GEOMETRY REDUCTION IN ROOM ACOUSTICS MODELING

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1 INTRODUCTION

In the design of concert halls and other acoustically demanding spaces computer models form an essential part. Currently, the 3D models for room acoustics prediction are created manually, by inserting vertices and surfaces one by one to the model. Manual construction of the model guarantees that models are suitable for room acoustics prediction software and that models contain acoustically relevant information. However, the model construction process is time consuming and hard work. It would be nice if acousticians could apply the same 3D models as other designers—e.g., the models created for visualization purposes. Unfortunately, such models usually are impractical for acoustics prediction since they are very complex containing too many polygons and irrelevant small details.

In this paper we propose an automatic geometry reduction method that can take a complex 3D model and convert it to a reasonable acoustic model. Such automatic reduction gives acoustic consultants possibility to quickly verify the designs of architects. In addition, the reduction can be applied in games and virtual reality applications, in which real-time sound rendering is essential.

1.1 Room Acoustics Modeling

There are several methods for modeling room acoustics[1,2]. Finite element method (FEM) and boundary element method (BEM) try to solve the wave equation numerically. They are at their best when modeling low frequency behavior of sound. On the other hand, geometrical room acoustics modeling methods try to model the sound propagation by representing the sound as rays. In statistical methods a large number of rays is sent from the sound sources and their directions are determined by probabilities. The rays hitting the listener are considered audible. In this approach some reflection paths might get omitted.

Image source method is based on recursively mirroring the sound sources against each surface in the model thus creating image sources. This way the specular reflection paths of the sound can be modeled accurately. However, as the order of the reflections increases, the number of image sources grows exponentially[3]. Thus the image source method can be applied only to simple models or the order of reflections has to be very low.

To be able to model the acoustics of complex room models, the geometry of the models should be reduced. There exists several algorithms for geometry reduction, but none of them is specially tailored for the needs of geometrical room acoustics modeling. This paper represents a geometry reduction method, the goal of which is to provide simple acoustic model which retains the essential acoustical properties of the room as accurately as possible.

1.2 Previous Work

There has been extensive research in the area of model simplification. However, only a few highly relevant works from acoustics point of view exist and they are represented here. Andújar and Brunet described a framework for polyhedral simplification and mentioned its applicability to acoustics modeling[4]. The framework is roughly applied in the algorithm proposed in this paper as well. They also presented two simplification algorithms based on their framework. Later they have still improved the algorithms[5]. He et al. introduced an algorithm in which polygonal models are sampled into a density grid and an isosurface extraction algorithm is used to create the new surface[6]. Later they improved the algorithm by making the volume structure hierarchical[7]. Nooruddin and Turk proposed another volume raster −based algorithm which can be applied both for repairing and simplifying polygonal models[8].

2 VOLUMETRIC GEOMETRY REDUCTION

Reducing the geometry of a room model involves removing insignificant details while preserving the overall appearance of the model. To be more specific, it is necessary to choose the properties which are the most important from the acoustics modeling point of view.

Volume of the model is one of the most important properties to preserve, because changing it affects many acoustical parameters. Volume preservation also helps to keep the dimensions of the model unchanged. The absorption area of the room should also change as little as possible. In addition to the area of the surfaces in the model, the materials of the surfaces must be taken account. Therefore it might be necessary to blend the materials appropriately when several polygons are replaced with one bigger polygon.

This paper presents a novel technique for geometry reduction of models used in acoustics modeling. The method, described in the following sections, consists of two phases: topology simplification and surface simplification. The reduction process is illustrated in Fig. 1.

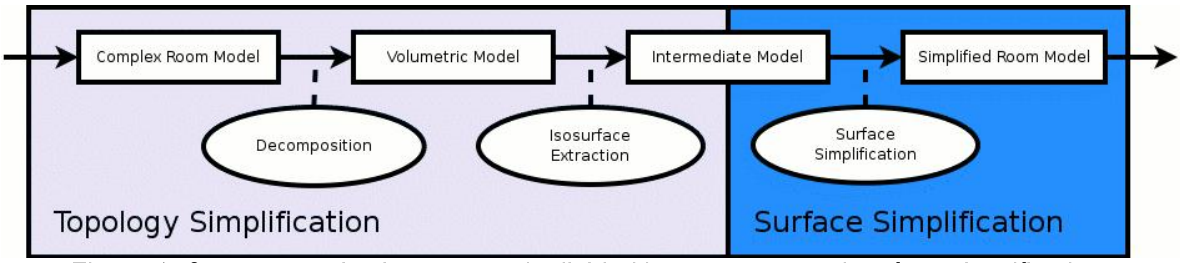

Figure 1: Geometry reduction process is divided into topology and surface simplification.

2.1 Topology Simplification

In the topology simplification part of the method, the complex room model is decomposed into a volumetric structure and then the surface is reconstructed. The purpose of this process is to remove details which would prevent further simplification when using mere surface simplification algorithms. Such details include small holes, cracks, and spikes which are acoustically insignificant.

The volumetric structure chosen for the topology simplification was an octree[9] which is a widely applied spatial data structure[10]. The input model is assumed to consist of a polygon mesh. The polygons are inserted into the octree. The depth of the octree is limited, so that the smallest cells are of the desired size. The maximum distance from the reduced surface of the original surface is the diagonal of the smallest cell size. Thus the error can be bounded.

The surface is reconstructed, to form an intermediate model, by using a variant of the marching cubes algorithm[11]. The marching cubes algorithm constructs an isosurface for a threshold density. The density is used both to determine whether a corner of a cubic cell is inside the object and to locate the isosurface position along the edges of the cell. However, there are no density values in the octree containing polygons. To determine whether a corner of a cell should be inside or outside the isosurface, one could cast rays from each corner to several directions, calculate the number of surface intersections along each ray, and utilize that information as proposed by Nooruddin and Turk[8]. However, this is computationally expensive and unreliable when the initial models are not composed of closed surfaces, which is the case with typical room models. Thus, a simpler and more reliable approach was used in which a corner is inside the isosurface if the adjacent octree cell in the direction of positive coordinate axis is occupied. The minor inaccuracy caused by this approximation can be compensated while positioning the surface along the edges of the cell.

The surface position along the edges of the cell is determined by casting a ray along the edge and finding the first and the last intersection, and then using the average of these values. This results in a good approximation in most cases, especially when there is only one intersection which is the most common case. Alternatively, the surface positions can be clamped to the octree cell boundaries to favor surfaces along the coordinate axis, which are common in typical room models. The newly reconstructed surfaces build an intermediate model, as illustrated in Fig. 1. However, the new surfaces may contain a large number of small coplanar polygons due to the marching cubes algorithm. Thus, to minimize the number of polygons in the final model the surface simplification step is necessary.

2.2 Surface Simplification

During the surface simplification phase the geometric optimization algorithm by Hinker and Hansen[12] is applied. The algorithm merges coplanar polygons by collecting them into coplanar sets using representative trees[13], removing the edges shared by any two polygons in a set, tracing the remaining borders, and re-triangulating the polygons defined by those borders. The re-triangulation step is not needed if the simplified model is allowed to consist of arbitrary polygons.

Surface simplification does not cause significant errors in geometry, because only nearly coplanar polygons are merged. However, coplanar polygons might have different materials and they cannot be joined together directly. Therefore the material blending is performed by weighting the material properties by the areas of the polygons, i.e., the material properties are assumed to behave linearly.

3 EVALUATION OF THE PROPOSED ALGORITHM

The above described geometry reduction process was done for a detailed concert hall model, created for visualization purposes. The original model, containing 73771 polygons and the reduced versions of it are illustrated in Fig. 2. It can be seen that the visual appearance of the model is conserved quite well during the reduction, but naturally the radical reduction rates violate the original model quite a lot.

In this section the performance of the reduction is evaluated. The computation times of different reduction rates are presented and the quality of the reduction from acoustics point of view is assessed by computing room acoustical parameters with the reduced geometries.

3.1 Algorithm Performance

The computation times of a non-optimized version of the reduction can be seen in Table 1. It is apparent that the coarse reduction levels can be produced very quickly, but as the reduction rate decreases the reduction times increase rapidly. However, the computation times are still short compared to the manual construction of a model for example in a concert hall design project.

Reduction %	**4,2**	**23,0**	**47,4**	**63,3**	**71,6**	**81,4**	**87,3**	**92,9**	**96,3**	**97,2**	**99,8**
Topology simpl. (s)	498	459	119	104	86	77	27	22	15	10	3
Surface simpl. (s)	739	381	123	84	37	20	8	3	1	1	0
Total (s)	1237	840	242	188	123	97	35	25	16	11	3

Table 1: Reduction times with different volume raster resolutions. The reduction algorithm was run on a PC with 2,8 GHz Pentium IV processor and 1 GB of RAM. The original model consisted of 73771 polygons and it is depicted in Fig. 2.

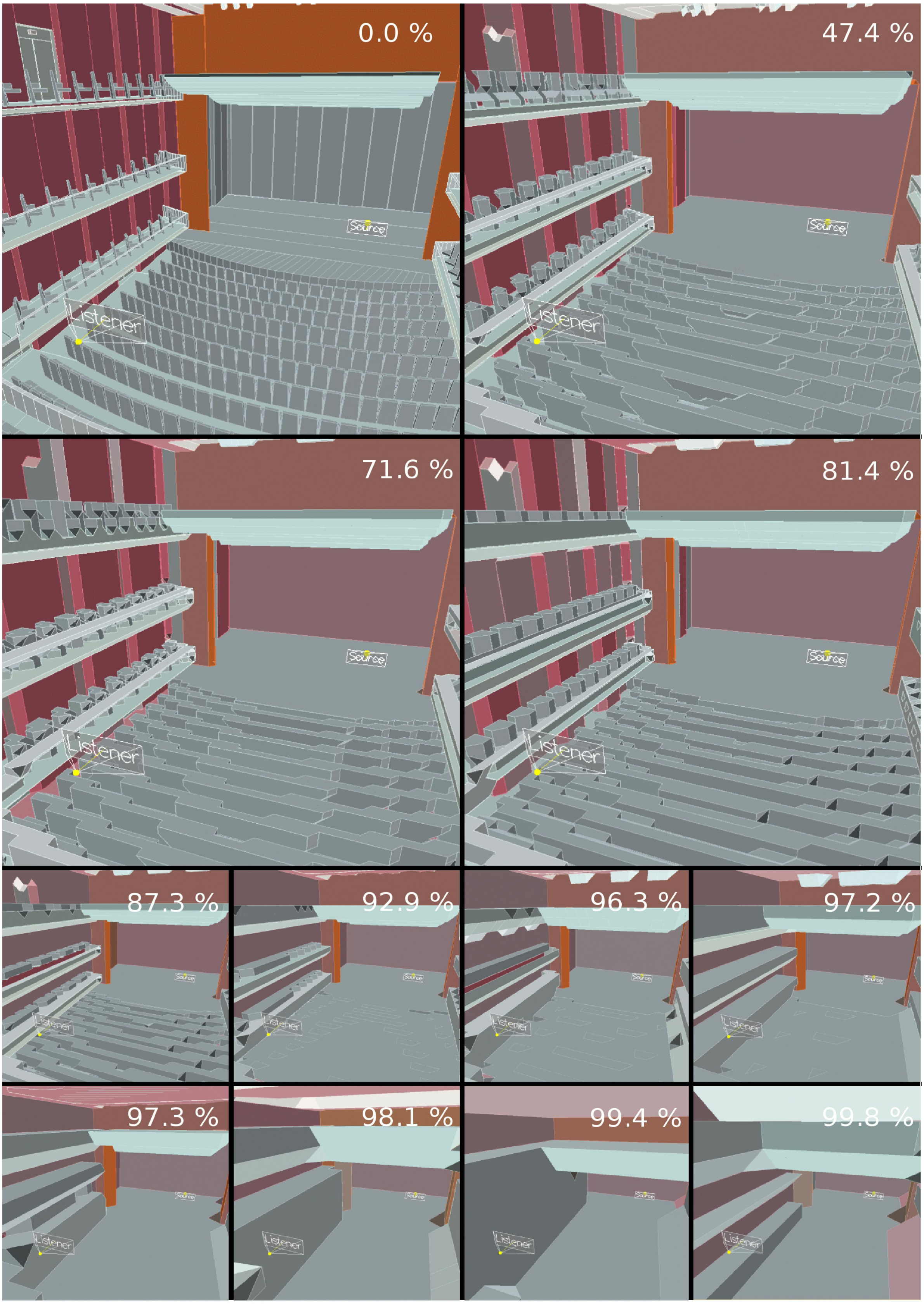

Figure 2: A few reduced models: the original model, containing 73771 polygons is marked with reduction rate of 0.0%.

3.2 Acoustical validation of the geometry reduction

The performance of the proposed geometry reduction can be validated by making room acoustical simulations in different geometries and computing room acoustical attributes. The easiest way to do such a comparison is to perform calculations both in the detailed (original) and reduced models with well-known commercial room acoustic prediction software. In this study we applied Odeon 5.0 for this purpose. Unfortunately, Odeon was not able to handle our original model, since it contains too many vertices and polygons. The reduced models could be simulated and in this section we show and discuss the simulation results obtained with different degrees of reduction. Six reduced models of the original concert hall model were chosen for the study. The properties of these models are collected to Table 2 and the models are depicted in Fig. 3.

Name of the model	hall900	hall928	hall964	hall981	hall990	hall996
Reduction %	90,0	92,8	96,4	98,1	99,0	99,6
Number of surfaces	3068	2248	931	527	304	137

Table 2: Properties of the models applied in the performance validation.

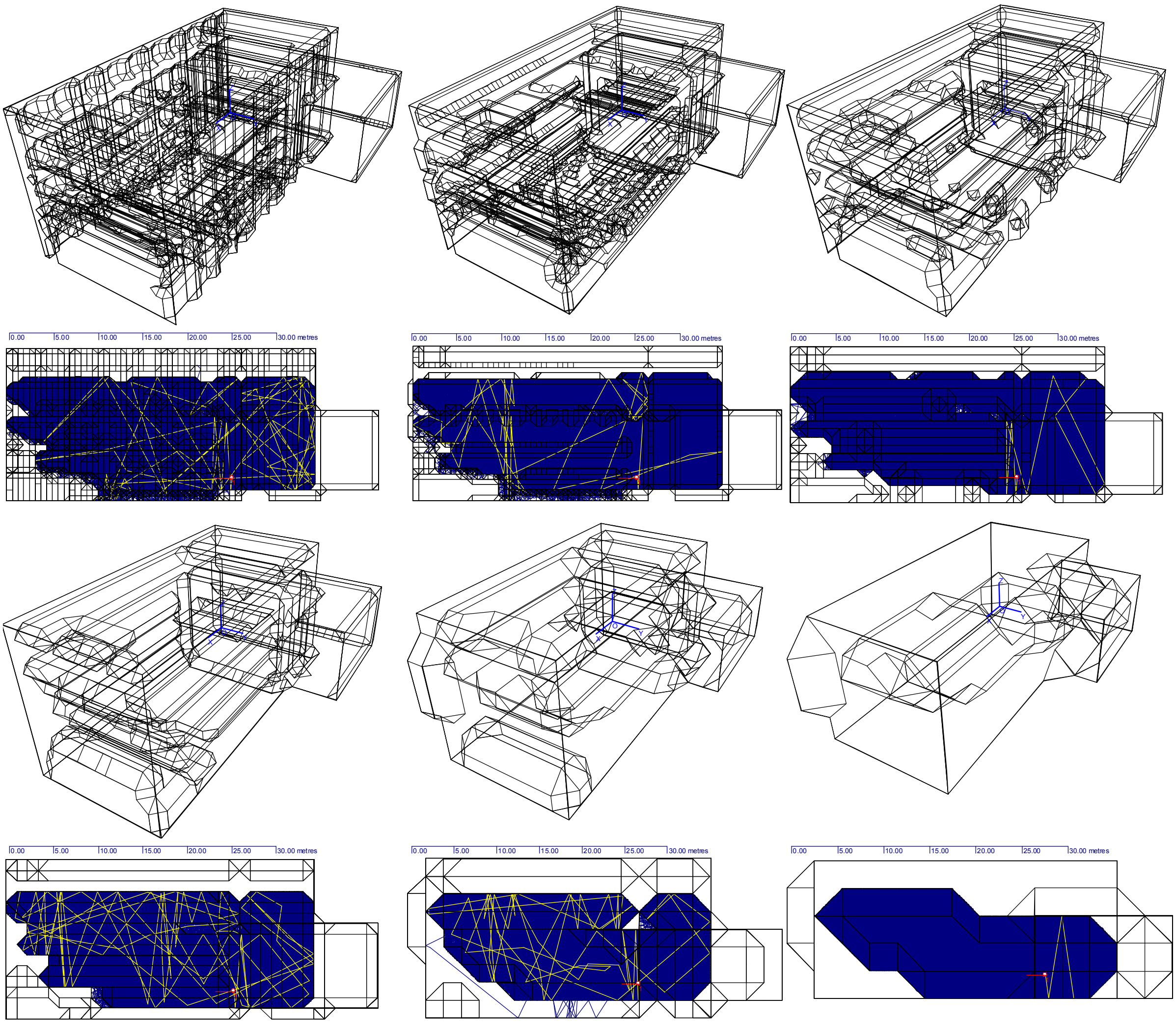

Figure 3: All six reduced models in Odeon 5.0 software, two top rows from left hall900, hall928, and hall964. Two bottom rows from left hall981, hall990, and hall996. The blue area indicates the volume of the hall, i.e., the volume where rays propagate and reflect from surfaces.

The set of acoustical parameters for comparison was chosen to include reverberation time (RT60), clarity (C80), and lateral energy fraction (LF). We assume that these parameters give good estimate to verify that the acoustical and spatial properties of the models are conserved during the reduction process. Additional parameters such as early decay time, center time, strength, or definition were not considered to give more information on the quality of the reduction method, although they usually are important parameters in room acoustics design.

The computation was performed in all six models with three source positions at the stage of the hall and three receiver positions in the audience area. The source and receiver positions were exactly the same in each model. Thus, with each model, nine responses in total were calculated and the presented results were averaged over nine values.

3.2.1 Simulation results

The reverberation times were computed with two different ways. First, the theoretical reverberation time was computed with the well know Sabine equation RT60 = $0.161V/A$, where V is the volume of the enclosure and A is the absorption area. Figure 4a shows the results at different octave bands as a function of reduction rate. The prediction results given by the Odeon software are represented in Fig. 4b. Simulated C80 values are plotted equally in Fig. 4c. Figures 4d-4f illustrate the average LF values in each receiver position. Since the reduction should not affect the acoustic properties of the model, all the values should be constant in relation to the reduction rate.

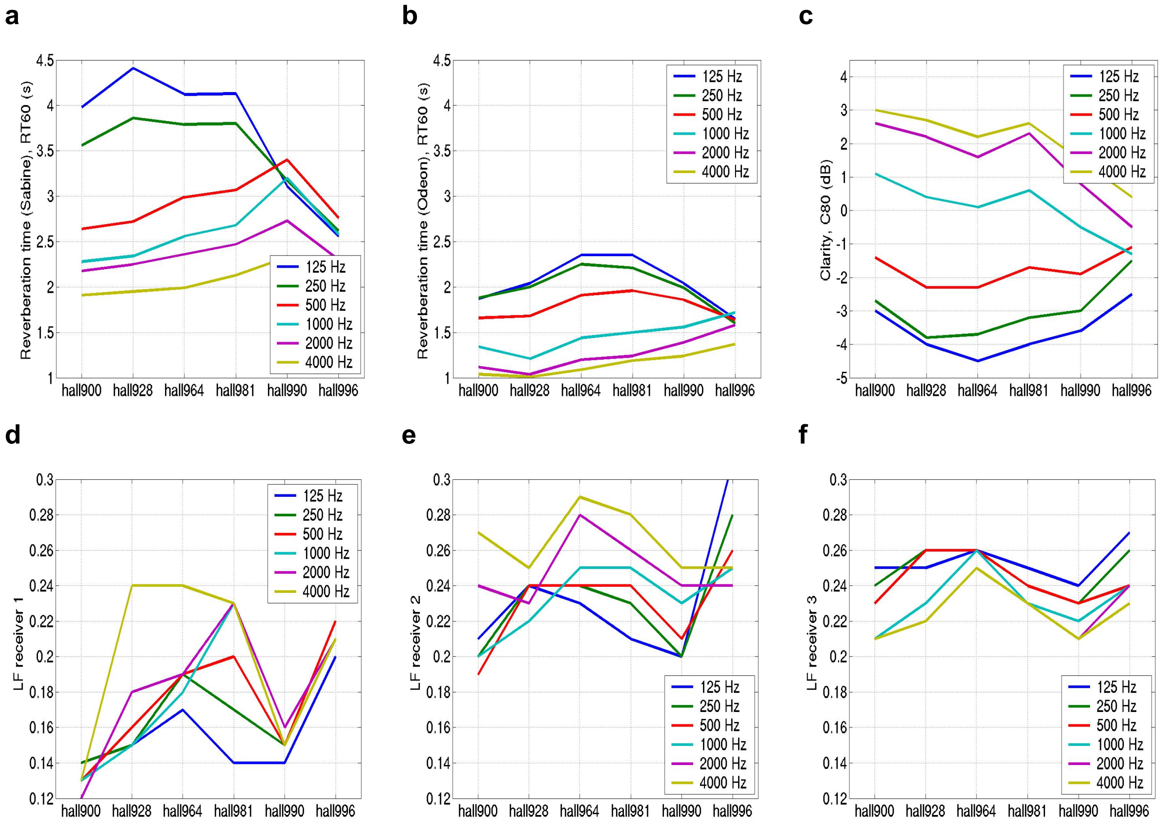

Figure 4: Results of the simulations performed with six different reduction rates.

4 DISCUSSION

There are many issues to discuss related to the proposed reduction algorithm. First, the properties of the algorithm are considered and then the validation results are discussed in more detail.

4.1 Properties of the reduction algorithm

The acoustical properties were prone to changes in the volume and absorption area of the room. Thus, such properties should have been preserved as accurately as possible. It is obvious that merging several small objects into a bigger one decreases the surface area. This can be compensated in materials by increasing the absorption coefficients appropriately. The volume of the objects tend to increase in merging which means that the volume of the sound transmitting medium decreases. Incidentally, these changes in volumes and absorption areas cancel each other in the reverberation time calculations at certain reduction rates.

During the topology simplification phase the orientation of the original surfaces is lost, because the intermediate data structure is volume−based, not surface−based. Only surfaces which are axis-aligned to the bounding box of the object retain their orientations well.

In the surface simplification phase of the method, there is a trade-off between quality and reduction rate. If the tolerance used in merging nearly coplanar regions is high, the model can be reduced more, but the directional properties of the reflecting surfaces suffer. On the other hand, strictly preserving the surface orientations prevents drastic simplifications and is not even sensible, because the topology simplification phase has already disturbed the orientations.

4.2 Validation results

Since the original model could not be applied in the simulation, it is quite hard to validate how accurate results the reduced models give. However, it is interesting to compare simulation results between the different reduction rates. In optimal situation all reduced models should give exactly the same results, since source and receiver positions as well as computation parameters were kept constant.

The theoretical reverberation times computed with the Sabine equations are not the same with all six models. As seen in Fig. 4a, the two coarsest reductions are too much reduced since the reverberation times differ significantly from the others. The same trend can be seen with the RT60 values predicted with Odeon software. The error is greatest at lower frequencies, because the absorption coefficients of the materials are small and thus the relative error caused by material blending during the reduction is high.

Based on predicted RT60 values it could also be stated that the most accurate models (hall900 and hall928) seem to contain too many tiny polygons for ray-based room acoustics prediction. The basic assumption for ray acoustics—surface area is big compared to the wave length of sound—is not true anymore.

Clarity values seem to be reasonable also with hall964 and hall981 models, but without a reference it is impossible to say anything about the prediction accuracy. However, the predicted values are in the range of typical C80 values for a concert hall.

Lateral energy fractions are presented in all three receiver positions separately. The LF values are most sensitive to the reduction, because the original orientations of the surfaces are lost in the topology simplification phase. Since the hall is traditional shoe-box hall and it is not very wide, the LF values should be over 0.20 in the audience area. In receiver positions R2 and R3, Figs. 4e and 4f, predicted values are at good range with all models, but in position R1 values are quite low. Once again, it has to be concluded that without a reference it is hard to say very much about the correctness of these results.

One possible error source for all reduced geometries can be explained as follows. The volume reduction preserves the volume of the hall, but portions of the total volume are isolated as the separated boxes around the main hall, as seen in Fig. 3. Since the reduction algorithm produces always watertight volumes the rays remain inside the main volume (the hall). This problem can not easily be overcome, since the original model was not watertight and contained additional spaces such as ceiling air ducts and backstage. The consequence of the separation of total volume in smaller volumes is that the volume of the main space becomes too small. Since the absorption area does not change significantly, the computed reverberation times seem to be too small compared to the Sabine values.

5 CONCLUSIONS

The proposed algorithm for geometry reduction is based on the volumetric reconstruction. It preserves the volume of the modeled space while reducing the acoustically irrelevant small details from the complex model. Therefore, the acoustical properties of the space should be conserved well.

The automatic geometry reduction is not yet reliable enough for concert hall design purposes. As a conclusion it must be said that the best acoustical model can still be obtained manually. When an experienced acoustician makes a model, the result is a simple and well parameterized model with which reliable predictions can be made. However, automatic geometry reduction could be applied in projects when designs of the architects need to be quickly evaluated. Already constructed computer models, e.g. for visualization purposes, could be applied also in acoustics prediction. Without geometry reduction, visualization models are too complex for current room acoustic prediction software.

Although the presented geometry reduction method is already applicable in some cases, it could be made to be more robust. One improvement would be to detect surfaces which are outside the main space, which contains the sound sources and receivers, and remove them from the model. The absorption coefficients of the materials could be adjusted to compensate the diminishing surface areas in some cases. Also surface orientations saved in the volumetric structure could be utilized in the surface reconstruction phase, which would not only help to preserve the orientations but also to position the reconstructed surface more accurately thus preventing significant errors in volumes.

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