ROOM ACOUSTIC PARAMETERS AND THEIR DISTRIBUTION OVER CONCERT HALL SEATS

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1 INTRODUCTION

International consensus about room acoustic parameters in performance rooms is more or less established by a set of five physical quantities and their corresponding subjective aspects, namely reverberance, strength, clarity, apparent source width, and envelopment (Table 1) [1][4].

Table 1: The five physical quantities assumed to characterize acoustic quality in performance rooms

Subjective listener aspect	**Acoustic quality**	**Single number frequency averaging**	**Just Noticeable Difference (JND)**
Subjective level of sound	Sound Strength, G, in dB	500 to 1000 Hz	1 dB
Perceived reverberance	Early Decay Time, EDT, in s	500 to 1000 Hz	Rel. 5%
Perceived clarity of sound	Clarity, C_{80}, in dB	500 to 1000 Hz	1dB
Apparent Source Width, ASW	Early Lateral Energy Fraction LF or LFC	125 to 1000 Hz	0.05
Listeners Envelopement	Late Lateral Sound Level, LG in dB	125 to 1000 Hz	1 dB

With five parameters there will be a set of five average values that is assumed to characterize the acoustics of the hall (or some sub-area of the hall). But what is the chance of finding a seat with this characteristic quality? Does the average seat exist? While it may be simple to find a seat with e.g. reverberance that is close to average, it may be worse to find a seat with all five parameters close to hall-average values. For example, in many seats in the front part of the hall one may find strength, clarity and envelopment higher than average, while apparent source width and reverberance is generally very different from average, see Figure 7 in Appendix. Several authors have pointed at the relation between average parameter values and preference of halls, e.g. Beranek [2], and preferred values have been suggested for some parameters. However, it is not evident that preference for one parameter can be set independent of the four others, e.g. even if both 1.8s and 2.0s are within preferred occupied EDT values, the preferred values of G, C80, LF and LG may be different if EDT=1.8s than if EDT=2.0s. One would expect that at a top reputation hall like Musikvereinsaal has a majority of seats where all five parameters are within established preferred values, assuming it takes a majority to maintain such a wide and long-lasting reputation. This expectation is not confirmed by this study. This paper demonstrates the probability of finding some set of five parameter values in the main seating area in three concert halls. The interrelation between the percentage of qualified seats and the qualifying criteria is demonstrated, revealing *the uncertainty principle* in concert hall acoustics. Methods for acoustic seat quality assessment are suggested and tested. It becomes evident that some halls have more variation in quality than others. This may in itself be a significant property for a concert hall.

2 COMPUTER SIMULATION

This study is based on simulated measurements in computer models of three halls, namely Oslo Concert Hall (Norway) 19.000m3, Elmia Concert Hall (Sweden) 12.000m3 and Musikvereinsaal in Vienna (Austria) 15.000m3. All halls are simulated in occupied condition in ODEON 8.5, see Figure 2. Measurement points are distributed over the main seating area. In particular, 200 choir seats in Oslo are excluded, boxes and seats close to side walls excluded in Elmia, and galleries at the side and at the back excluded in Vienna. Computed average values of the five physical quantities that are assumed to characterize the acoustics are given in Table 2, while standard deviations are given in Table 3, together with the number of measurement grid points in the simulation.

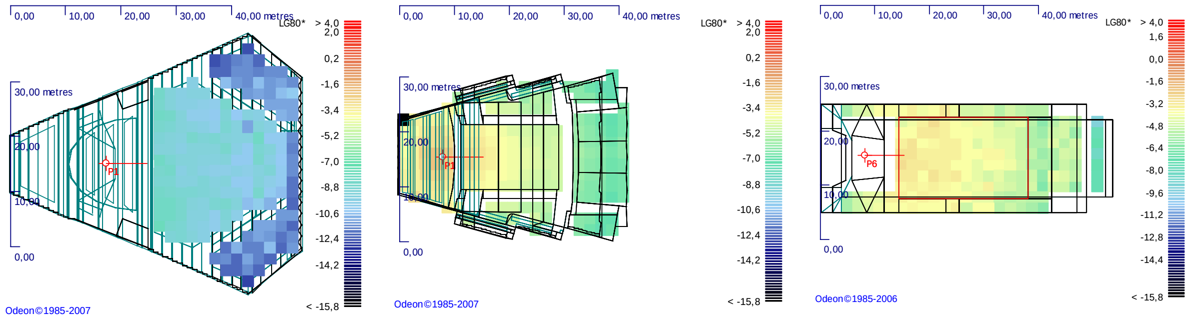


Figure 1: Computer models of the three concert halls, from left to right: Oslo, Elmia and Vienna; Colors represent values for LG (Envelopment) calculated with ODEON 8.5.

Table 2: Computed average values in the three halls

	EDT (s)	G (dB)	C80 (dB)	LF (1)	LG (dB)
Oslo	1,5	1	2	0,23	-8
Elmia	1,7	4	1	0,18	-5
Vienna	1,9	3	2	0,20	-3

Table 3: Standard deviations of N simulated measurements in the three concert halls

	N	EDT	G (dB)	C80 (dB)	LF80	LG80 (dB)
Oslo	*202*	16%	1,8	1,6	0,09	1,5
Elmia	*127*	6%	1,9	1,8	0,04	1,3
Vienna	*159*	9%	1,4	1,1	0,06	0,8

3 RANKING BY THE NUMBER OF SATISFYING ASPECTS

First we shall test a simple method, namely ranking by the number of satisfying listening aspects (among Reverberance, Level of Sound, Clarity, Source Width, and Envelopment) at a listener's ear. The ranking of a seat is obtained by answering the question: At this seat, how many of the five quantities in Table 1 satisfy a given criterion?

3.1 Criterion 1A: Parameter value close to average

Assume that a listener's aspect is satisfying only if the parameter value is less than noticeably different from the averages of the hall, as given in Table 2. The qualifying range for each aspect in each hall is then as in Table 4, according to the criterion defined by m ± JND. Then the percentage of seats in each hall having a qualifying value is given in Table 5. If the five parameters where statistically independent, the Product column would predict the expected percentage of seats having all five aspects satisfying at once.

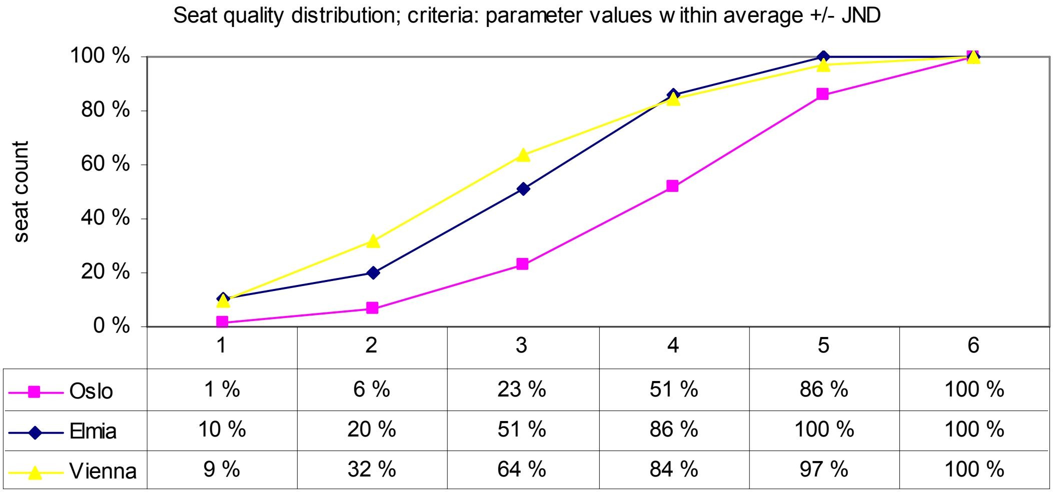
Table 4: Values assumed to correspond to each satisfying aspect

Listener Aspect:	Reverberance	Subjective Level	Clarity	Apparent Source Width	Envelopment
Quantity:	EDT (s)	G (dB)	C80 (dB)	LF (1)	LG (dB)
Oslo	1.5 to 1.6	0 to 2	1 to 3	0.18 to 0.28	-9 to -7
Elmia	1.6 to 1.7	3 to 5	0 to 2	0.13 to 0.23	-6 to -4
Vienna	1.8 to 2.0	2 to 4	1 to 3	0.15 to 0.25	-4 to -2

Table 5: The percentage of seats having a parameter value un-noticeably different from hall average

	EDT	G	C80	LF	LG	Average	Product
Oslo	22 %	19 %	52 %	46 %	30 %	34 %	0,3 %
Elmia	59 %	34 %	45 %	83 %	46 %	53 %	3 %
Vienna	37 %	47 %	64 %	62 %	76 %	57 %	5 %

The resulting cumulative seat quality distribution for each of the three halls is given in Figure 2:



	1	2	3	4	5	6
Oslo	1 %	6 %	23 %	51 %	86 %	100 %
Elmia	10 %	20 %	51 %	86 %	100 %	100 %
Vienna	9 %	32 %	64 %	84 %	97 %	100 %

Figure 2: Computed results for the three concert halls; Criterion: Less than noticeable differences from average parameter values.

As can be seen from Figure 2, when requiring a seat where each of the five listener aspects differs un-noticeably from average values in the hall, the chance of finding such a seat (seat rank 1) becomes small (1%-10%). In particular only 9% of the listeners in Musikvereinsaal are able to experience the acoustics corresponding to the five average values at once. This is too few to explain the preference for this hall by the combination of its five average parameter values. It is assumed that the long time established top rating of Musikvereinsaal is due to a majority of listeners having found the acoustic quality to be first class five aspects at once. The assumed criterion (m±JND) is therefore rejected.

3.2 Criterion 1B: Global Criterion 1 satisfying top rating of Musikvereinsaal

Now, we shall accept parameter values to vary more than above, but just enough to result in a seat quality distribution that can explain the long-time established top rating of Musikvereinsaal in Vienna.

In particular we shall require that a 2/3 majority of the seats have first class acoustics in all five aspects. This condition was achieved by trial and error, by increasing the qualifying interval, until the interval was defined by the average value ± 2.455 times the just noticeable difference from average, m ± 2.455*JND. The total variation inside this interval is therefore 5 JNDs. Absolute values are given in Table 6.

Table 6: Qualifying intervals of the global criterion 1B

	EDT	G	C80	LF	LG
max	2,1	6	4	0,33	-1
average	1,9	3	2	0,20	-3
min	1,7	1	-1	0,08	-5

Applying the global criteria for each parameter in Table 6 to all three halls, the probability of finding a seat with a qualifying parameter value is given in Table 7. The product of all five probabilities is given in the rightmost column.

Table 7: Probability of finding a seat with a qualified parameter value, looking at one parameter at the time

	EDT	G	C80	LF	LG	avr	product
Oslo	20 %	54 %	90 %	77 %	1 %	48 %	0 %
Elmia	56 %	83 %	76 %	100 %	86 %	80 %	24 %
Vienna	75 %	93 %	97 %	96 %	100 %	92 %	62 %

The resulting cumulative seat quality distribution for the three halls is presented graphically and numerically in Figure 3.

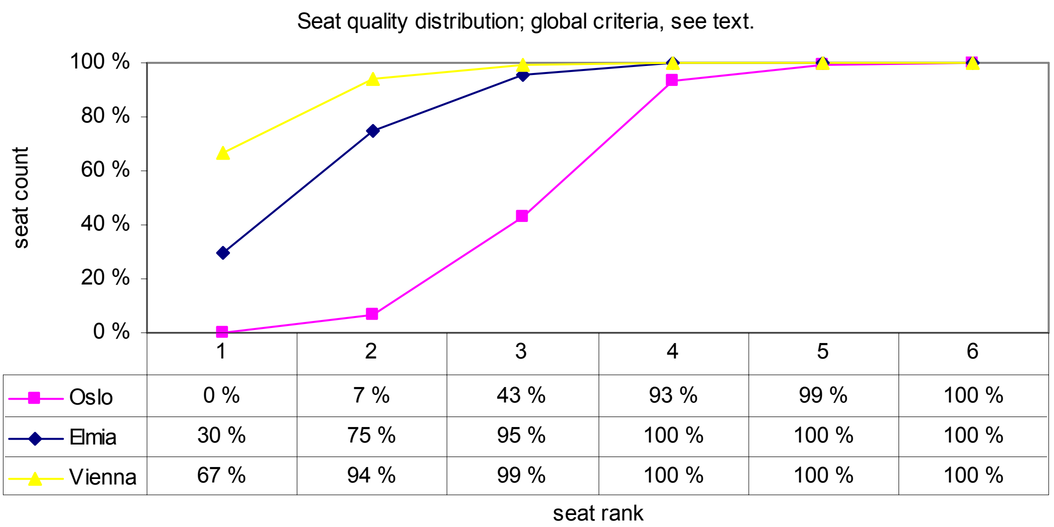


Figure 3 (above): Cumulative seat quality distribution given the global criteria in Table 6.

As can be seen from Figure 3, the cumulative distribution shows 67% probability of finding a seat in Vienna that has the optimum acoustic quality for this hall. In other words, the famous acoustics of Musikvereinsaal can be experienced by a 2/3 majority of listeners. This result confirms that the qualifying criteria in Table 6 offers a far better explanation to the top rating of the hall, than does the criteria with more narrow intervals around the average values applied in sections 3.1. The method distinguishes clearly between halls when the same global criteria are applied to all of them However, the result requires that the individual values of the five parameters are allowed to vary as much as 5 JNDs. Such large intervals allow very different combinations of parameters, e.g. the two sets “max” and “min” in Table 6, and it is hard to explain how such extreme combinations can be preferred. Also, for example EDT=1.7-2.1s, G=1-6dB, and LF=0.08-0.33 are wider ranges than preferred ranges commonly suggested by authors.
Note the slight difference between Product values in Table 7 and the seat rank 1 column in Figure 3, indicating some degree of statistical independency of parameters.

Despite being able to explain the top rating of Musikvereinsaal, the large interval of qualified parameter values seems to be in conflict with previous investigations of preferred values. The qualifying criterion is not accepted. We therefore proceed by searching for an improved method.

This chapter has apparently demonstrated the uncertainty principle in concert hall acoustics: One cannot both demand high certainty of position (seat) and a high certainty of parameter values. E.g. if less certainty in parameter values in a seat is accepted, then certainty in finding such a seat is higher, and vice versa.

4 SEAT QUALITY ASSESSED BY AVERAGE NOTICEABLE DIFFERENCE FROM PREFERRED VALUES

We shall in the following assume that, at a given seat, the less the set of five parameter values differ from preferred values, the more the listeners prefer the seat. The quality of the seat is defined by the average difference from preferred value, expressed in units of JNDs: Here, Acoustic Seat Quality is defined as:

$$ASQ=(|EDT-EDT_{pref}|/JND_{EDT}+|G-G_{pref}|/JND_{G}+|C-C_{pref}|/JND_{C}+|LF-LF_{pref}|/JND_{LF}+|LG-LG_{pref}|/JND_{LG})/5$$

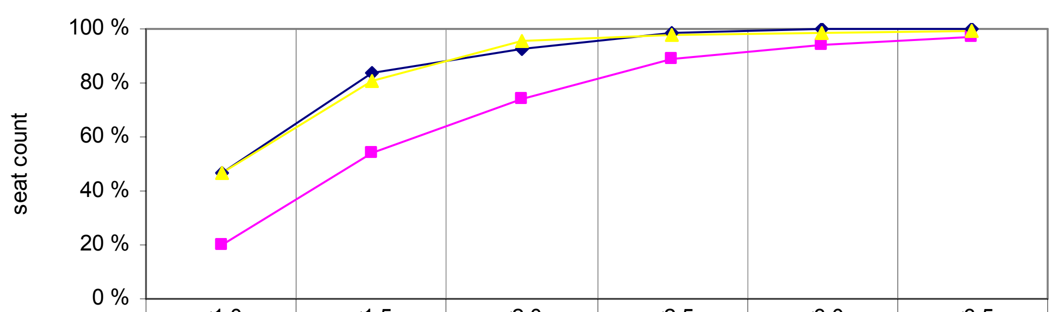
The optimum seat quality corresponds to ASQ ≤ 1.0

There are at least two candidates for the set of five preferred values: The averages over the seats in the hall (local criteria), or a set of five values based on global preference. Global means here any group of concert halls comprised by a consensus of five preferred values. As a starting point, one may choose the five average values of a top rated concert hall, e.g. Musikvereinsaal in Vienna or Concertgebouw in Amsterdam.

Conditions in the three halls are the same as above, i.e. as given by Table 2 and in Table 3.

4.1 Local Criterion 2A: Preferred value = hall average

When choosing the five average parameter values in the main seating area of the three halls as the preferred values above, the results are as presented in Figure 4.



	<1.0	<1.5	<2.0	<2.5	<3.0	<3.5
Oslo	20 %	54 %	74 %	89 %	94 %	97 %
Elmia	46 %	83 %	93 %	98 %	100 %	100 %
Vienna	47 %	81 %	96 %	98 %	99 %	99 %

seat quality (JNDs from hall average)

Figure 4: Percentages of seats as a function of seat quality, measured in difference (in units of JND) from average in each hall.

Note the similarity between Elmia and Vienna despite the fact that they are geometrically different, and have noticeably different average values (Table 2). This similarity can be interpreted as similar probability for listeners to find a seat with the average acoustics of the hall. In contrast, Oslo differ significantly from Elmia, even though one might find more common geometry between the two halls (e.g. fan shape). In Oslo, there is only 20% probability of having a seat with the average acoustics of the hall. Conclusion: Elmia and Vienna have more even seat quality than Oslo, which can not be explained by geometry alone, but maybe partly by RTs.

It is concluded that the average values are the most representative set of values, since tests of other preference values did not result in significantly higher percentages of top quality seats, leaving no better candidate for preference values than the five average values.

The seats with quality <1.0 JND are plotted over the footprint of Oslo and Vienna halls in Figure 5.

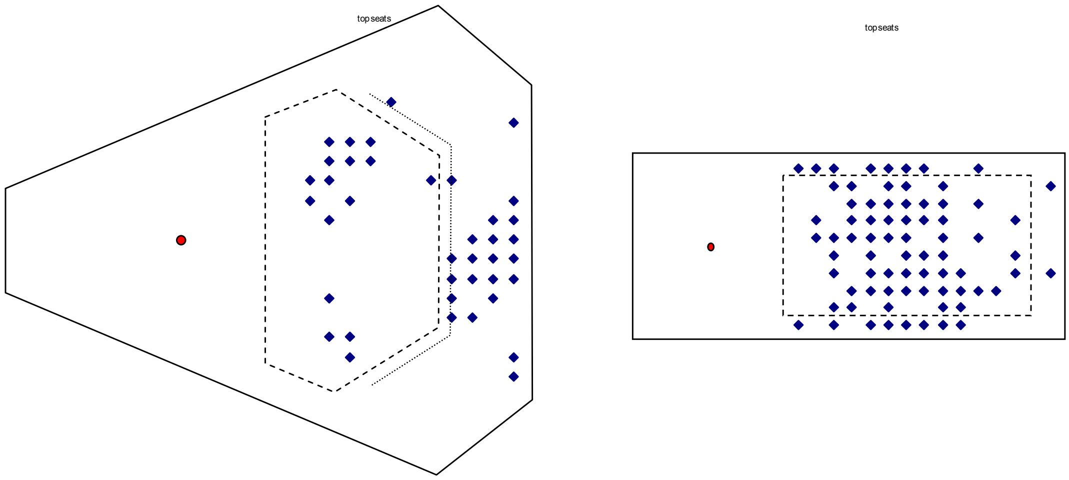
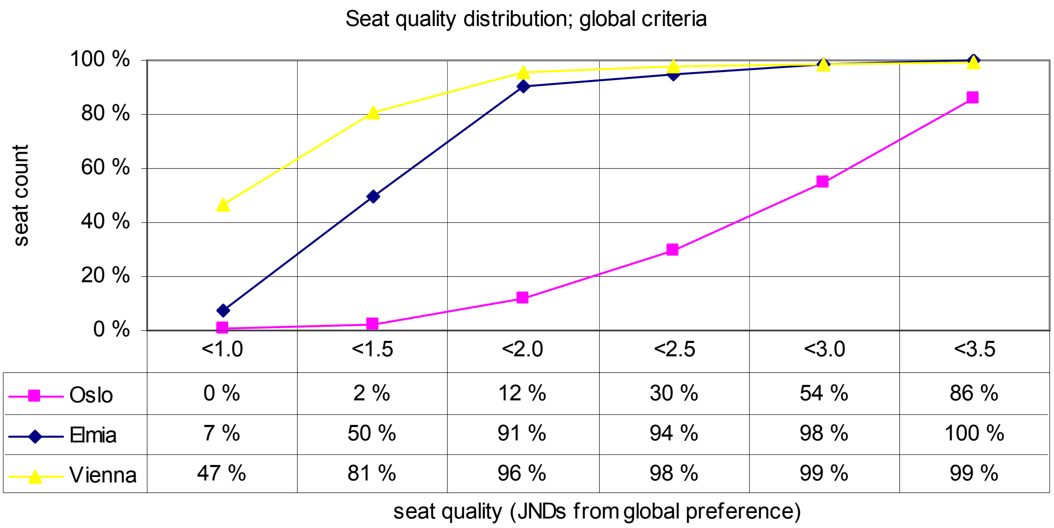


Figure 5: Seats of top quality by the local criterion 2A: Each plotted seat has five parameter values that on average differ less than 1.0JND from the set of five averages from the main seating area.

4.2 Global Criterion 2B: Preferred value = global preference average

When choosing the five average parameter values in Musikvereinsaal as a global preference, the results are as presented in Figure 6.



	<1.0	<1.5	<2.0	<2.5	<3.0	<3.5
Oslo	0 %	2 %	12 %	30 %	54 %	86 %
Elmia	7 %	50 %	91 %	94 %	98 %	100 %
Vienna	47 %	81 %	96 %	98 %	99 %	99 %

Figure 6: Percentages of seats as a function of seat quality, measured in difference (in units of JND) from averages in Musikvereinsaal, Vienna.

5 DISCUSSION

Comparing the results in Figure 6 with Figure 3 shows that criterion 2B gives almost the same percentage (47%) of top ranked seats in Vienna as the criterion 1B (51%), despite the fact that the methods are quite different, and that criterion 2B is considerably stricter than 1B. The 1B criterion allows all of the five parameters to vary within ±2.5 JNDs all at once, in contrast to 2B allowing only within ±1.0 JND at once, at top ranked seats. On the other hand, with 2B, there is freedom for one parameter to differ as much as 5JNDs from average as long as the rest of the parameters are equal to average. If we assess two extreme cases by the two different methods, we get the following differences in assessment:

1. All parameters at a seat are nearly 2.5 JND above average, rating
    a. Rank 1 by criterion 1B, meaning “no seat is better than this one”
    b. Seat quality 2.5 by criterion 2B, meaning “96% of the seats are better than this one”
2. EDT at a seat is nearly 5 JND above average EDT, while the four other parameters are equal to average
    a. Rank 2 by criterion 1B, meaning “51% of the seats are better than this one”
    b. Seat quality 1.0 by criterion 2B, meaning “no seat is better than this one”

The two extreme cases above are rated by 1B as “0-98% of the seats have better acoustics than this one” and by 2B as “0-51% of the seats have better acoustics than this one”. We conclude that extreme cases are assessed more precisely and strictly by 2B than by 1B, which also holds in general, since 2B gives fewer top rank seats than does 1B.

Still, it is appropriate to discuss whether a method that top rates “only” 47% of the seats can be reliable. Are 47% of the listeners sufficient to establish a reputation or not? The slightly lower seat quality defined by <1.5 JND is represented by 81% which is a clear majority. But then - is <1.5 JND from a preferred value an acceptable criterion for top quality seats, and can it be supported by investigations of parameter preferences? If this method can explain the international ranking of famous concert halls by applying a proper seat quality (JND) criterion, then one will need to look at the implications this criterion has to our conclusions about preferred parameter values. Several authors have pointed at evidence that room acoustic parameters are not orthogonal quantities or statistically independent quantities. This implies that one parameter, say EDT, does in practice not vary independently of the other parameters, and further: The preferred value or preferred range of values can not be established for one parameter, say EDT, independently of preferences for the other four parameters. The acoustic seat quality ASQ assessment method presented above may be the key to describe the dependency between parameters.

Even if it is accepted that the five parameters are varying spatially and that the average value not necessarily is characteristic for a large seating area, there is yet to find a more proper set of single-values to represent “the center of gravity” in concert halls where the general impression of the acoustics seems to dominate a vast majority of the seats. In halls with long-time wide reputation for their first class acoustics, like Musikvereinsaal and Amsterdam Concertgebouw among others, one expects to find a clear majority of seats having favorable value-combinations of the five parameters, or the equivalent statement: The majority of value-combinations must be favorable. We do not know which seats these value-combinations belong to, but if we knew, we could find the average parameter value for this group. Assuming this favorable majority is at least 2/3, the average values of this majority will be little different from the average of all the seats. In the case of Musikvereinsaal, the average values of the favorable 2/3 seats must be less than noticeable different from the average of all the seats. The differences were: EDT<4%, G<0.5dB, C80<0.2dB, LF<0.01, and LG<0.0dB. This was tested by in turn removing the value-combinations that had at least: one value that was very low, one that was very high, one that was either very high or very low, or one that was close to average, until only 2/3 of the value-combinations remained.

In stead of using the average single-value, the expected value from a function of distance, RT and volume may prove to be an improved center of gravity for the group of favorable seats. Another alternative is the regression lines in the diagrams in 10 Appendix.

6 REAL MEASUREMENTS VS COMPUTER SIMULATIONS

One may object that the investigations reported in this paper are not based on real measurements. On the other hand, there have been done comparisons between simulated measurements and real measurements, e.g. in Elmia Concert Hall, in the international Round Robin 2. From the results in 6 points it can be shown that the difference between simulated and real values are on average 1.07 JNDs, for the parameters EDT, G, C80 and LF. LG was not measured, and the JND of LG is still being investigated. A similar comparison has been done by this author with 8 points in Oslo Concert Hall, resulting in the average of 0.80 JNDs between simulated and real measurements of the three parameters EDT, G and C80.

7 FURTHER WORK

Among the issues that are natural to pursue in further work are:

- The investigation should be extended,
  - to see if the method can explain the ranking of many halls, and
  - to reveal more about preferred combinations of the five parameter values
- Are fixed preference values, e.g. average values, adequate in the assessment of acoustic seat quality? Instead, could maybe the expected values of the parameters, being functions of distance, RT and room volume, as suggested for G and C80 by Barron [3][4], provide
  - improved explanation of preferred concert halls,
  - less average noticeable differences from preferred values,
  - more knowledge about preferred sets of parameters, and
  - better prediction of acoustic seat quality in concert halls?
- Can statistical dependence between parameters be further explained by their co-variation with functions of distance, RT and room volume?
- Does some categories of halls based on course geometry, e.g. shoebox halls, have more seats with preferable combinations of parameter values than other categories of halls?
- There is need for further investigations of preferred parameters, including listening tests, with the purpose to
  - confirm whether the five individually preferred values or preferred ranges also form a preferred set of five values or ranges
  - test whether there is a preferred set of five parameter values or ranges that can not be deduced from concert hall averages and their ranking
- Can the assumption in this paper, that two seats having the same average noticeable difference from preferred parameter values are preferred equally by listeners, be confirmed by listening tests? In particular, can it be confirmed that nearly 5 JND difference from preferred value of one parameter is fully acceptable if the four other parameters are equal to preferred values?
- The term parameter is somewhat misleading, preventing us from discovering genuine parameters, in the sense: a para-meter, i.e. a measure on the side that indirectly appears to affect the primary measure, e.g. G appears to have an expected value as a function of the distance R from source to receiver. The traditional RT is not among the five parameters that describes the listener's aspect. However, Barron (1993), showed that RT is a parameter in functions that gives expected values for G, D and C80 [3]. It may turn out to be so in LG, too.

8 CONCLUSION

A high number of measurements have been simulated in the main seating area of three concert halls. It is assumed that the perceived acoustic quality is constituted by five subjective listener's aspects associated with a corresponding set of five physical quantities (parameters). These quantities vary spatially. An assumption that the five averages EDT_{avr}, G_{avr}, $C80_{avr}$, LF_{avr} and LG_{avr}, form the most representative set of values, and assuming that the precision of perception is ±1JND, leads to the result that there are just a small percentage of seats (1-10% in the three halls) where representative values can be perceived. This would be in conflict with the high reputation of one of the halls. Since an attempt to find a more representative set of values than the averages failed, the assumed precision of perception was reconsidered. A seat quality assessment method based on *average noticeable difference* between the five parameter values representing the seat and the five averages representing the hall showed improved explanation of concert hall reputation. A method for assessment of acoustic seat quality is suggested, together with further improvements and research topics. The investigation should be extended to see if the method can explain the ranking of many halls, and to reveal more about preferred combinations of the five parameter values.

9 REFERENCES

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10 APPENDIX

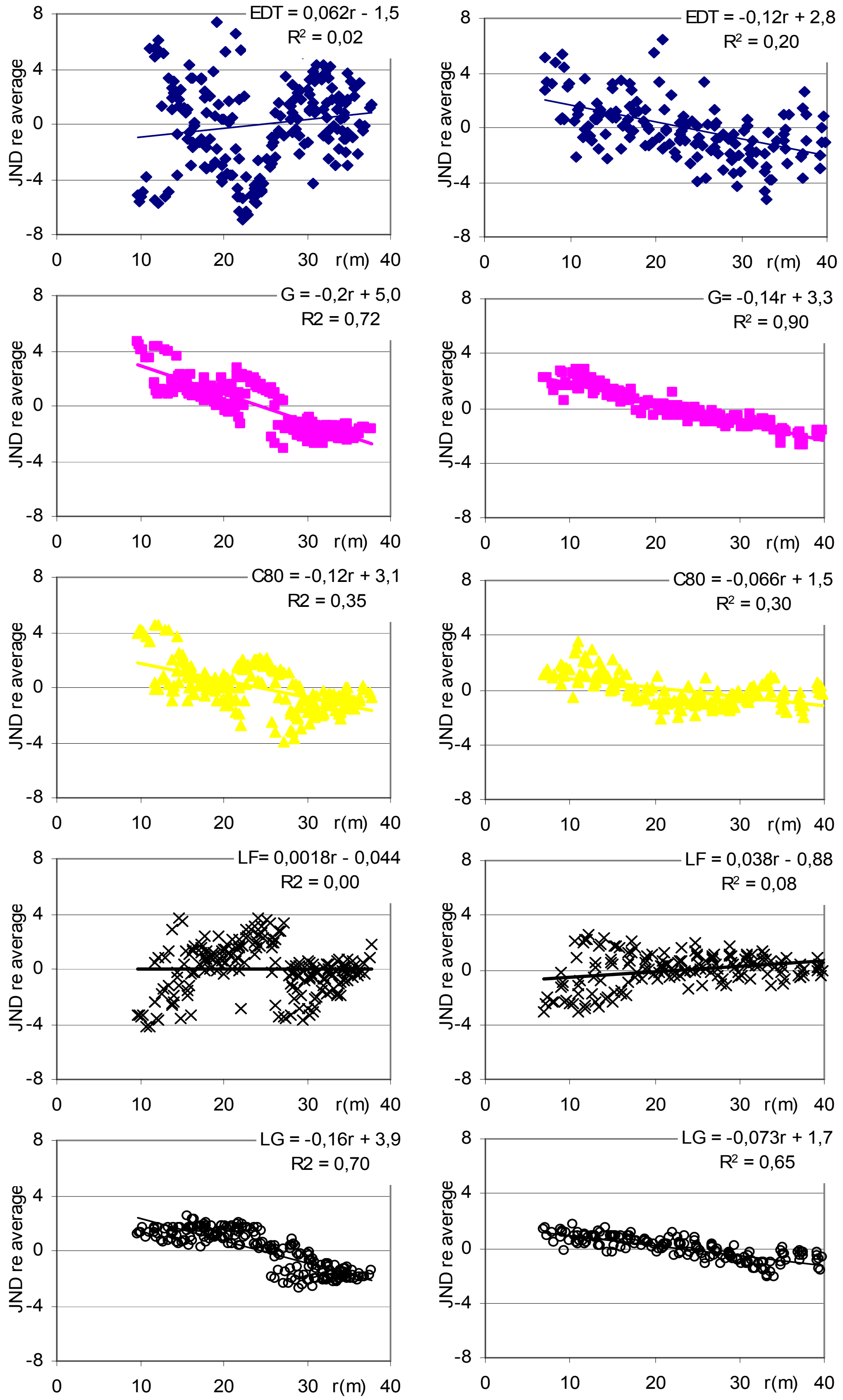

Figure 7: Plots of simulated measurements against source receiver distances in Oslo (left) and Vienna (right). All vertical scales have units in JND relative to average of the seating area. Correlation (Pearson) R2 with distance is high for G and LG, lower for C80, and very low for EDT and LF