Room geometry acquisition and processing methods for geometrical acoustics simulation models

Lukas Aspöck, Michael Vorländer

Institute of Technical Acoustics, RWTH Aachen University, Aachen, Germany
{las,mvo)@akustik.rwth-aachen.de

Abstract
The process of a room acoustical simulation usually begins with the acquisition of the room geometry of the investigated object. Although guidelines for the creation of a room model are available, the interpretation of these rules might lead to significant deviations of the simulation results. If the room or building is already constructed, the room geometry is usually available (drawings or models of the architect). Otherwise the geometry can be recaptured manually by using a tape measure or a visual capture system, e.g. by processing images or using a laser distance measurement system. Another option is an inverse acoustical approach based on an image source model of a room acoustical measurement of the room. On top of the measurement uncertainty of these methods, the processing of the acquired data produces additional uncertainties. An important question for the processing of the room geometry is the desired level-of-detail. If the simulation is conducted in different frequency bands, it is also possible to use different room geometries for each frequency band. Examples for the acquisition and the processing of the data are presented and their impact on the results of the room acoustical simulation is discussed.

Keywords: room acoustics, simulation, geometry, geometrical acoustics

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1 Introduction

In the few decades room acoustic modelling techniques have been developed and extensively investigated [1], covering various fields of application. Especially due to the increase of computational power of computers, room acoustical simulations based on Geometrical Acoustics (GA) today have become an established tool for architects and acoustic consultants. All simulation models have to go through a validation process, which is usually conducted by a comparison to a measurement of reference situations. These situations are often very simple, controlled scenarios (e.g., [2]) or represent typical examples for the application of the investigated simulation model. With advances in signal processing and reproduction, psychoacoustic validation [3][4] of the simulation models also became possible in addition to the analysis of room acoustic quantities.

The SEACEN research group[1] currently prepares a Round Robin on auralization. Within this project, multiple rooms and scenarios relevant to room acoustics simulation are analyzed. Therefore geometric data of these scenes has to be provided. Although there are guidelines of how to capture the geometry of a room for an acoustical simulation [5] and some studies have been published in this domain [6][7] variations in the process of the generation of the room model may lead to distinguishable auralizations. In the past Round Robins on room acoustical simulation [8][9][9], room geometries were handled differently. In the first Round robin, information about the geometry of the investigated room was provided in form of a drawing of the room, containing a ground plan and a side view, leading to surface counts from 44 and 1833 among the participants. In the second Round Robin a room model in the *dxf* format was distributed to the participants, however only five in the first and seven in the second phase out of 14 participants in total used the provided room model for their simulation. Here a variation between 566 polygons (provided model) down to a minimum of 94 polygons was reported. The treatment of the room geometry in the third Round Robin was especially relevant as the investigated room (a musical studio) contained two complex surfaces, a diffuse wooden absorber on one wall and on the ceiling. Phases two and three of this comparison compared a detail model to a simple model with adjusted scattering coefficients. The results showed no substantial deviations for most simulators, which also confirmed the design rule for GA room models to use geometrical dimensions in the range of wave lengths and apply estimated or measured scattering coefficients for structured surfaces.
During the time of the last round robins, computational power was limited. Thus, often less geometric detail was preferred to reduce computation time of the simulations. Today a reduction of the polygon count due to computational reasons should be less relevant as the calculation times, especially for GA models, have been drastically reduced, reaching the capability of providing results in real-time [11].
Although results of the established modern simulation software might be more consistent today, variations are still to be expected, especially for sensitive parameters and auralizations. With the motivation of providing a suitable common room model for future comparisons and validations of simulation models and auralization concepts, this work presents and discusses possibilities for the acquisition and processing of room models for GA simulations.

2 Geometry processing for GA models

Apart from the Round Robins, the handling of geometrical data of GA models have been discussed in several other recent publications [5][6][12]. However, as the design guidelines for GA room models are rather flexible and depend a lot on the implementation of the GA model, so far no recommendation for a standardized procedure or tool for the generation of adequate GA room models exist. The approach to model only larger surfaces and use scattering coefficients includes the challenging task of assigning correct frequency dependent scattering coefficients. An overview of various aspects of the process from the physical object to the GA room model is shown in Figure 1.
The required accuracy of the geometry depends a lot on the application the room model is being used for. If room acoustics simulations (and auralizations) are used for to create a virtual environment with roughly defined acoustic characteristics, the representation of the model does not need to be as accurate as the representation for an inverse calculation of the boundary conditions [13][14]. Examples are listening experiments or virtual reality presentations of ancient buildings [12]. Here, the simulation is calibrated to match the measurement of the building with the goal to create the same audible impression within the virtual environment as in the real physical building.
For recently emerged inverse simulation-based calculation models for the boundary conditions, which are motivated by a possible future replacement of the reverberation chamber measurement [15], the

[1] www.seacen.tu-berlin.de

room model has to be prepared very carefully, as small deviations lead to high uncertainties for the inverse methods.

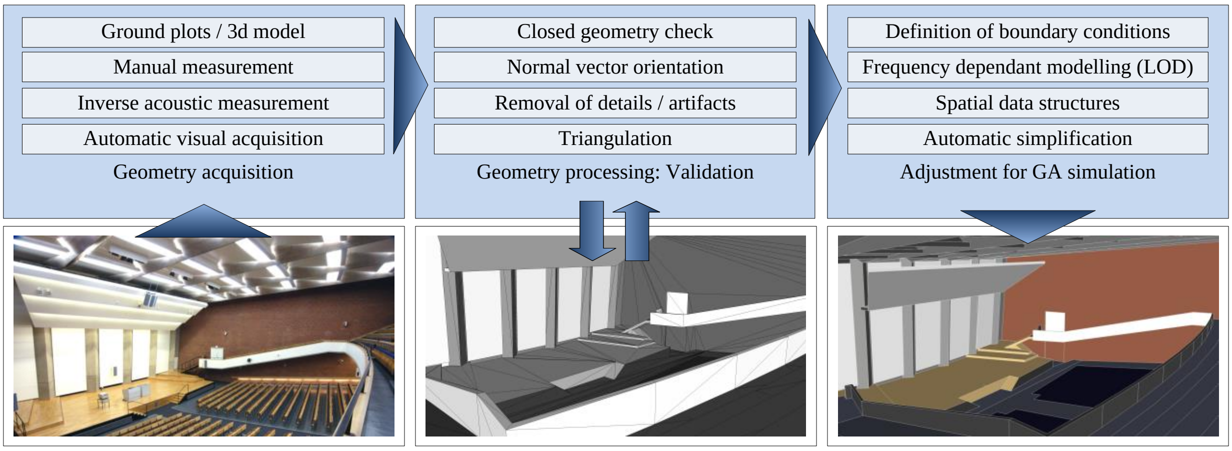

Figure 1 - Geometry acquisition and processing options for a GA-based room acoustical simulation

2.1 Acquisition methods

2.1.1 Manual measurement of room dimensions

Whenever a room acoustics simulation for an existing object should be conducted, one of the first steps is to check whether a ground plan or even a 3d model can be provided by the owner or the designer of the room. If this data can not be provided, the room dimensions have to be captured. Depending on the geometry of the room, this can be a time-consuming process and the question arises of which accuracy is required. In addition to the general guideline to only model geometric details in the range of the acoustic wavelength, Pelzer et al. determined a threshold for a minimal structure size of 70 cm in a listening experiment [6]. This value can be regarded as an upper limit for broadband auralizations – a theoretical lowest limit for the accuracy can be chosen according to the sampling rate used for the filter synthesis of the GA simulation. If a sampling rate of 44100 Hz is used, a shift of one sample corresponds to a spatial shift of 7 mm. The recommendation to avoid objects and structures of less than 70 cm does obviously not mean, that the outer dimensions of the room can be determined with deviations up this length. An measurement error in this range can quickly lead to a substantial deviation of the room's volume, which has a strong impact on the simulation results.

Based on the assumption, that the reverberation time is proportional to the volume of a room (as described by Sabine's equation) in a shoebox room all three dimensions have to be measured with a relative accuracy of less than 1.67% which leads to a maximum relative room volume and reverberation time deviation of 5% (JND according to [15]). This allows a maximum error of a few centimeters for smaller rooms (e.g., with the smallest dimension being 3 m). Such precision can be easily achieved with manual meausrement devices such as a tape measure. Affordable laser distance meters achieve an accuracy of 1.0 to 1.5 mm.

2.1.2 Automatic geometry aquisition based on visual sensors

With emerging available sensors in different technical devices as well as various software solutions using modern digital image processing methods, the automatic geometry aquisition is another option for the documentation of the geometry of existing rooms and buildings. Such methods have been studied and applied in the domains of digital image processing, computer graphics and architecture, e.g., for buildings or entire urban areas. Algorithms to reconstruct the interior design based on stereo images often come with various requirements, e.g., camera calibrations, and typically extensive additional image processing has to be conducted to achieve acceptable results for acoustical simulations. Although first own approaches of using image based reconstructions of room models for GA simulations were not satisfactory, such methods will be considered for further research. Furukawa et al. developed a fully automated system for the reconstruction of challenging textureless indoor scenes [16]. The only known approach so far for an automated geometry acquisition of a 3d representation adjusted for GA simulations was presented by Markovic et al. [17]. The room interior is scanned with a commercially available depth-camera (Kinect, precision of 3 mm) and processed with a 3d scanning software. Post processing operations transform a 3d point-cloud into a room model. A drawback of this method is that it requires various post processing steps (e.g., filling of holes) leading to a less precise reprentation in comparison with a manual measurement of the room dimensions. Especially for rooms with a rather simple geometry, a manual measurement is preferable.

2.1.3 Inverse geometry calculation based on room acoustical measurements

Another approach for the estimation of the room geometry is based on an acoustical measurement of the room. To find all details which are acoustically relevant, one or more room impulse responses (RIRs) can be processed to create a room model which can directly be used for a GA simulation. Multiple approaches for the estimation of a room geometry based on room acoustics measurements have been proposed. Most of them are based on an image source model and use an optimization process to match detected reflections to first or higher order image sources and in this way reconstruct the faces of the room. While Tervos model [18] requires various measurements with a B-format microphone rotating around a loudspeaker, Dokmanic [19] was able to recover a 3d geometry of a convex polyhedral room based on a few room acoustic measurement positions using omnidirectional pressure sensors.

Due to the promising results of Dokmanic and the fact the inverse geometry estimation can automatically deliver the adequate level of detail for the room model, part of our ongoing research concentrates on a similar algorithm to estimate the room geometry based on room acoustic measurements. Here, we have the vision to evaluate a typical precision room acoustic measurement and automatically generate a matching room model for documentation and simulation purposes.

Our approach starts with a peak detection for a set of RIRs. The implemented method is robust for simulated RIRs, while for measured RIRs the success rate of detecting all relevant reflections including their time of arrival is substantially lower. The detected peaks are then used for the generation of all possible combinations for all receiver positions. Euclidean distance matrices (EDMs) are created, containing the distances of all receiver points as well as the distance of each receiver to a potential image source candidate. An optimization based on a multidimensional scaling minimizes the distance to a valid EDMs containing the position of the image source. A first impression of the results is presented in Section 3.1. The existing publications as well as our results indicate that the robustness of the inverse geometry estimation approaches depend a lot on the number and the setup of the microphones. In general, it can be expected, that an increase of the number of positions and measurements leads to more information and thus a more reliable result.

While for a project of greater extent such as the upcoming Round Robin, the effort of using a microphone array in the room of interest is acceptable, for smaller projects, a room acoustical measurement including a specific microphone array might be too much effort especially if the required equipment is not available.

2.2 Manual geometry processing and validation

Before the geometric models are used for the room acoustical simulation, the model should be validated. Some simulators require triangulated polygons, and most of the GA models only work with

closed geometries. To repair room models a lot of 3d modelling environments (e.g., *Meshlab*) contain a set of tools to detect and fix problems such as separated polygons. If these operations are not available, plug-ins can be installed (e.g., for *SketchUp*). To detect holes and tiny gaps in room models, a room acoustics simulation plugin [20] for *SketchUp* is capable of visualizing the paths of the ray tracing algorithm. As soon as rays leave the enclosure, the room model requires a revision.
For more complex geometries containing various irregularities (e.g., gaps and holes), an automated process for filling holes in meshes [21][22] could also be applied.

2.2.1 Geometry simplification

Whenever geometric information is acquired by an automated detection method or when a 3d model with too many details was provided, an algorithm for simplification of these models becomes an important tool. With the goal of increasing the computational efficiency by reducing the polygon count of the model Siltanen et al. [23] proposed a reduction algorithm based on volumetric subdivision approach. Geometrical details and complex topological structures are removed by generating an octree structure and using a marching cubes algorithm to create small faces within each octree cell. The final step is a coplanar polygon merging, resulting in a model with a reduced polygon count. An automatic simplification of the room geometry using a regression plane algorithm was suggested by Drechsler [24]. Groups of neighboring polygons are iteratively replaced by their regression plane. This algorithm works well on slightly structured polygon meshes, e.g., acquired with a laser scanning system. Drawbacks of the algorithm are problems with structures which do not have planar characteristic, e.g., round objects or openings in larger walls.
For a semi-automated simplification process we adjusted the algorithm that it would only simplify selected polygons of the room model, e.g., only the ceiling area as shown in Figure 2. The simplification can be efficiently done by an expert checking each step of the model’s simplification.

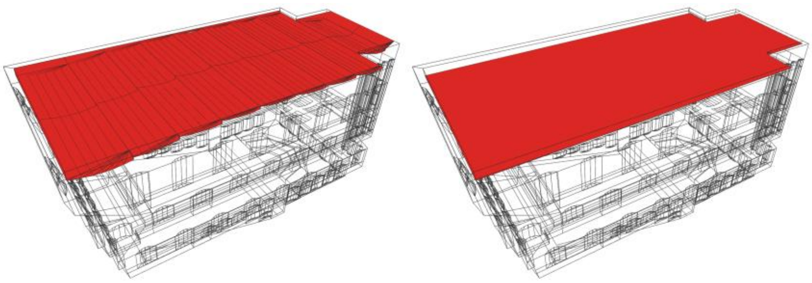

Figure 2 – Example showing the simplification of the ceiling area for a concert hall

In general, a semi-automated simplification with the possibility of parameterization is a suitable way for the preparation of the polygonal scene model. Another robust solution for the reduction of the polygon count is integrated in the ODEON software. Here the *Glue surfaces option* enables to automatically reduce an imported model using a stitching algorithm [25]. In addition to the presented algorithms, the free software *MeshLab* offers various options for geometric simplification (e.g., quadric edge collapse). However, these algorithms do not consider the acoustical properties (absorption and scattering coefficients) of the simplified polygons. Although the focus lies on smoothing visual renderings, *SketchUp* plug-ins such as *CleanUp*[3] or *Artisan* also provide useful functionality for removing details from 3d models.

2.2.2 Level of detail processing

With the tools being available to simplify room geometries based on techniques presented in the previous section, room models with a different level of detail can easily be generated. Based on the idea from computer graphics, Pelzer extended the GA simulation engine *Raven* with the functionality to process multiple different room models adequately for separate frequency bands [6]. The application of the LOD concept also yielded a significant speed-up of the simulation. A listening test using differently detailed models lead to a detection threshold of 70 cm. Models containing structures smaller than this size could not be distinguished from a higher detailed reference model.

3 Analysis of aquisition and processing methods

3.1 Inverse aquisiton based on room acoustic measurements

First results of the concept presented in Section 2.1.3 are shown in Figure 3. The geometry of the real room is visible Figure 4. While the algorithm worked properly for convex shoebox geometries, in case of a (non-convex) real seminar room both estimations did not succesfully esimate the room's geometry.

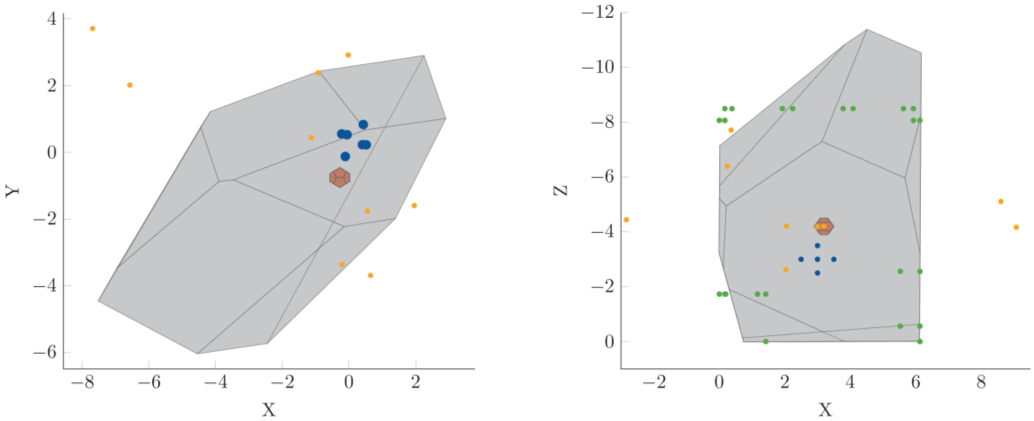

Figure 3 – Results of inverse geometry estimation method of a seminar room. Left figure shows the geometry estimation based on measured RIR, on the right the estimated geometry is based on a simulated RIR. Blue dots indicate the receiver positions, yellow dots detected image sources and green dots show vertices of the original simulated model.

As the current implementation is based on first order reflections, it was expected that the algorithm is not capable of detecting the faces which do not correspond to an audible image source. Although the estimation algorithm was not able to reconstruct the room's faces correctly, the deviation of the volume of the estimated volumes is still acceptable: 2% for the measured RIR and -4.3% for the simulated RIR estimation. In comparison to results of Dokmanic [17], the results the presented inverse approach heavily depend on the selection and the setup of the receiver positions. The development of a more robust algorithm detecting reflections and generating the corresponding room model is currently still ongoing research.

3.2 Seminar room: manual measurement vs. laser-based model

Two models for the same room were created by different persons using different methods for the documentation of the geometry. Figure 4 shows the seminar room model determined by the SEACEN research group with the *VariSphear* system [26] using a computer-controlled pointing device (precision of ±0.002°) and a laser distance meter to determine points in the room. The final model contains 46 polygons and has a volume of 148.98 m³ and a surface of 191.7 m².

This model is compared to an older drawing according to a manual measurement of the room using a tape measure. This model resulted in 68 polygons, has a volume of 144.39 m³ and a surface of 187.8 m², a deviation of 3.1% for the volume and 2.0% for the surface compared to the laser distance meter measurements. The maximum error of one of the measured distances in both models was 9 cm.
For the simulations, which were conducted with the software Raven, only one material with an absorption coefficient between 0.05 and 0.1 for the investigated frequency range was selected (unrelated to the real materials of the room). The hybrid simulation model was configured to use 2nd order image sources and a ray tracing of 15000 particles for each octave band. To reduce the influence of the variation of the stochastical model, each simulation was run 10 times for each source-receiver combination. As room acoustic parameters are one of the most relevant measures for the room acoustician, three relevant parameters were evaluated for the generated RIRs. The averaged results for all receiver positions are presented for four octave bands in Table 1.

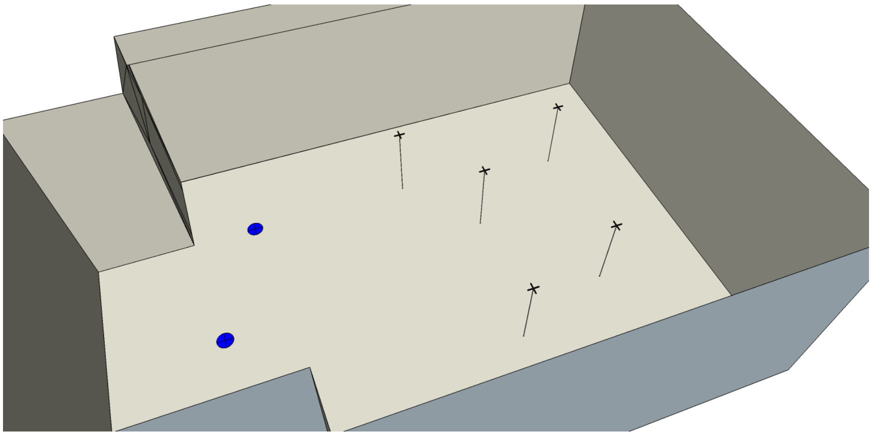

Figure 4 – Room model of seminar room determined with the VariSphere measurement system. Blue circles indicate the sound source positions; Black crosses show the microphone positions

Table 1 – Comparison of seminar room simulation results for differently acquired room models

	EDT [s]				**T30 [s]**				**C80 [dB]**			
	250	**500**	**1k**	**2k**	**250**	**500**	**1k**	**2k**	**250**	**500**	**1k**	**2k**
VariSphere	1.62	1.56	1.37	1.19	1.68	1.60	1.42	1.24	-1.4	-0.0	0.9	2.1
Manual meas.	1.61	1.49	1.34	1.17	1.67	1.59	1.42	1.23	-1.9	-0.5	1.0	2.0

The results show that the minor deviation of models does not have a substantial effect on the simulated room acoustic parameters. The maximum deviation for the calculated EDT is 0.07 s, which is equivalent to a relative deviation of 4.5% (below the JND according to ISO-3382 [15]). The T30 values all have a relative deviation of less than 1%, C80 values are also below the JND of 1 dB.

3.3 Modelling of coupled volumes in a chamber music hall

The next example is a small chamber music hall in Berlin with a main hall volume of approx. 1800 m³ and a stage room of around 500 m³. The attic of the hall adds another 1000 m³ to the total volume. The model was constructed based on measurements with the *VariSphear* system for the main hall and manual laser distance meter measurements in the stage area and in the attic. Three different models were created (see Figure 5): Concert hall without the attic area (1187 Polygons, V=2337.9 m³, S=1895.3 m²), the concert hall coupled to the attic via the stage room (1233 Polygons, V=3322.5 m³, S=2722.3 m²) and a second coupled situation, where the main hall is connected to the attic via slots (each with an area of ~0.5m²) which are typically used for lighting installations (1585 Polygons, V=3342.4 m³, S= 2719.7 m²). Room impulse responses of these three models were simulated and processed in the same way (two sources, five receivers) as described in Section 3.2.

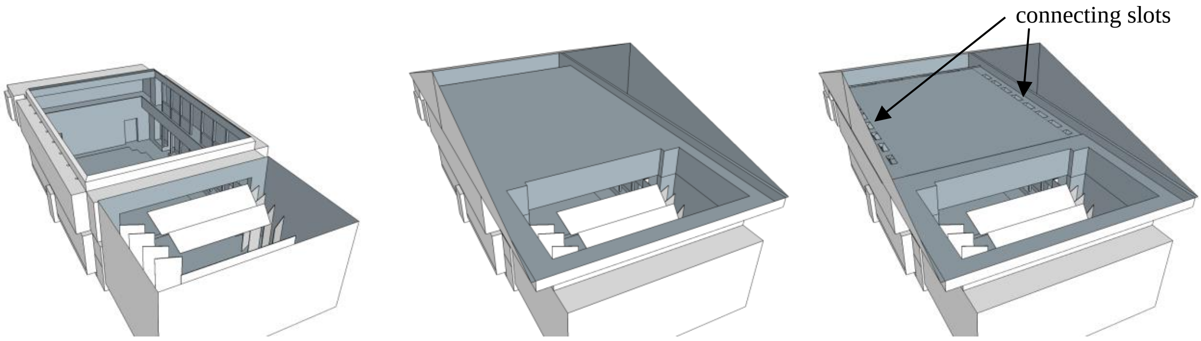

Figure 5 – Three models of a chamber music hall in Berlin. Left model only contains the main room and the stage, in the middle model, the attic was added (connected via the stage area), in the third model on the right hand side, connecting slots (for lighting) were added to the model. Ceiling parts are hidden in all models.

Results of the room acoustic parameter evaluation are listed in Table 2. In comparison to the seminar room evaluation, the values show larger differences, especially for the EDT parameter. Here the deviations lie between 5% and 10% and thus imply audible differences if the scenarios are auralized. This evaluation does not answer the question of which model represents the real situation in the best way and in how far the used simulation model provides reliable results for coupled room situations. To answer these questions, the simulated results have to be compared with measured results and a detailed analysis of more than room acoustic parameters have to be conducted.

Table 2 – Comparison of simulation results for three chamber music hall models

	EDT [s]				**T30 [s]**				**C80 [dB]**			
	250	**500**	**1k**	**2k**	**250**	**500**	**1k**	**2k**	**250**	**500**	**1k**	**2k**
MainHall	2.72	2.54	2.26	1.91	2.70	2.58	2.30	1.98	-3.0	-3.2	-1.9	-0.7
+ Attic	2.63	2.47	2.21	1.85	2.68	2.56	2.28	1.98	-2.6	-2.9	-1.6	-0.5
+Attic/Slots	2.50	2.44	2.11	1.80	2.67	2.55	2.24	1.96	-2.6	-2.8	-1.4	-0.4

Due to the coupled volumes a non-linear energy decay can be expected. The curvature parameter C was calculated according to ISO 3382-2 [27]:

$$C = 100 * \left(\frac{T_{30}}{T_{20}} - 1\right) \ [\%] \tag{1}$$

The results of the curvature parameter C for the three scenarios are: 1.54%, 2.60% and 1.63%. These values indicate that despite of the coupled scenario situation, the energy decay curves can still be regarded as being linear and therefore the evaluation procedure of the reverberation time is reliable. The effect of the coupled volumes on the energy decay is rather small because a homogeneous material coefficient was used for all faces in the room, which does not correspond to the real situation. To select the adequate room model for the validation of simulation software for this concert hall however, the difference of the curvature parameter for simulation and measurement result could represent an additional useful indicator.

4 Conclusions

This worked presented and discussed various options for the acquisition and processing of geometrical data for geometrical acoustics simulation models. It is motivated by the goal of providing adequate room models for upcoming validations of room acoustic simulation and auralization software.

In addition to classical methods of setting up a room model by using ground plans or manual measurements, various methods have emerged to automatically capture the room model, either using visual or acoustic sensors. Although first results are acceptable, these methods currently cannot be recommended for a robust acquisition of arbitrary room geometries. Mostly additional processing steps are required, e.g., for stitching, repairing or simplifying the polygonal structure of the model. For these operations, various algorithms and plug-ins are available, which support the modelling process in general. However, a careful application is recommended as especially simplification methods which are not developed for acoustic modelling do not account for the acoustical properties (absorption and scattering coefficients) during the transformation process.

In general, processing geometry for room acoustical simulation depends a lot on the required accuracy and the used simulation model. There is not one optimal solution for a room model as every simulator is different and similar room models might lead to identical results.

The investigated room models will be published and publicly available in the scope of the upcoming international round robin on auralization (see http://rr.auralization.net for details).

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