, they were calculated and checked for a choice of existing large concert halls of various architectural shapes, in order to confirm their validity and estimate an ideal value for a concert hall such as the Philharmonie de Paris. The seven reference halls chosen are listed in table 1 below.

	Opening date	Seat count	Volume (m3)	General shape
Amsterdam Concertgebouw	1888	2040	18780 [6]	Classic shoebox
Boston Symphony Hall	1900	2620	18750 [6]	Classic shoebox
Berlin Philharmonie	1963	2340	21000 [6]	Vineyard
Christchurch Town Hall	1972	2660	20500 [6]	Surround, elliptical
Manchester Bridgewater Hall	1996	2360	25000 [6]	Shoebox/ vineyard
Sapporo Kitara Hall	1997	2010	28800 [6]	Vineyard
Luzern KKL Concert Hall	1998	1890	19000 to 25400	Shoebox with reverberation chambers

Table 1: the seven chosen reference halls

The seven halls chosen do all have a relatively large number of seats, from 1890 in Luzern to 2660 in Christchurch. Except for two classic shoebox halls (Amsterdam and Boston) and two vineyards (Berlin and Sapporo), they are all of different general shape and their volumes spread from 18750 m^3 for Boston to 28800 m^3 for Sapporo. On one side, Amsterdam's Concertgebouw is known for its richness and quite low clarity, while on the other side Luzern and above all Christchurch are known for their very high clarity and high presence of the sources. This should make this selection quite representative of the various possibilities for the design of a large concert hall.

The two volume values given for Luzern are respectively representative of a setting with all reverberation chamber doors closed and any other setting with reverberation chambers open and included in the total volume of the hall.

2.2 Results obtained

S_{EE} and Ω_{EE} parameters were calculated for each of the seven reference halls. For the Luzern Concert Hall two extreme settings were considered, representative for the range of acoustic settings of the hall: one with reverberation chambers fully open and the other with all reverberation chamber doors fully closed.

All parameters have been calculated from the plans and sections given in [6]. It is probable that these calculations are not absolutely precise as these plans and section are of relatively small scale, and short sections are generally not provided. Calculation from electronic CAD plans or larger scale paper plans would surely lead to less imprecision, but these were not available for all of the seven concert halls studied.

The results obtained are listed in table 2, together with traditional acoustic parameter values obtained from [6]. Figure 1 provides a graphical representation of these results. Each of the eight configurations tested is represented as a point in the (S_{EE} ; Ω_{EE}) plane.

A first look at the results is quite encouraging for the legitimacy of the parameters: Amsterdam obtains the lowest values for both S_{EE} and Ω_{EE}, while Christchurch obtains the highest value for Ω_{EE} and Luzern the highest value for S_{EE} when the reverberation chamber doors are closed. The variations of the two parameters seem logically correlated to general opinions on *source presence* in these halls.

The next step to validate the two parameters is to test their correlation with objective acoustic parameters related to *clarity* and *source presence*. C80 is certainly the easiest choice, as reliable measured values of this parameter can be obtained from [6] for most of the chosen concert halls. However, it is not sure whether C80 would be the most representative parameter to test "early acoustic efficiency": S_{EE} and Ω_{EE} parameters are defined to describe the behaviour of early sound only – ignoring secondary effects on late sound such as an increased absorption due to early sound being directed to the audience areas in some "very efficient" concert halls – whereas C80 also depends on the level of the late sound (and is thus not independent of the volume and reverberation time of the hall). In this respect, C80 is more representative of the balance between *source presence* and *room presence*.

	RT occupied (s), from [6]	C80 unoccupied (dB), from [6]	S_{EE} (m2)	Ω_{EE} (%)
Amsterdam Concertgebouw	2.0	-3.63	650	10,1
Boston Symphony Hall	1.9	-2.64	740	15,5
Berlin Philharmonie	1.9	-0.65	811	19,6
Christchurch Town Hall	*No data*	1.60	1328	33,0
Manchester Bridgewater Hall	2.0	-1.25	1052	23,1
Sapporo Kitara Hall	1.8	0.65	717	14,5
Luzern KKL, rev. chambers closed	1.8	*No data*	1650	30,7
Luzern KKL, rev. chambers open	2.1	*No data*	1165	20,2

Table 2: C80, RT, S_{EE} and Ω_{EE} values

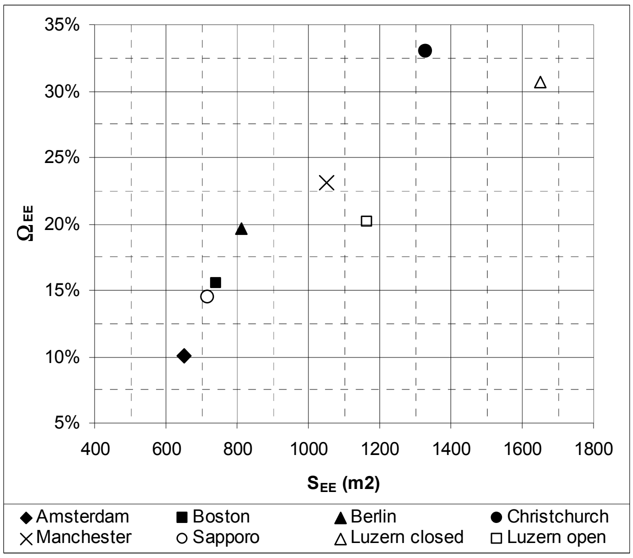

Fig.1: Graphical representation in the (S_{EE} ; Ω_{EE}) plane of the results obtained

G80, defined as the strength of the early sound, might be a better parameter to be tested for correlation [4, 5], but reliable values of this parameter are not available in the literature, and therefore only C80 was considered for this study.

C80 is plotted against S_{EE} in figure 2 and against Ω_{EE} in figure 3. Linear regressions are also drawn.

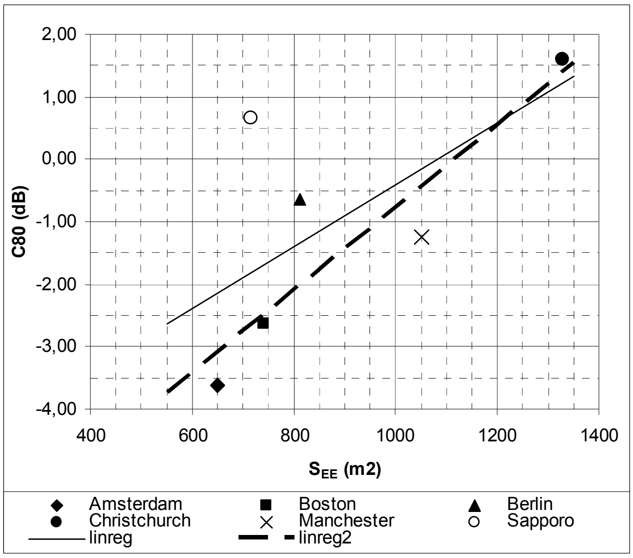

Fig.2: C80 versus S_{EE}

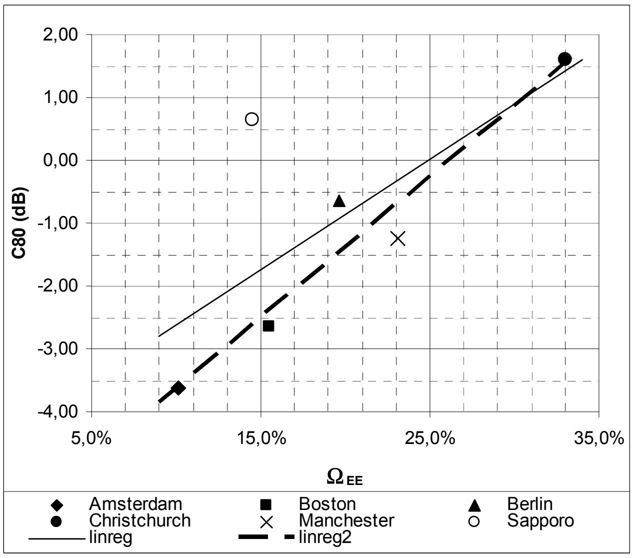

Fig.3: C80 versus Ω_{EE}

On both graphs, all points appear to be well aligned, with the exception of Kitara Hall in Sapporo. A possible explanation for this gap may lie in the fact that C80 is also dependent on the level of late sound: in cubic meters, Sapporo is the largest of the 6 halls represented, and also one with a comparatively low reverberation time. A simple calculation of total acoustic absorption from reverberation time and volume figures shows that Sapporo has ~1.55 times more absorption than the average of the 5 other halls represented, which should logically lead to a significantly lower reverberant level and therefore a higher C80 independently of the early efficiency of the hall. Using the traditional theory for reverberated sound energy, the level of the diffuse reverberant field can be predicted to be about 1.9 dB lower (= 10log(1.55)) than the average of the 5 other halls, which may therefore explain a C80 about 2 dB higher in Sapporo.

The gap between Sapporo and the 5 other halls tends to decrease the quality of linear regressions. For this reason two different regressions were tested, the first one (*linreg)* taking into account all 6 halls for which reliable C80 measurements are available, while the second one (*linreg2)* ignores the point corresponding to Sapporo.

It is observed that halls with a larger amount of total acoustic absorption generally lead to larger deviations from the linear regressions obtained. As a first guess from the available data, *linreg2* should be correct for concert halls with less than ~ 2000m² Sabine of absorption. However, one should not conclude from this that S_{EE} and Ω_{EE} loose their validity for halls with a larger amount of absorption: it indicates that these parameters are less correlated to C80 when halls of very different late responses are compared, and early efficiency parameters should still properly relate to the early efficiency of the design and *source presence*, independently of its late response. The possibility of using S_{EE} and Ω_{EE} – parameters based simply on architectural plans and sketches – to predict C80 values (in conjunction with other architectural parameters like seating area and volume) can be seen as an interesting tool in the design process of a concert hall, and as corroborating the perceptual and acoustic relevance of the parameters for the subjective perception of *source presence*.

The quality of the regressions is described by the coefficients of determination r^2 listed in table 3:

	linreg (on 6 halls)	*linreg2* (on 5 halls)
C80 as a function of S_{EE}	0.43	0.82
C80 as a function of Ω_{EE}	0.52	0.93

Table 3: r^2 coefficients for the linear regressions

Unsurprisingly, correlation between C80 and the two new parameters is generally not ideal when considering all 6 halls: S_{EE} and Ω_{EE} only explain about 50% of the variations of C80. But as soon as Sapporo is taken out of the test sample, the correlation becomes much stronger. Ω_{EE} also appears to be more efficient than S_{EE}, which may justify the use of the refined solid angle based version. Considering only the 5 halls finally selected (Amsterdam, Boston, Berlin, Christchurch and Manchester) S_{EE} is found to explain 82% of the variations of C80, which is further improved to 93% with the use of Ω_{EE}.

Ω_{EE} is also very promising in the prospect of a generalization of the new criterion for different hall sizes and type of music played. Whereas S_{EE} can get smaller as the size of the hall decreases to compensate for the generally shorter distances of the efficient surfaces to the sources, Ω_{EE} is always representative of the proportion of energy produced on stage that is directed to the audience or the musicians on stage. It is supposed that the optimum value for Ω_{EE} will depend on the type of music played as well as orchestral formation: late romantic symphonies require lower values of Ω_{EE} than the classical and baroque repertoire, and large symphony orchestras require a lower early efficiency than chamber orchestras and chamber music. Optimizing the acoustic quality for the same type of repertoire, i.e. keeping a similar Ω_{EE}, in a smaller concert hall with shorter distances to the source automatically requires fewer surfaces. All halls considered in this study are large concert halls dedicated to symphonic music, a generalization of the early efficiency parameters for various sizes of halls and types of use seems both promising and interesting.

In this context it is interesting to further discuss the two settings considered for the Luzern Concert Hall. The two extreme cases (all doors open and all doors closed) lead to an available range for Ω_{EE} between 20% and 30%, the early energy parameter being highly influenced by the setting of the reverberation chamber doors close to the stage. Studying preferred settings for the reverberation chamber doors in Luzern, one observes that those doors are generally set in a more closed position for smaller orchestral ensembles and chamber music than for larger symphonic ensembles, reducing Ω_{EE} for larger orchestral ensembles and for the late romantic repertoire.

3 Conclusion

The calculation of early efficiency parameters for a set of existing concert halls was found to confirm their validity for the estimation of *source presence* and *early efficiency* in concert halls directly from architectural plans. The results indicate a strong correlation of the early efficiency parameters and the subjective listening impression in the halls.

The correlation of the early efficiency parameters with C80 was also studied. From the 8 configurations initially considered only 5 were finally retained in the regression, leading to strong correlation coefficients. Certain configurations needed to be excluded as the dependence of the C80 values on late energy levels was found to disturb the correlations. The early efficiency parameter is not meant to take into account the late response of the room, and if this geometrical architectural parameter is to be used for correct predictions of C80, other aspects of the room design related to the level of the late reverberant field need to be considered in addition. A study of a larger number of concert halls would be desirable to fully validate the linear regressions obtained.

The early efficiency parameters defined are found to have interesting and promising potential to quantitatively guide the architectural design of concert halls, including during early phases.

The results obtained were found sufficiently encouraging and concluding to include the early efficiency parameters in the acoustic brief for the Philharmonie de Paris concert hall competition. In the context of this brief, a total area S_{EE} = 1400 m² of surfaces being able to create early reflections was requested, with 500 m² being less than 15 meters from the stage. An Ω_{EE} value of 24% was also set as a desired value. These relatively high values were motivated by other requirements specific to this project such as the large seat count of 2400 requested by the client, the high reverberation time goal of 2.2 to 2.3 seconds fully occupied and the generally high appreciation of clarity by French audiences.

The results of the study indicate that a generalisation of the early efficiency parameters, especially Ω_{EE}, to different types of musical repertoire, orchestral formations and hall sizes could lead to highly interesting results and insight to concert hall design. It is expected that different musical repertoires as well as orchestral formations will have different optimum values for Ω_{EE}, while optimum values for the same repertoire should be more or less independent of hall size.

Acknowledgments

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