

Multidimensional Visual Cluster Analysis of Room Acoustical Parameter Values as Means to gain Scientific Insights and Design / Consulting Tool

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ABSTRACT

At the conference DAGA 2017, a method of multidimensional visual analysis of basic room-acoustical parameter values incorporating reverberation time RT_{Mid} , strength G_{Mid} and volume V was presented. Using this method, it is possible to demonstrate that different room types such as e.g. concert halls, opera or chamber music halls form separated clusters in partial volumes of the acoustical parameter space spanned by the acoustical parameters. For concert and opera halls rated as "good" regarding their acoustical quality it has been shown that these are localized in narrow partial volumes within the centers of the room type clusters. At the DAGA 2018 this approach was extended by investigating additional room types and by comparisons of the spatial positions of several halls before and after renovations. In the present paper, this method will be shown to serve as a valuable tool obtaining new scientific insights as well as being a helpful planning tool: For the room type "concert hall" the historical development is analyzed from the beginnings to the 21st century yielding characteristic trajectories across the parameter spaces clarifying the evolutionary trends as well as geographical differences. The immediate practical advantage of the method described here as a consulting and design tool will be demonstrated by application to orchestral rehearsal rooms.

Keywords: Room-Acoustics, Acoustical Parameter Space, Acoustical Quality

1. INTRODUCTION

For a long time, the analysis and presentation of room acoustical parameter values of rooms rated for their acoustic quality relied on tables with two-dimensional graphs based upon two variables. By means of recent computer programs the available possibilities of data analysis and presentation now allow for a multi-dimensional analysis of more than two room-acoustical parameters simultaneously. In (1) a new method using multi-dimensional visualization was presented showing how new insights can be derived with different examples of various room types plotted into a parameter space spanned by basic room-acoustical parameters (without loss of generality by this method in the first instance e.g. reverberation time RT_{Mid} , strength G_{Mid} and room volume V). In such initially three-dimensional parameter spaces the room examples are represented by characteristic parameter triples with characteristic positions within the parameter space. Insights into the nature of the room types can be gained fast by visual analysis from the graphs by different angles. In (1) it was further shown, that different room types form clusters in separate parameter space sub-volumes in characteristic parameter-value ranges with comparatively small overlap regions.

Moreover, in (1) and (2) was shown how this data analysis method can be expanded by another dimension to data quadruples, e.g. by adding a quality rating, and an adapted visual data representation, e.g. by means of marker color. It could further be demonstrated that the rooms rated as "good" with

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regard to their acoustical quality meant for their genuine use (here: concert halls and opera houses) are located in smaller sub-clusters within the certain room-type clusters and therefore displaying even a separation of the different room types. In reverse, this analysis may lead to sets of requirements for the parameter-value ranges which are necessary in order to achieve acoustical properties rated as “good” for the different room types.

In (2) this multi-dimensional method was extended by incorporating a larger number of rooms and additional room types: churches, rehearsal rooms, lecture halls and theatres. This expansion of the data basis confirmed the result of cluster formation. Furthermore, it has been demonstrated in (2) how this cluster analysis can be used for consulting purposes. A comparison of the location of a room before/after a refurbishment or reconstruction in the parameter space can reveal if, and to what extent construction measures are able to move the position of the room under examination in the parameter space (with help of actual examples, among them the Tonhalle Düsseldorf, Staatsoper Berlin and Kulturpalast Dresden) if possible even towards the sub-clusters with high quality ranking.

For adequate acoustical conditions in a room in regard to the main use, the first-order necessary condition in general is a value of the reverberation time in the value ranges judged as appropriate for the use of the room examined. However, for adequate acoustical conditions sufficient conditions should be met as well. This means that also the values of the other room acoustical parameters ought to be in the value ranges judged to be adequate for the use of the room type, e.g. early decay time EDT, binaural quality index BQI, Clarity C₈₀ etc.. Therefore, one-dimensional considerations are insufficient for covering the sufficient conditions of the acoustical quality. In order to examine first-order necessary and sufficient conditions simultaneously, considerations had to be given to two-dimensional methods; for an adequate simultaneous consideration of more than two parameters more-dimensional methods are necessary. Dependencies between more parameters are not easily detectable in two-dimensional representations. Figure 2 in (1) exhibits an example from (3) of a two-dimensional graph of the parameters reverberation time RT and strength G, where a third parameter - the room volume V - is added as a family of curves. Conform the revised diffuse field theory after Kuttruff and Barron, in the diffuse sound field the three quantities V, RT and G are strongly coupled by equation (1):

$$G_{\text{theo},\text{Diff}} = 45 \text{dB} - \left[10 \text{dB} \cdot \log_{10} \left(\frac{V}{T} \right) \right] \quad (1)$$

In (1) common analysis methods of existing data sets were described and the disadvantage of these common methods discussed namely that many tables of two-dimensional graphs have to be taken into consideration. Because of the a priori unknown interdependencies between the common room-acoustical parameters, the conventional analysis methods lead to limited informative values. Therefore the conclusion in (1) and (2) was drawn that in order to understand and measure the sufficient conditions of acoustical quality in rooms regarding their use in addition to the first order condition - namely that the reverberation time shows values in the range adequate for the use - a multi-dimensional analysis method is required. At its best, such a multi-dimensional analysis method is able to reveal the mutual interdependences of the parameters.

2. DATA BASIS

The following quantities are at least in principle capable of being controlled and therefore they have to be taken into consideration in any acoustical design process: room volume V and main geometry / room shape, absorption and especially the audience capacity (seating/persons/position of audience areas); consequently, reverberation time RT and strength G; room width (and maximum distance from the stage), and last but not least structure and acoustical behavior (reflection, absorption or diffusion) of bounding surfaces. As data basis for the comprehensive multidimensional analysis in this context, per room data from the following categories were collected:

- name, city, country, continent, opening year;
- shape (cuboid, hexagon, fan, horseshoe, surround/vineyard, ellipsoid); room width w;
- volume V, number of seats N (resulting in values of the specific volume (V/N));
- quality rating (from (14));
- spatial averages of the room acoustical parameters for seats with stage distance d > 2 r_H:
 - reverberation time RT_{Mid,seated};
 - Clarity C_{80, Mid, unseated};
 - strength G_{meas, Mid, unseated};
 - G_{theo, Mid, unseated} resulting from equation (1);
 - BQI_{Mid, unseated};
 - AL_{cons, P88, seated}.

Data collections of room acoustical parameter values of culture buildings provide numerous objective data (4-17) as well as correlations with subjective preference ratings (14-16), in which especially the rating results in (14) are only one of the possible quality judgments and therefore questionable to a certain degree. The collected data were sorted in sets of n-tuples per room in an extensive table, see tables 1 in (1) and (2), the structure of which is given in table 1, showing the averages of the values per room type, as well as of all values available in the actual study:

Table 1 – Structure of the data sets, average values of the room types and average of all values (last line)

Room type	City	Hall	Rating	Volume V [m ³]	Number of Seats	RT _{Mid,s} [s]	G _{meas,Mid,u} [dB]	G _{theo,Mid,s} [dB]	BQI _u	Width W [m]	C _{80,Mid} [dB]	Shape	opening year
Concert Halls	(14)	16.000	2.000	1,8	5,8	6,3	0,56	27	-0,8				1933
Chamber Music	-	3.400	425	1,6	12,9	12,6	0,72	15	-0,1				1911
Opera Halls	(14)	9.100	1.325	1,4	4,7	7,8	0,57	26	+2,8				1885
Churches	-	15.000	515	3,1	13,7	11,2	-	20	-2,4				1771
Lecture Rooms	-	3.900	390	1,5	11,1	13,7	-	17	+7,7				1953
Theatres	-	6.000	1.150	1,2	7,0	8,5	-	20	+4,3				1939
Rehearsal Rooms	-	4.000	190	1,4	12,9	11,9	-	17	+0,7				2000
All Room Types	-	11.200	1.290	1,8	7,8	8,6	-	24	+1,0				1900

Note: for some rooms not all data has been available (lacking are e.g. Rating, BQI, C₈₀ and G_{meas}), but for all room data sets the parameter values of V, RT, G_{theo}, W, shape, type and opening year are collected and incorporated (for churches mostly the RT_{Mid,unseated}).

Note: the values in table 1 are displaying the averages of the data sets per parameter. They are not meant as a reference of how concert halls, opera halls and other buildings should be built.

2.1 Enlargement of the Data Basis

For the study in (1) a selection of 32 concert halls, 11 opera houses and 8 chamber music halls from (14) served as data basis, in (2) this was extended by data sets taken from (4-12) to 150 rooms, among them 59 concert halls, 19 chamber music halls, 20 opera houses and four new room types: churches (40 examples), lecture halls (14 rooms), rehearsal rooms (8 rooms), theatres (4 additional rooms).

In the present study, this data basis was extended by all examples from (4-14) and (17) as well as by additional data from the Peutz group to 403 room data sets, which are available for analysis, with 147 concert hall data sets, 39 chamber music halls, 118 opera halls, 50 churches, 15 lecture halls, 17 theatres and 17 rehearsal halls. The actual number of different rooms though is somewhat below 400 in total, for multipurpose rooms like for instance the "Spiegel" in Zwolle the corresponding parameter values for their uses as theatre, opera and concert hall has been added also in all applicable room types.

3. EXTENSION TO (3+)-DIMENSIONAL ANALYSIS: TOOL FOR NEW INSIGHTS

The analysis method presented here is a valuable tool to obtain new scientific insights. Computer technology allows a comparatively simple (3+)-dimensional graphic representation of data. For the visual analysis of the data n-tuples per room presented in (1) and (2), a MATLAB®-script was used. For the present study the code was totally newly implemented within the open-source software GNU octave, version 4.2.1 in order to plot the available parameter values of the data sets into (3+)-dimensional graphs on arbitrary axes within a Cartesian coordinate system.

A multitude of parameters in these graphs as viewing angle (azimuth, elevation), axis scaling (linear, logarithmic, range) as well as marker color and marker size for additional dimensions above

three allow for the presentation of the input data n-tuples to be illustrated in comparison to each other, see e.g. figure 1.

For the representation proposed here a parameter space can be assumed without loss of generality as orthogonal in the first instances, as long as the inter-parameter dependencies are unknown, e.g. $RT_{mid,bes}$; $G_{meas,mid,u}$ and V . In order to examine these 3-dimensional representation of triplets in a visual analysis, see e.g. figure 1 showing all rooms of this study; marker color indicates the room type as additional dimension.

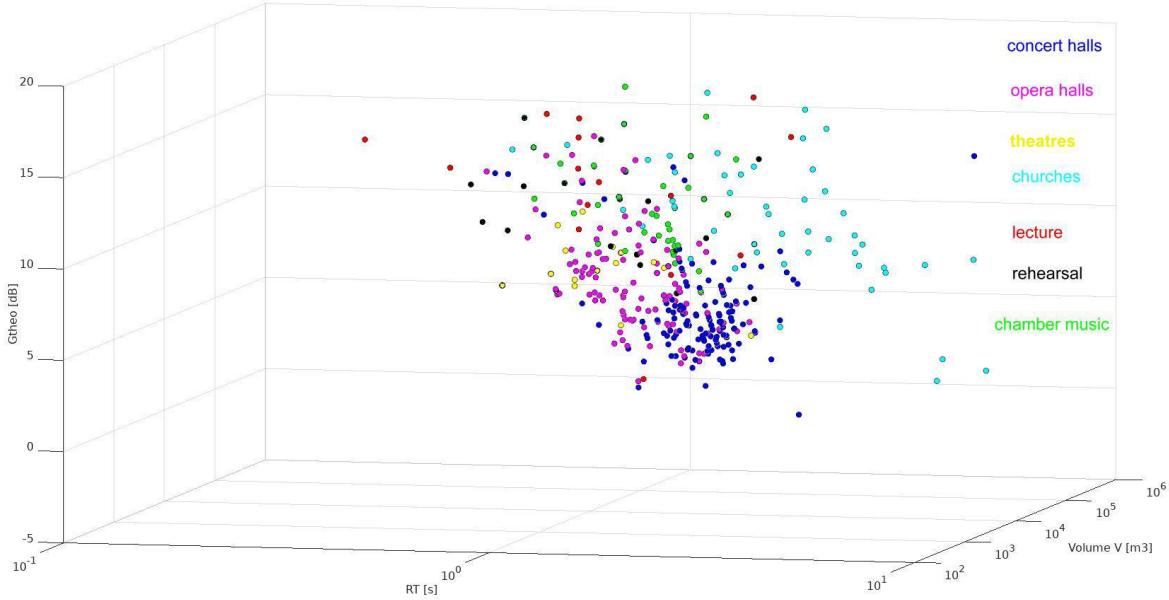


Figure 1 –RT - V - G_{theo} plot of all data sets examined, color indicates room type.

3.1 (3+)-Dimensional Representation of Dependent Parameters

In such (3+)-dimensional graphs, a dependency between correlated quantities becomes directly visible while rotating the graph by choosing an appropriate angle of view of the data sets:

Obviously, there is a strong correlation between the quantities RT, G and V, see figure 2:

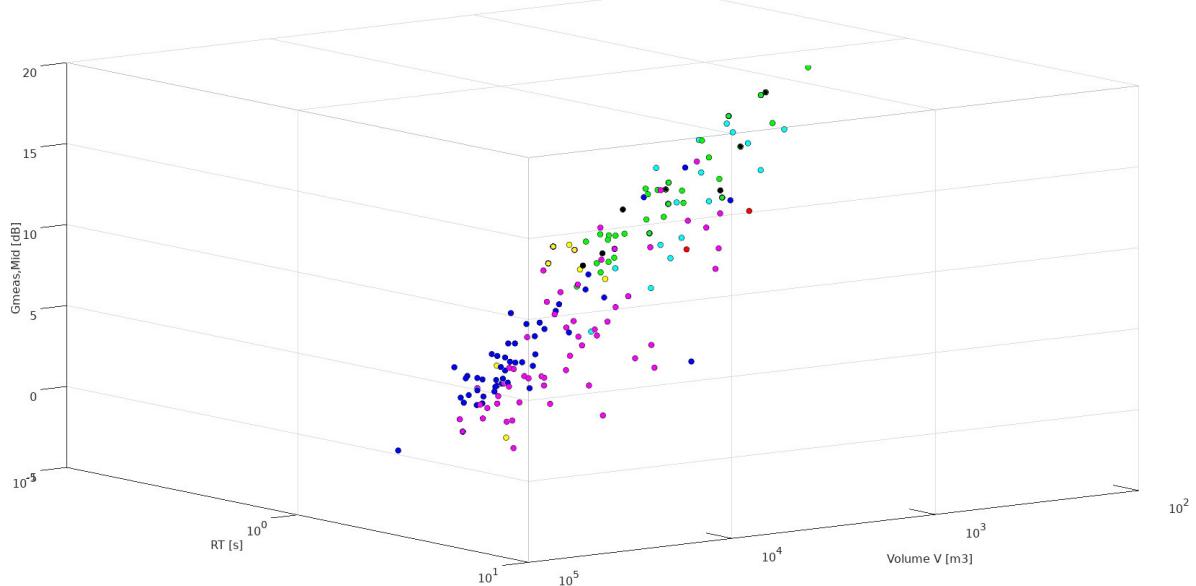


Figure 2 – RT - V - G_{meas} plot of all data sets with G_{meas} , color indicates room type (see figure 1)

Figure 2 shows that the in the first instance w.l.o.g. chosen quantities $RT_{mid,seated}$, $G_{meas,mid,u}$ and V to span the parameter space obviously are correlated; if viewed in an appropriate viewing angle, the

majority of the data sets are located along a straight line in the parameter space. Exceptions appear in the data sets of opera houses and churches, where a correct estimation of the acoustically effective volume is non-trivial due to coupled spaces as stage tower or naves etc.. Nevertheless, the value of Pearson's correlation coefficient of $G_{\text{meas},u}$ and $G_{\text{theo},s}$ is 0,87 for the data sets examined here. The conclusion may be drawn that in the majority of the rooms analyzed here, in source distances of $d > 2$ times the reverberation radius a nearly diffuse field behavior can be assumed. This allows in the following sections for transferring findings from the smaller number of rooms with measured date of $G_{\text{meas},u}$ to that ones, where $G_{\text{theo},s}$ is calculated by equation (1), which is valid in the diffuse field.

When viewed vertically, already in (1) and (2) was shown that the RT / G / V - triples of the rooms are located in or at least near a plane in the parameter space, see figure 1. Moreover, the diverse room types are located in partly disjoint subspaces. Within these subspaces, the majority of samples cumulate in clusters in specific subspaces characteristic for the genuine room type. In the analysis here with extended number of data sets, it can be observed that the separation in clusters according to the use turns out to be slightly less distinctive than in the earlier data sets due to many rooms, which are built as multipurpose halls or as a compromise between different applications desired without altering of the acoustical parameters: these are located in between the subspaces characteristic for the room type. Moreover, in the actual data samples of known acoustical appropriateness are included as well.

3.2 (3+)-Dimensional Representation of Independent Parameters

The visual representation of samples in a multi-dimensional parameter space can be assumed to be especially significant if a parameter space is chosen in which the quantities to span this space are independent. In order to identify independent parameters, in (1) the correlation of each pairs of room acoustical parameters was tested.

As independent parameters turned out to be, among others e.g. $RT_{\text{mid},\text{seated}}$, $G_{\text{meas},\text{unseated}}$, and BQI_{unseated} . In figure 3 the actual data n-tuples are displayed in a parameter spaces spanned by these three little correlated quantities.

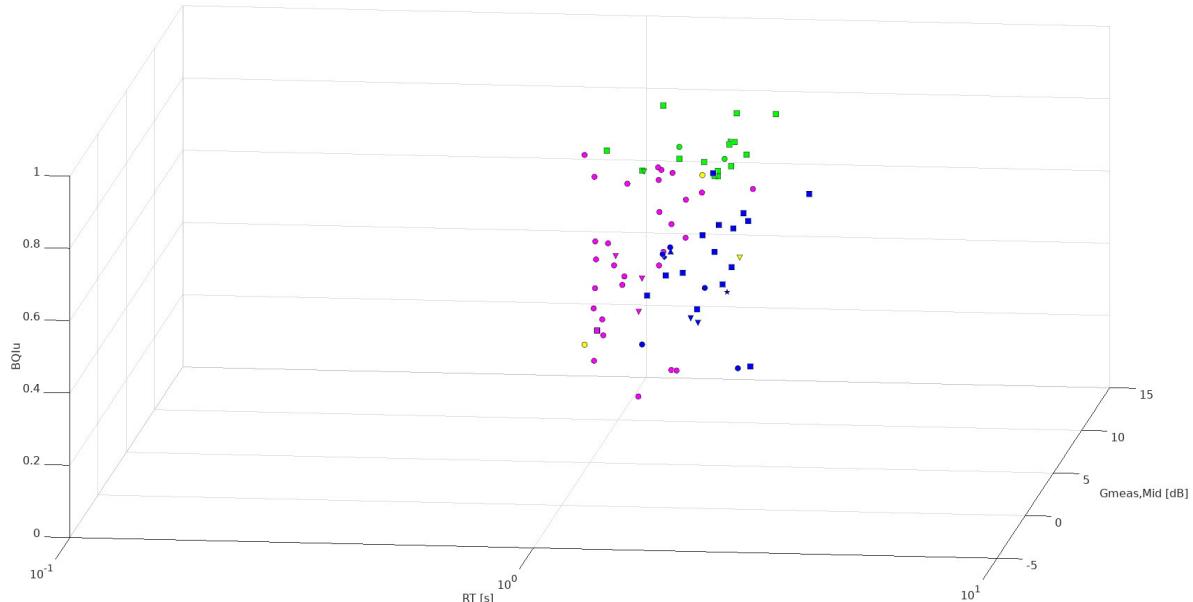


Figure 3 – RT - G_{meas} - BQI plot of all data sets with BQI-values, color indicates room type, marker the shape

A visual analysis of figure 3 shows a clear separation of the room types chamber music halls (green), concert halls (blue) and opera halls (magenta) in clusters in almost disjoint subspaces of the chosen parameter space RT - G - BQI with some data samples in between two adjacent room types.

3.3 Cluster Accumulation of Rooms with High Quality Rating Score

Within the clusters of the room types, sub-clusters can be identified with rating scores from (14):

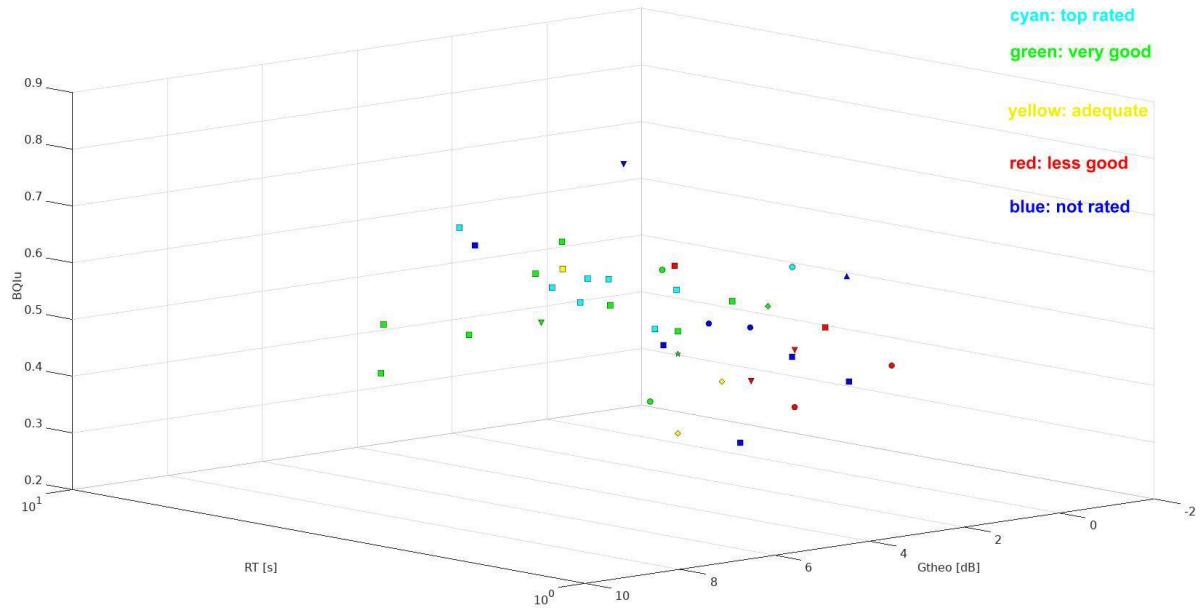


Figure 4 – RT - G_{theo} - BQI plot of concert halls with BQI-values, color indicates rating, marker the shape

In figure 4, it can be seen that in (14) higher rated concert halls have higher BQI values and higher RT-values as well as high G-values, and form a sub-cluster within the concert hall cluster (cyan marker color: top rated) with characteristic parameter values within a certain range and room shape (rectangle: shoebox-style halls). Concert hall data sets with lower rating exhibit lower values of RT, G and BQI.

3.4 Historical Development of Room Types

Let us regard the development of for instance the room type concert hall with time: In figure 5 the historical development is analyzed from the first examples of this room type to the 21st century, plotting number of seats against room volume and opening year.

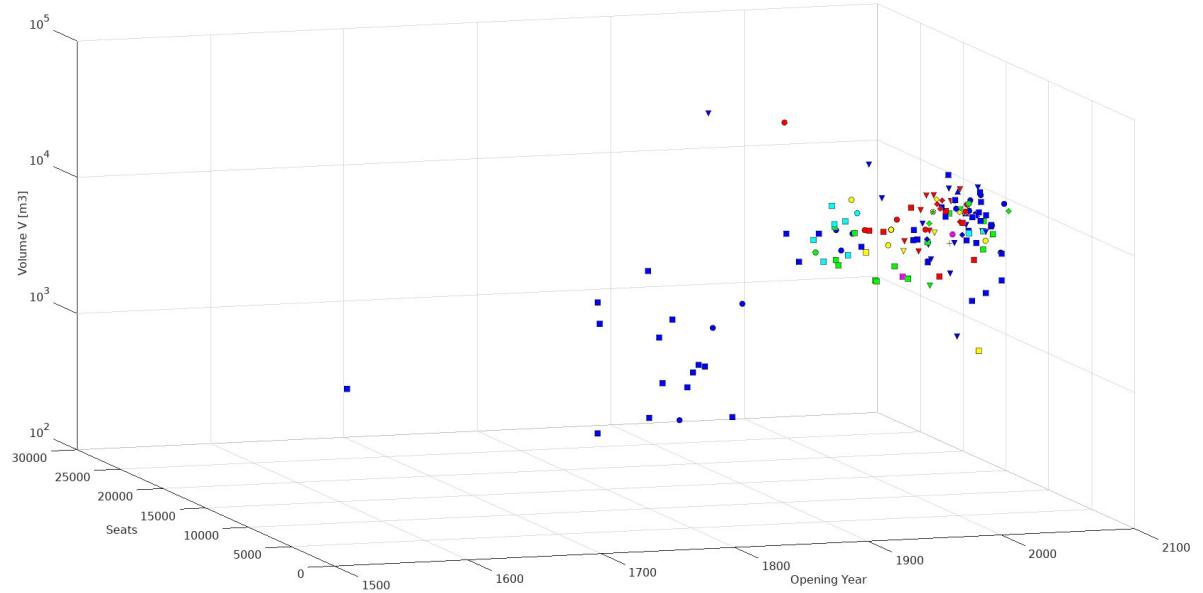


Figure 5 – Time - Seats - Volume plot of concert halls, color indicates rating, see fig. 4, marker: shape

In figure 5 it is obvious, that characteristic trajectories across the parameter spaces through time clarify the evolutionary trends of this room type: starting with a low number of small halls (see (12)), which would nowadays serve as chamber music halls, the room type over time has changed dramatically by adding more and more seats (i.e. more and more sold tickets as motivation), requiring higher and higher room volumes. Not visible in the figure: the resulting demand to enlarge the orchestra to compensate for the loss of strength. Within a certain slot of some 40 years around 1890,

the halls mostly are rated (14) as excellent, followed by decades with rather mediocre ratings caused by even larger number of seats (a trend especially in North America) and high volumes (as well as hall widths), resulting in low values of G and BQI, respectively.

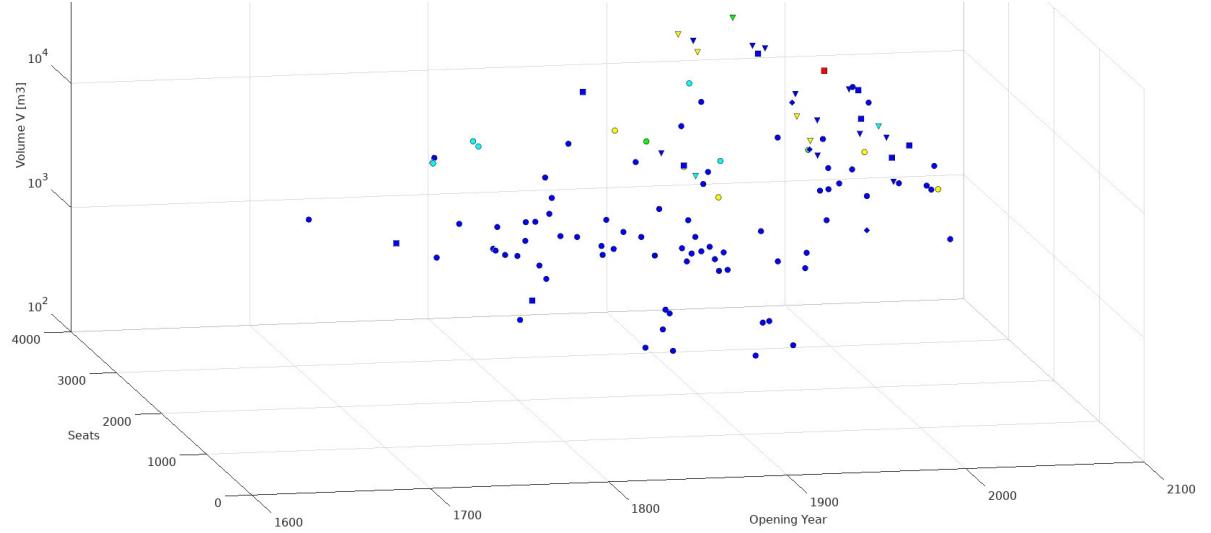


Figure 6 – Time - Seats - Volume plot of opera halls, color indicates rating, see fig. 4, marker indicates shape

Figure 6 shows the same view as chosen in figure 5, but now displaying the historical development of opera halls. Whereas the quality rating is not that clear, it can be seen easily that the room type “opera hall” starts to exist earlier and spread out at first in Europe all over the continent, whereas the concert hall room type was just at its beginning (the first data point in figure 4 indicates an old building in Vienna which has a hall inside, which has been used in the 18th century for concerts, see (12)).

4. BENEFIT AS CONSULTING TOOL

Objective of room acoustical consulting is the judgment whether an existing or prospective room is able to exhibit room-acoustical qualities adequate to the (main) intended use of the room.

The analysis method presented here offers a real benefit in terms of consulting purposes: already in the very early states of consulting the room acoustical conditions of a newly to build room or before a refurbishment with the basic data V and RT_{Mid} (which is strongly linked to the number auf audience) and resulting value of $G_{mid, theo}$ (assuming a diffuse sound field in the room further away from the source) can indicate the relative position of this new room in relation to the room type clusters, if within a type cluster or even in the subspace with high ranking scores, inside the type-clusters, but outside the subspaces with good ranking scores, or even beyond the type clusters. In discussions with clients and architects, consequences of global decisions defining the acoustical quality can be visualized.

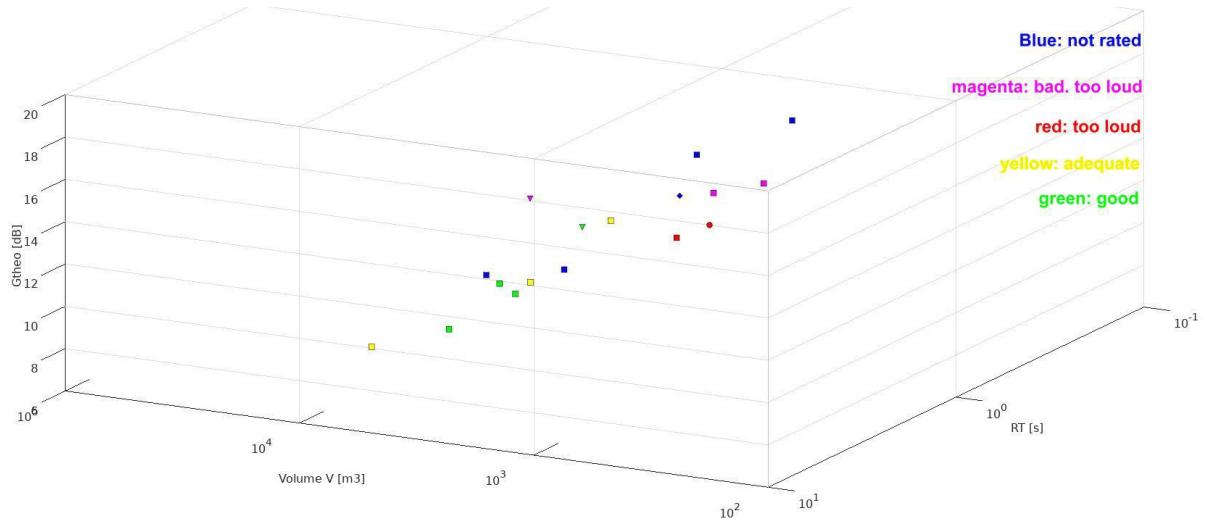


Figure 7 – RT - V - G_{theo} plot of orchestra rehearsal halls, color indicates rating, marker indicate shape

Figure 7 displays orchestra rehearsal rooms inclusive ratings by the users. A clear pattern is identifiable: if the volume of a rehearsal room is large enough for the intended ensemble size there is the chance that an acoustically successful rehearsal room can be built within the geometrical frame.

If room acoustical conditions in given rooms by the users are judged as suboptimal, measures should be defined to improve the rating for the intended use. For this proposal the analysis method presented here offers possibilities to judge the effect of alterations before going into the consulting process with computer simulations or scale models: if the spatial position of a room in the chosen parameter space is outside the room type cluster or inside the type cluster, but still outside the subspace cluster with high rankings, planned measures can be pre-viewed within the same plot and analyzed for the spatial position change in the parameter space, the planned or discussed measures would cause.

Effective proposed measures are visible as spatial position change in the parameter space, as well as whether the aim can be achieved by the proposed measures: then the parameter n-tuple of the room with measures should meet the subspace clusters of room type or of the desired rating, see (2).

The Effect of refurbishment measures can be tested before building activities on a very basic level.

5. CONCLUSION

The method presented in this paper, multidimensional visual cluster analysis of room-acoustical parameter values in three- or moredimensional parameter spaces based upon numerous data-sets of existing halls, represented as parameter n-tuples with well-defined spatial positions offers comprehensive possibilities as means to gain scientific insights into the nature of usage-dependent room acoustics and can be very beneficial as a fast consulting tool for planning new rooms or refurbishment measures of existing ones.

Further work still has to be done e.g. by adding acoustical quality rating scores to other room types, especially chamber music halls, and to find the just noticeable difference (JND) for spatial position changes in the parameter spaces.

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