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Geometry Reduction in Room Acoustics Modeling

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Summary
The complexity of a room model affects to the computational resources required to model its acoustics by means of geometrical acoustics modeling methods. Thus, a method for reducing the geometry of the room models is presented for static room geometries. The topology of the model is simplified in a process where the model is first decomposed into a volumetric structure. The surface is reconstructed by utilizing this structure, and subsequently simplified by merging coplanar regions. The results of the method are verified by extracting room acoustical attributes from the original and reduced models with the ODEON room acoustics prediction software. It is shown that the most important acoustic properties have been preserved, even with relatively high reduction rates.

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1. Introduction

Being able to predict the acoustic properties of concert halls, auditoriums, and other large buildings early in the design process, can save expenses and effort since late changes are often costly. Computers equipped with room acoustics prediction software can perform that task efficiently, provided that a three-dimensional (3-D) model of the space is given as input. Thus, it is important to obtain such models easily. However, the models created for visualization by architects are usually too complex and contain acoustically irrelevant details. In addition, they seldom are watertight as the preference often is for room acoustics prediction programs. Hence, either the prediction software cannot handle the amount of data or the computation would take too long to be repeated frequently during the early stages of the design process. Consequently, the models for acoustics modeling are often constructed manually by an acoustic consultant. Although the acoustic quality of the model is thus guaranteed, the construction is time consuming and strenuous work. It would be more convenient if the acousticians could apply the same 3-D models as the other designers.

In this paper we offer one possible solution to this problem by presenting an automatic geometry reduction method that can convert a complex 3-D room model to a simple model while retaining the acoustically important information. The goal of this method is to produce high quality reduced models from large models, consisting of dozens of thousands of polygons.

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1.1. Room acoustics modeling

Different approaches to model room acoustics have been developed [1, 2]. Some of these methods benefit from the reduction more than the others. One approach is deriving the solution from the wave equation which is the physical basis for modeling sound propagation. Finite element method (FEM) and boundary element method (BEM) try to solve it numerically. They are computationally demanding methods and are at their best when modeling low frequency behavior of sound. They might not benefit much from the reduction since the model is already implicitly reduced in the discretization of space used in those methods.

On the other hand, geometrical room acoustics modeling methods use an approximation where the sound is represented as rays. This approach is accurate enough when the modeled wavelengths are significantly smaller than the surface details [3]. The number of elements in the model affects greatly to the performance of the geometrical methods which makes the reduction very useful.

A statistical approach is to shoot a large number of rays from the sound source and trace them as they reflect on surfaces [4]. A small portion of the rays hit the listener which is usually represented by an object with a finite volume. These rays can be utilized in calculating the energy response. However, there are systematic errors in this approach which must be compensated to get more accurate results [5].

In the image source method [6, 7] the first order image sources representing first order specular reflections are created by mirroring the sound source against each planar surface in the model. Similarly, higher order image sources are calculated by recursively mirroring the previous image sources against each surface. The reflection paths are constructed from the listener to the source with help of the image sources. Thus, all specular reflections up to the desired order are found accurately. Unfortunately, the number of image sources grows exponentially in relation to the reflection order [3] making it difficult to model high order reflections in even moderately complex models.

Beam tracing methods calculate the image sources more efficiently by using advanced spatial data structures and beam-based visibility checking which prunes invisible image sources early in the process [8, 9, 10].

Regardless of the geometric acoustics modeling method, the geometry of the complex room models should be reduced to be able to model their acoustics efficiently. The ray collisions can be calculated more efficiently in the statistical ray tracing method, there are less image sources, or the beams are not split in narrow slices too often.

Reducing the geometry of 3-D models has been a fruitful research topic in computer graphics since the early 90's. There are dozens of different algorithms with slightly differing goals [11, 12]. But until recently, there has not been any algorithms which would take into account the needs of geometrical room acoustics modeling. The contribution of this paper is to present and evaluate a geometry reduction method, which has the goal of providing simple acoustic models retaining the essential acoustical properties of the room as accurately as possible.

1.2. Previous work

The research in the area of model simplification has been extensive, although most of the work is less relevant from our point of view. One approach which is worth considering is volumetric geometry simplification. Andújar and Brunet proposed a framework for simplifying polyhedral models using the volumetric approach, and presented two simplification algorithms based on it. They also mentioned the applicability of their approach to acoustics modeling [13]. Later they have still improved the algorithms [14], but it was not clear how to adjust them for preservation of acoustic properties, and thus they are not applied here directly. However, the suggested framework is general enough to be applied in the algorithm described in this paper.

An earlier contribution to volumetric geometry simplification research was the algorithm by He et al. in which the model was sampled into a density grid. An isosurface extraction algorithm was used in reconstructing the surface from the grid [15]. This approach is flexible since the surface reconstruction algorithm can be modified easily. In addition, He et al. later made the volume structure hierarchical [16] which is also used in our algorithm in the decomposition phase, although not directly in the reconstruction phase. A similar volume grid structure was also used by Nooruddin and Turk in their algorithm which can be applied both for repairing and simplifying polygonal models [17]. Their approach is very similar to ours, although the reconstruction phase is different. The reviewed volume-based techniques work best at small models which are viewed from outside. This is exactly the opposite case to the typical models of acoustic spaces, which are both large and viewed from inside. This paper intends to provide a volume-based algorithm which does work with such models. The algorithm has been presented earlier [18], but a proper evaluation is presented in this paper.

2. Geometry reduction method

In geometry reduction the number of geometric elements in the model should be reduced while preserving its most important features. There are several application areas where geometry reduction is used, and thus it is necessary to choose the properties which are considered significant in each case. In this case the acoustic point of view is chosen.

Room acoustics is often evaluated by using several acoustical parameters. Most of these parameters change when the volume or absorption area of the space changes. In addition to the shape of the room, these are properties to be preserved through the reduction process. Retaining the volume also helps to keep the change in the room dimensions small. Retaining the absorption area implies preserving the surface area and the absorption of the materials or compensating the change in one of those by the other. When two parts of the model with different materials are merged, it might even become necessary to blend materials.

The presented method consists of two phases: topology simplification and surface simplification. The reduction process is illustrated in Figure 1.

2.1. Topology simplification

The purpose of the topology simplification phase is to remove geometrical details and complex topological structures from the model. Thus, the model is decomposed into volumetric structure. The surface of the model is then reconstructed by using the volume data only. This process removes parts of the model which would prevent radical simplification and makes the distribution of the geometric elements in the model more even.

The volumetric structure which is used in the algorithm is octree [19]. The input model, consisting of a mesh of polygons, is inserted into the octree, see Figure 1c. The error in this phase can be bounded by choosing an appropriate limit for the smallest cell size in the octree. The maximum error is the diagonal length of such a cell. On the other hand, fixing the smallest cell size also limits the depth of the tree.

The next step is to create an intermediate model by utilizing the volumetric data structure, see Figure 1d. The

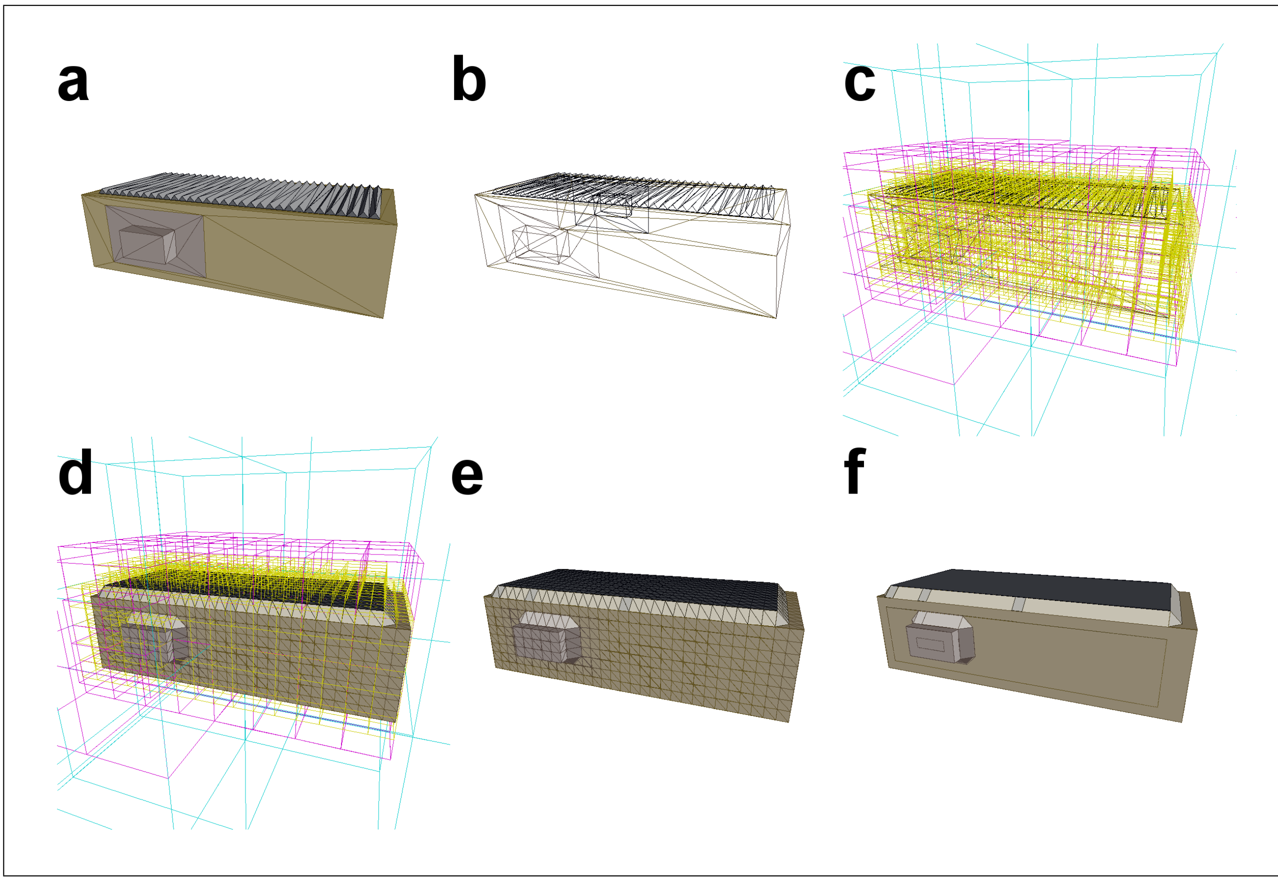

Figure 1. The volumetric geometry reduction process, a) the detailed original model, b) the original model as wire-frame drawing showing the polygon borders, c) the octree structure into which the detailed model is inserted, d) the octree structure is utilized to construct an isosurface, e) an intermediate model consisting of the isosurface has a large number of small polygons, f) the final reduced model after the coplanar polygon merging.

marching cubes algorithm [20] is an algorithm for constructing an isosurface for a threshold value in a regular grid of density values. The corners of a cell in a volumetric grid can be occupied (its density is greater than some threshold value) in $2^8 = 256$ ways. The fact that all cases can be achieved by complementing or rotating one of the 15 basic cases (illustrated in Figure 2) is utilized in the marching cubes algorithm. The triangulations for these cases can be placed in a lookup table. These triangulations are shown in the figure. The dots present occupied corners, while the other corners are unoccupied. In the algorithm, every cell is visited and classified. Then the appropriate triangulation is chosen and the vertex positions along edges are interpolated according to corner density values. Rotation and inversion of triangle orientations are performed if necessary. The output of the algorithm is a consistently oriented 2-manifold surface.

The basic marching cubes algorithm can be modified to our purposes. Instead of using the density values to classify the cell corners and determine the location of the surface in the edges of the cells, other techniques can be used. Nooruddin and Turk proposed shooting rays to several directions from each cell corner and counting the intersections [17]. In closed two-manifold models an odd number of intersections indicates that a corner is inside a model. However, there are irregularities and defects in typical complex room models. Thus, in addition to the heavy computational requirement of that approach, the quality of the results would be poor. A more reliable approach was chosen where a corner is considered to be inside if the adjacent octree cell in the direction of the positive coordinate axis is occupied by a polygon. This results in minor inaccuracies, but they can be compensated by translating the surface accordingly along the edges of the cell.

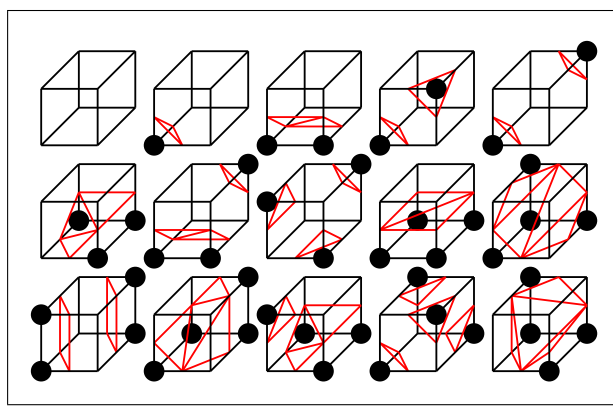

Figure 2. All 15 basic cases applied in the marching cubes algorithm.

There are several strategies to determine the surface position along the edges of the octree cells without the density data. One possibility is to trace rays in the direction of the edge and find the first and last intersections inside that cell. An average of these is a decent choice, especially since usually there is only one intersection which results in an accurate position. This approach would approximately preserve the surface orientations. Another alternative is to clamp the surface positions to octree cell boundaries. This results in rectangular geometry which might be desirable in some cases since the input models usually contain such geometry, although the surface orientations would be changed when the geometry contains non-rectangular surfaces.

The surface reconstructed by the variant of marching cubes forms the intermediate model. This is illustrated in Figure 1e. The algorithm produces at most four triangles per octree cell and the surface is guranteed to be 2-manifold. The absorption area might change, especially if the original model had plenty of details smaller than the octree cell size. In a typical model the changes are small, however. After topology simplification there is a large number of small, almost equally sized polygons. Thus the number of geometric elements must still be reduced in the surface simplification phase.

2.2. Surface simplification

There is a large number of algorithms for geometry simplification [11, 12]. In this case the aim is to merge small polygons, especially in flat regions of the model. Therefore, the geometric optimization algorithm by Hinker and Hansen [21] was applied. The algorithm collects the polygons into coplanar sets by using representative trees [22]. In the coplanar sets the edges shared by any two polygons are removed leaving only edge segments that border large areas. These segments are sorted so that they form borders of large polygons, see Figure 1f.

Since the simplification is performed inside coplanar sets, the changes in geometry are insignificant. However, there might have been polygons with different material properties in the sets. Thus, the borders between the polygons with differing materials can be preserved. Or, alternatively, the materials can be blended by weighting them properly by the surface areas. In this case, it is assumed that the material properties behave linearly. Then, if the material properties are presented by absorption coefficients for, i.e., octave bands, the total absorption area does not change in the linear interpolation of those coefficients with areas as interpolation weights.

2.3. Parametrization

There are two parameters which affect the quality of the reduced model: the octree cell size and the angular tolerance in co-planar set merging. The former value should be chosen according to the accuracy required in the modeling. When modeling higher frequencies, smaller values should be used. The latter parameter value was fixed to a very small value in our experiments. This is usually advisable since increasing the tolerance would not improve the reduction rate significantly in typical models which have been through the surface reconstruction phase.

Table I. Properties of the models applied in the performance validation. Reduction percents are given in relation to the original model and to the model reduced by GLUE-algorithm in ODEON (in parenthesis).

Name of the model	Number of surfaces	Reduction percent	Octree depth	Cell size (m)
Usher_unglue	9251	0.0	-	-
Usher_glue	2386	74.3 (0.0)	-	-
Usher605	3597	60.5 (-50.8)	7	0.54
Usher636	3316	63.6 (-39.0)	7	0.61
Usher735	2416	73.5 (-1.3)	7	0.68
Usher772	2073	77.2 (13.1)	7	0.78
Usher842	1439	84.2 (39.7)	7	0.91
Usher861	1266	86.1 (46.9)	6	1.09
Usher913	793	91.3 (66.8)	6	1.36
Usher953	432	95.3 (81.9)	6	1.82

3. Evaluation of the reduction method

In this section the performance of the presented reduction method is evaluated. The performance can be validated by making room acoustical simulations in different versions of an example geometry and compare predicted room acoustical attributes. The easiest way to do such a comparison is to perform calculations both with a detailed original model and with reduced models with a room acoustic prediction software used by acoustic consultants, namely the ODEON 9.0beta software.

A model of the Usher hall in Edinburgh, Scotland was chosen for evaluation purposes. The original DXF model was created in AutoCAD and has a level of detail which is typical for geometries which has been created for visualization purposes. Details such as rows of seats and stairs are included in the model. In total ten different models were studied; the original model, the model “glued” by ODEON software, and eight models reduced with the proposed algorithm. The models are depicted in Figure 3.

3.1. Technical data and computation parameters

The reduction rates and numbers of surfaces of the applied models are collected to Table I. In addition, the table contains octree depths and cell sizes. Computation parameters in ODEON were the same in all simulations. The number of rays applied was 250 000 and the transition order was 2. Thus, reflection orders 1 and 2 were carried out using the image source method combined with a special ray tracing method which accounts for the scattered energy. Higher order reflections were modeled using a special ray based radiosity method. All surfaces in all models had a scattering coefficient of 0.3. ODEON expands this mid-frequency

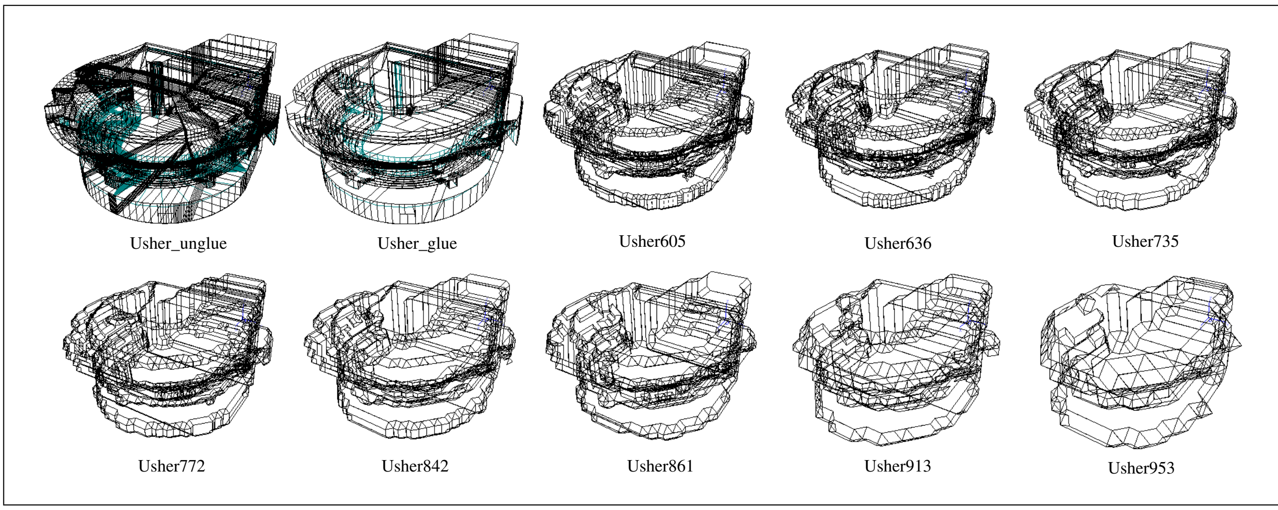

Figure 3. All ten models in ODEON 9.0beta software.

value into frequency dependent scattering taking into account typical frequency functions for materials with different surface roughness as well as the frequency dependent diffraction caused by limited surface size (distance dependent diffraction), using the methods described earlier [23]. It should be noted that lower scattering coefficients could have been assigned in the detailed models and higher in the simple geometries in order to account for structures which have not been included in the models. However, this has not been done in order to limit the number of variables in the experiments.

The absorption coefficients for each octave band were assigned by using proper material descriptions. Since the scattering coefficients were constant, changes in the absorption coefficients could be observed more easily as they were the only material-dependent values that could change during the reduction.

3.1.1. The ODEON Glue surfaces algorithm

The ODEON program itself offers a geometry reduction option and it was also applied to process one model (Usher_glue) for evaluation. The main principles of this algorithm are described here. Surfaces in CAD drawings are usually chopped into three or four-point surfaces, either as single surfaces or clustered as sub elements in meshes. Often large surfaces are subdivided into many quite small triangles, see Figure 4. There may be good reasons for this, but for use in ODEON it is not desirable - it increases calculation time, decreases visual quality and most importantly - the small surfaces do not have areas which are acoustically relevant to the diffraction algorithms in ODEON [23].

The Glue surfaces algorithm is developed for use in the ODEON software, therefore the geometries it outputs may not be suitable nor compatible with other room acoustics calculation programs. First of all, the surfaces in geometries used by ODEON can have edges containing many points and the surfaces may have concave shapes such as H, L, or U shapes. This is allowed because the *point within area* algorithm used for collision detection is similar to the one proposed by Lehnert [5]. Surfaces should in principle be planes, however it is allowed that surfaces can have a small warp of one or two centimeters, the plane equation created for each surface by ODEON is fitted taking into account all the edges on the border of the surface. Therefore small mismatches in some of the border points do not lead to poorly defined planes.

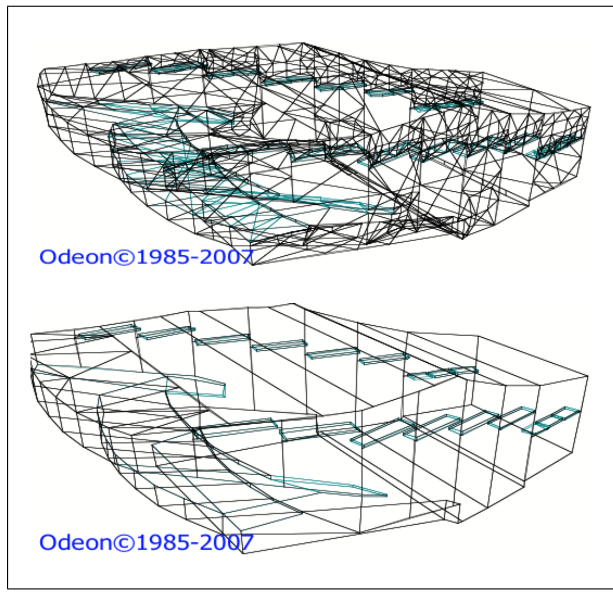

Figure 4. An example of ODEON importing a geometry. On top the geometry before ODEON applies it Glue surfaces algorithm, on bottom the useful geometry which has been enhanced for calculations as well as for visualization. The processing has reduced the number of surfaces from 1362 to 209.

The Glue surfaces algorithm makes use of the following rules [24]. First step is to import the raw data, surface points which are closer than a predefined tolerance, e.g., one centimeter, are merged together. This way small insignificant edges are removed. Second step is to chop all surfaces into triangles. Then if surfaces are on a same drawing layer and share two or three points, it is examined if they can be stitched together without creating a surface with a warp greater than allowed. Also surfaces with differing materials are not stiched together. The process is repeated recursively until all combinations have been tested and the number of surfaces has been reduced as much as possible. If the geometry to be imported was modeled using solid modeling techniques in AutoCAD, then the resulting number of polygons is typically reduced to one fifth. More importantly the surfaces have areas which are acoustically significant and the surface planes continue to have the orientations they initially had. For example, the sloped audience area and angled ceiling of the hall in Figure 4.

3.2. Results

The predictions were performed in all ten models with three source positions at the stage of the hall and seven receiver positions in the audience area. The source and the receiver positions were exactly the same in each model. Thus, with each model, in total 21 impulse responses were predicted and the acoustical parameters were provided by the ODEON program. The presented results are averages with standard deviations of all source-receiver combinations. With these values it can be estimated how well the acoustic properties of the models are preserved during the reduction process. The results are presented at four selected octave bands as a function of reduction rate. Note that in the most radically reduced cases some average values are real bad since one (or two) receiver positions were outside of the model or on the same plane as the polygon resulting problems to the prediction software. These cases are evaluated with the help of selected positions.

It should be noted that the GLUE algorithm produces 74.3 % reduction already, and that is achieved mainly by merging coplanar surfaces. Thus, the reduction percents are given both in relation to the original model, and the model reduced by GLUE (in parenthesis). The latter percentage corresponds roughly to the effects of the topology simplification.

The first results are predictions of Early Decay Times (EDT) and Reverberation Times (T60), see Figure 5. Reduction rates up to 86.1% (46.9%) give reasonable results at least in the mid frequency bands. At low frequency bands Usher605–Usher735 (-50.8% – -1.3%) give values which are pretty close to the values of the original model (Usher_unglue), but more radical reduction seems to diminish the accuracy.

The Clarity (C80) and Definition (D50) give similar results, see Figure 6. It seems that geometry reduction slightly lowers the values, but at mid frequency bands the values hardly vary up to Usher842 model (39.7%).

The Strength values (SPL) are presented in Figure 7. Again the averages as well as changes in standard deviations remain in the limits of subjective difference limen (1dB) [25] up to Usher842 (39.7%) model at mid and high frequency bands. At low frequency bands the reduction raises the SPL levels slightly.

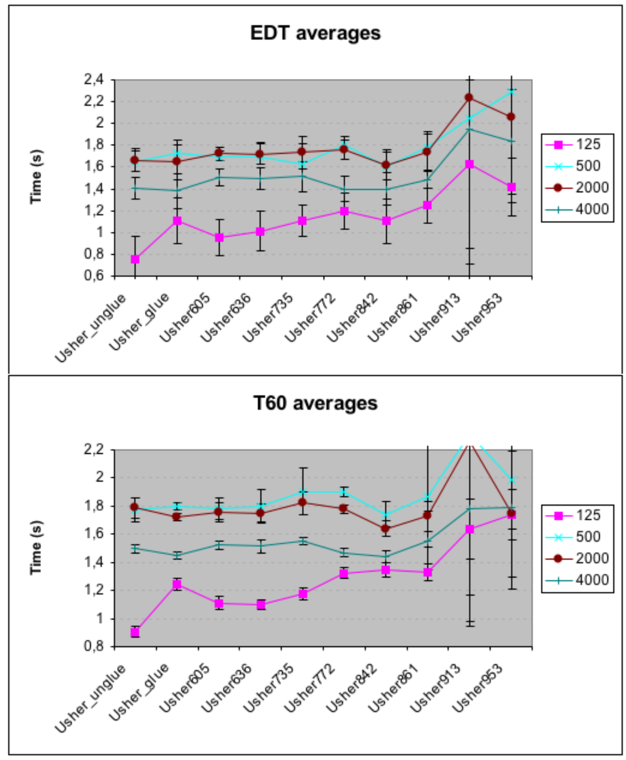

Figure 5. EDT and T60 values at four octave bands as a function of reduction rate. Averages and standard deviations of 21 predicted source-receiver pairs are plotted.

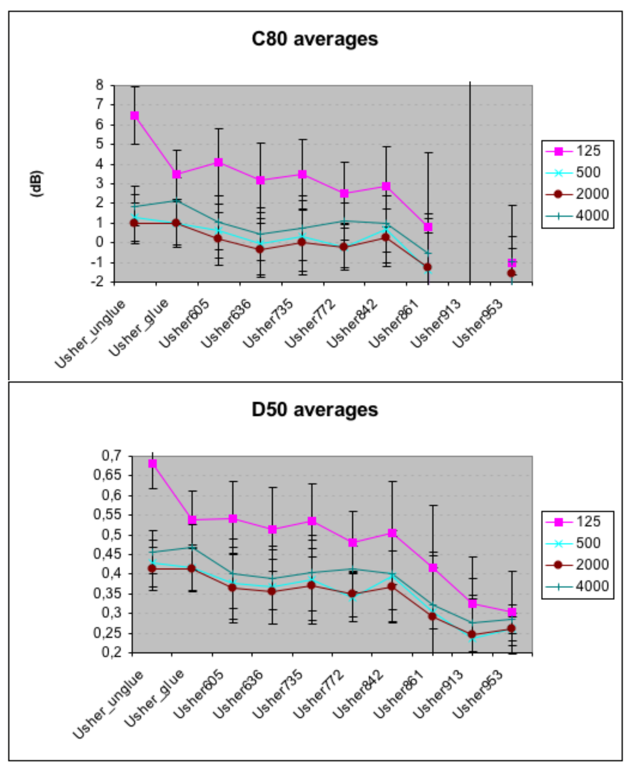

Figure 6. C80 and D50 values at different octave bands as a function of reduction rate.

The Center Time (TS) prediction are plotted in Figure 8. They behave similarly as other parameters, although

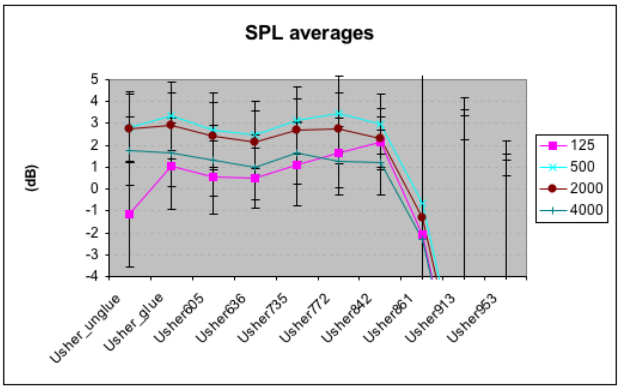

Figure 7. Strength (SPL) values at different octave bands as a function of reduction rate.

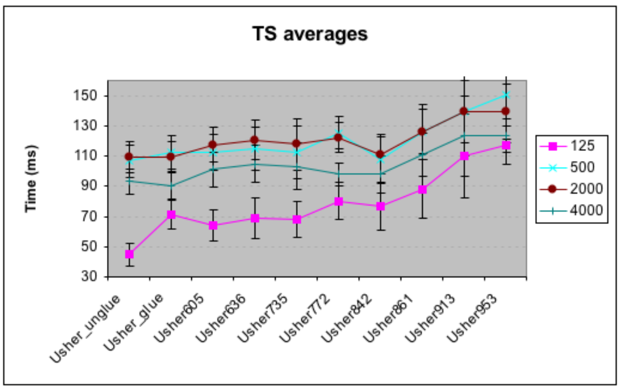

Figure 8. TS values at different octave bands as a function of reduction rate.

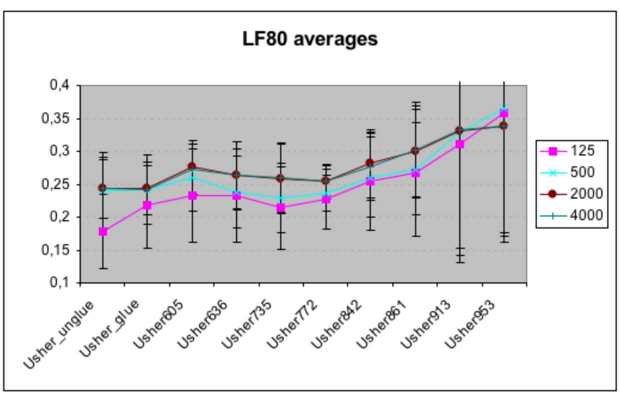

Figure 9. LF80 values at different octave bands as a function of reduction rate.

Usher772 (13.1%) deviates from other reduced models. Usher772 (13.1%) seems to give a little higher EDT and T60 values also, see Figure 5.

Finally, the Lateral Energy Fraction (LF80) tells how much energy is reaching the listener position from the side. Thus, this parameter can be used to verify how well spatial properties of the models are preserved during the reduction process. In addition, the LF80 values are most sensitive to the reduction, because the original orientations of the surfaces might be lost in the topology simplification phase. The results are seen in Figure 9 and it seems that there is

Table II. 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 119434 polygons and it is depicted in Figure 10.

Reduction (%)	Topology simpl. (s)	Surface simpl. (s)	Total (s)
70.7	25	82	107
79.0	23	58	81
79.6	21	37	58
83.3	20	24	44
87.2	15	14	29
91.5	6	5	11
94.2	5	3	8
97.0	4	1	5
99.2	2	1	3

some variation between the different reduction rates. However, the trend is similar as with other parameters and up to Usher772 (13.1%) the values are within the limit of subjective difference limen (5%) [25].

3.3. Another evaluation with more complex model

The geometry reduction process was done also for a detailed model of a complete building. The model has been originally created for visualization purposes and it contains 119434 polygons. The original model and the reduced versions of it are illustrated in Figure 10. It can be seen that the visual appearance of the model is preserved quite well during the reduction, but naturally the radical reduction rates violate the original model significantly.

The computation times of a non-optimized version of the reduction can be seen in Table II. 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.

3.4. Limitations

The acoustical properties are 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. In addition, the scattering coefficient should be modified to compensate the simplified geometry which would cause additional scattering. However, this is still a topic of future research. On the other hand, the volume of the objects tend to increase in merging which means that the volume of the sound transmitting medium decreases.

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. However, most rooms

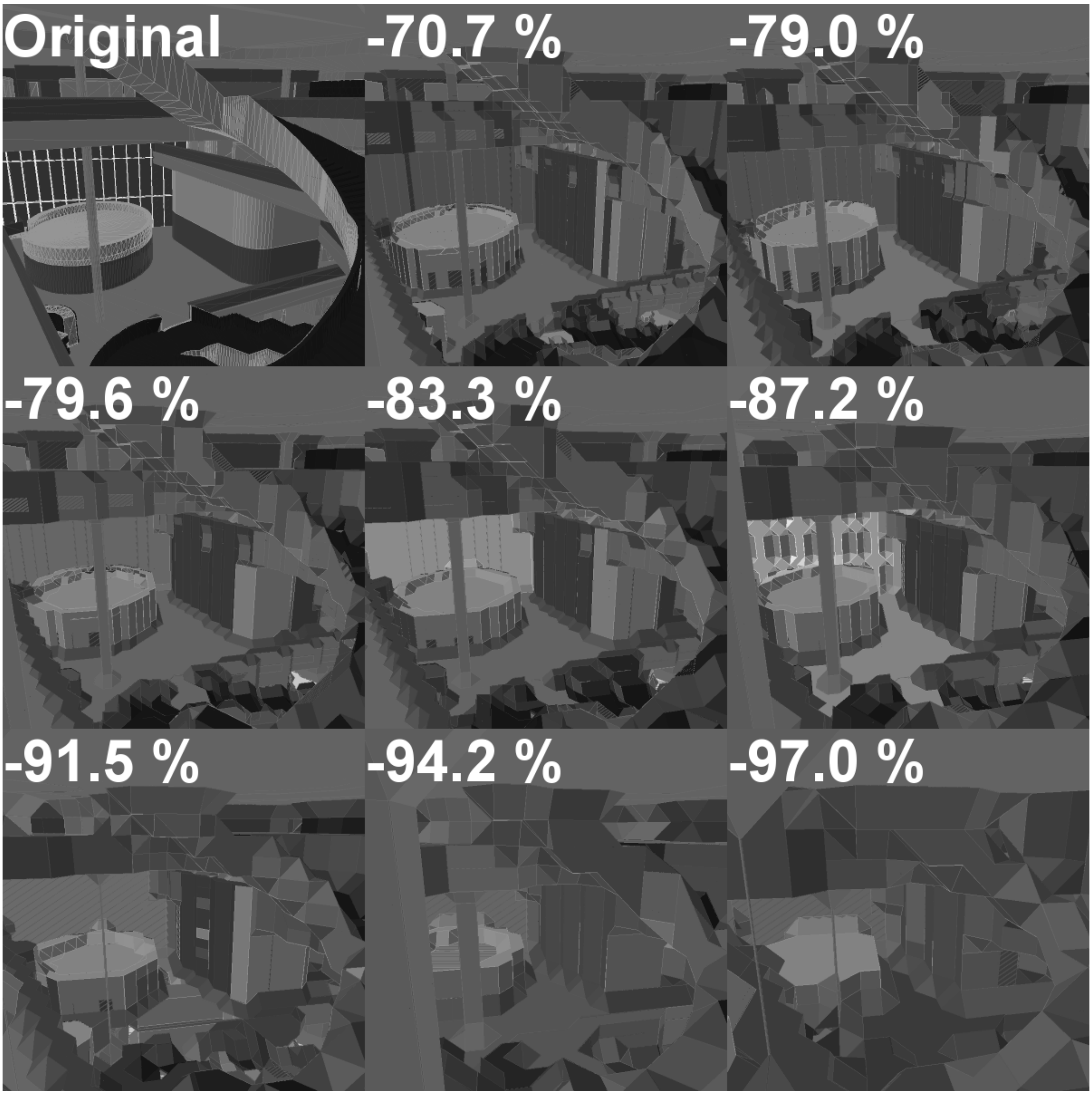

Figure 10. A few reduced models. The original model contains 119434 polygons.

have regular walls which are not affected by this limitation. Only large walls in non-straight angle might be split into several smaller axis-aligned parts.

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.

Finally, the volumetric reduction preserves the volume of the hall, but portions of the total volume might get isolated as separated boxes around the main hall with the very large reduction rates and cell size. Thus, the volume of the main hall might decrease since the inner and outer surfaces of the model might be separated by a volume of the wall. In addition, parts of the volume originally connected to the main volume by narrow passages might be cut off.

4. 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. The simulation results with one concert hall model showed that the number of polygons can be reduced 75-80% without violating the acoustical properties of the geometry.

The automatic geometry reduction is not yet reliable enough for demanding concert hall design cases. 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 might be 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. The absorption and scattering coefficients of the materials could be adjusted to compensate the diminishing surface areas in some cases. In addition, 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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References

[1] L. Savioja, J. Huopaniemi, T. Lokki, R. Väänänen: Creating interactive virtual acoustics environments. Journal of the Audio Engineering Society **47** (1999) 675–705.

[2] U. Svensson, U. Kristiansen: Computational modeling and simulation of acoustic spaces. Proc. AES 22nd Int. Conf. on Virtual, Synthetic and Entertainment Audio, Espoo, Finland, 2002, 11–30.

[3] H. Kuttruff: Room acoustics. 4th ed. Spon Press, 11 New Fetter Lane, London, England, 2000.

[4] A. Krokstad, S. Strom, S. Sorsdal: Calculating the acoustical room response by the use of a ray tracing technique. Journal of Sound and Vibration **8** (1968) 118–125.

[5] A. Lehnert: Systematic errors of the ray-tracing algorithm. Applied Acoustics **38** (1993) 207–221.

[6] J. B. Allen, D. A. Berkley: Image method for efficiently simulating small-room acoustics. The Journal of the Acoustical Society of America **65** (1979) 943–950.

[7] J. Borish: Extension to the image model to arbitrary polyhedra. The Journal of the Acoustical Society of America **75** (1984) 1827–1836.

[8] P. S. Heckbert, P. Hanrahan: Beam tracing polygonal objects. Computer Graphics **18** (1984) 119–127.

[9] T. Funkhouser, P. Min, I. Carlbom: Real-time acoustic modeling for distributed virtual environments. Proceedings of the 26th annual conference on Computer grahics and interactive techniques (SIGGRAPH'99), 1999, 365–374.

[10] S. Laine, S. Siltanen, T. Lokki, L. Savioja: Accelerated beam tracing algorithm. Applied Acoustics (2008). In Press.

[11] M. Garland: Multiresolution modeling: Survey & future opportunities. State of the art report, Eurographics '99, 1999, 111–131. Available as http://graphics.cs.uiuc.edu/∼garland/ papers/STAR99.pdf.

[12] D. Luebke: Developer's survey of polygonal simplification algorithms. IEEE Computer Graphics & Applications **21** (May 2001) 24–35.

[13] C. Andújar, P. Brunet: The discretized polyhedra simplification (dps): A framework for polyhedra simplification based on decomposition schemes. Tech. Rept. LSI-99-3-R, Universitat Politécnica de Catalunya, 1999. Also available as http://www.lsi.upc.es/dept/techreps/ps/R99-3.ps.gz.

[14] C. Andújar, P. Brunet, D. Ayala: Tolopogy-reducing surface simplification using a discrete solid representation. ACM Transactions on Graphics (TOG) **21** (2002) 88–105.

[15] T. He, L. Hong, A. Varshney, S. W. Wang: Voxel based object simplification. Proc. of Visualization '95, 1995, 296–303.

[16] T. He, L. Hong, A. Varshney, S. W. Wang: Controlled topology simplification. IEEE Trans. Vis. Comput. Graph. **2** (1996) 171–184.

[17] F. S. Nooruddin, G. Turk: Simplification and repair of polygonal models using volumetric techniques. Tech. Rept. GIT-GVU-99-37, GVU Center, Georgia Institute of Technology, 1999.

[18] S. Siltanen, T. Lokki, L. Savioja: Geometry reduction in room acoustics modeling. The Sixth International Conference On Auditorium Acoustics, Copenhagen, Denmark, May 5-7 2006, Institute of Acoustics, 409–416.

[19] A. S. Glassner: Space subdivision for fast ray tracing. IEEE Computer Graphics & Applications **4** (Oct 1984) 15–22.

[20] W. E. Lorensen, H. E. Cline: Marching cubes: A high resolution 3D surface construction algorithm. ACM SIGGRAPH Computer Graphics **21** (1987) 163–169.

[21] P. Hinker, C. Hansen: Geometric optimization. Proceedings of Visualization '93, 1993, G. M. Nielson, D. Bergeron (eds.), 189–195.

[22] D. Salesin, F. Tampieri: Grouping nearly coplanar polygons into coplanar sets. – In: Graphics Gems III. D. Kirk (ed.). Academic Press, 1992.

[23] C. L. Christensen, J. H. Rindel: A new scattering method that combines roughness and diffraction effects. Forum Acusticum 2005, Budabest, Hungary, August 29 - September 2 2005. Paper 524-0.

[24] C. L. Christensen: Odeon import of cad files in the dxf format - problems and solutions. Technical note, http://odeon.dk/pdf/ODEON_Import_of_CAD_files_in_the_DXF_format.pdf, 2007.

[25] I. Bork: Report on the 3rd round robin on room acoustical computer simulation - Part II: Calculations. Acta Acustica united with Acustica **91** (July/August 2005) 753–763.