Case study: the influence of model size on local room acoustic parameters in Odeon

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Abstract
Contemporary architects can design buildings with complex geometry and construction more easily thanks to modern CAD tools such as BIM and other parametric design tools. Also, some material innovations, such as the introduction of ETFE cushions into architecture, make complex and designs with complex geometry more accessible to designers. In large spaces where day light intrusion is important ETFE cushions are a good alternative for glass. The construction of the cushions makes it possible to design curved organic shapes in a cost-effective way. However, simulating the acoustic environment in such spaces is challenging. Even though a CAD model is likely to be available, preparing a CAD model for geometrical acoustics software is a labour-intensive manual task, time-savings can be made especially if only part of the model is of interest. In this paper we investigate a case study of a mall in Liège, Belgium. By comparing three model sizes, the possibility of only partly modelling this large space as a time-saving measure is investigated.
The full model, a moderately truncated version and severely truncated version were compared in terms of their impact on the local acoustics in the area of interest. T30, STI, the spatial decay curve and G(average) were all compared using the same receiver positions.
A parametric study shows that for modelling a specific part of such a large and long space, reducing the model size to the “medium” size has a negligible impact on any of the parameters. The strongly truncated model is found to be adequate for all parameters in the area near the source.

Key Innovations
• Impact of model truncation on room acoustic parameters

Practical Implications
The acquired knowledge that truncating a substantial part of a large hall does not affect the acoustic parameters of the remaining area of interest allows acousticians and architects to ignore the truncated part and save a lot of design time when optimizing the acoustics.

Introduction
Simulating the room acoustic properties of large spaces with complex geometries is challenging. The many irregularities that can be found in contemporary buildings might require more modelling time and increase the computational load for geometrical acoustics simulation purposes (Lisa et al., 2004). If only a part of the room/hall is of interest, modelling only that relevant part of the room or hall can save time and energy.
The geometrical acoustic simulation software Odeon was used to simulate the acoustic field of an existing shopping mall in Liège, Belgium. The mall’s main hall is 400m long. The roof construction of the hall is irregular and features ETFE cushions supported by a steel structure. The geometry of this steel structure is unique, no part resembles another, this makes modelling it more time consuming.

ETFE
ETFE is a fluoropolymer that, for architectural purposes, is extruded into thin films approximately 100-300µm thick. ETFE membranes can be assembled as air cushions that are held under constant (relatively low) pressure by a compressor. Two or more membranes are usually clamped together by aluminium profiles that hold the cushions in place at the edge. The membranes are cut and welded together to form into the desired shape after inflation. ETFE cushions usually have a convex curved shape. ETFE cushions are the core of a type of construction that is most commonly found in medium to large spaces where sound insulation is not a priority (Maywald, 2017). Implementing this material into an architectural design can be a way to reduce unwanted late reverberation in large spaces (Rychtarikova et al., 2020) (Urban et al., 2017) (Rizzo and Zazzini, 2016).
The cushions in Mediacité, Liège reach lengths of up to 60m and widths up to 5m. single ETFE cushions are very large in comparison with single glass panes. Large glass panes are usually not applied horizontally in architectural applications, whereas ETFE cushions can more easily be integrated because of their low surface weight (Lamnatou et al, 2018).
These properties make the membranes a good candidate for retrofitting in renovation projects or projects involving architectural heritage (Polomova et al 2013 and 2019).
Modelling

For research purposes related to the acoustic absorption characteristics of ETFE cushions, an area of interest in the middle of the length of the hall was chosen. A top view of the entire hall, without shops, is shown in Figure 1. A precise CAD model of the steel structure, along with the boundaries (floors and walls) of the entire space, was available. This model was virtually cleaned and adapted to be used in Odeon. Any irregularities smaller than 30 cm were simplified. As shown in Figure 2, the model contains some curved surfaces, these were simplified so that a geometrical approximation of the curves was obtained (Savioja and Svensson, 2015).

As the curvature is quite subtle; the typical height of the curve is maximum 1/16th the length of shortest side of the cushion (based on observations in the mall), the curves of the ETFE cushions themselves were simplified as flat surfaces. It is currently not known whether this is a correct approach, as the scattering characteristics of ETFE cushions have not been studied yet. Scattering by ETFE cushions is likely to be low, as they are transparent to sound in the low and mid frequencies (Urbán et al., 2016).

To reduce modelling time further the steel structure was only modelled for the entirety of the “small” model (indicated in Figure 1). The steel structure was not modelled outside this area. The surface area of the steel structure was not deemed high enough at further distances from the area of interest, where the only source is located, to justify the time investment.

Materials

All surfaces were assigned a material that has a specific absorption coefficient per octave from 63Hz to 8000Hz. All materials in the models (except ETFE) are standard materials found in the material library. Those characteristics roughly correspond to the real characteristics of the building this model is based on. These absorption coefficients were slightly tuned to make the resulting reverberation times match the measured reverberation times in situ.

Two versions or material configurations were created, one in which all the surfaces representing the ETFE cushions in the real building were assigned absorption properties roughly resembling that of ETFE cushions, the other in which those same surfaces were assigned the same absorption properties as double pane glass. The addition of glass is to check whether another commonly used transparent building material in malls changes the outcome. In the low and middle frequency range, glass is more reflective than ETFE (Rychtarikova et al. 2017). A comparison of a view inside of the model in the area of interest and the real building is represented in Figure 2. The resulting mix of materials in the model, considering the respective surface area of each material, can be summarized into one total sum of absorption areas (A) per material, per octave band. This absorption area A is calculated as follows:

\[ A = \alpha \sum S \]  

where:

- A = absorption area
- \( \alpha \) = absorption coefficient specific for each material
- \( \sum S \) = sum of surface areas per material

Dividing the absorption area (summed across all materials and per octave band) by the total surface area of all the surfaces in the room yields the average absorption coefficient (Figure 3).

![Figure 1: Top view of the entire model](image1.png)

![Figure 2: Comparison of real building and model (below), with ETFE cushions visible](image2.png)
The acoustic parameters were assessed in the whole model and near the omni-directional source. To achieve this, two receiver planes were positioned at 1.2 m above the second floor of the mall and one 1.2 m above the ground floor of (visible in Figure 2). Two receiver planes that cover the entire floor area of the second floor of the higher part of the model were used two assess the overall acoustic field, one smaller receiver plane was used to assess the acoustic field near the source on the second floor. Figure 4 shows the difference between two groups of receiver planes.

**Room acoustic parameters**

T30, G, STI and DL2 were assessed near the source, on average over the whole receiver plane and near the edges of the receiver plane (that coincides with the edges of the "small" model).

- T30 is the reverberation time in seconds. It represents two times the time it takes for the Sound Pressure Level to drop from -5dB to -35dB with respect to the starting value.
- G or Sound Strength indicates the effect of room reflections on the sound level. It compares the sound energy of the measured impulse response at a certain distance to the response measured in free field at 10m.
- STI or Speech Transmission Index is an index that classifies the speech intelligibility on a scale from 0 to 1. A score in the range of 0-0,3 is labelled “bad”, 0,3-0,45 is labelled “poor”, 0,45-0,60 is labelled “fair”, 0,60-0,75 is labelled good, 0,75-1 is labelled as “excellent”.
- DL2 or The Spatial Sound Distribution Curve (ISO 14257:2001) is a curve that indicates the spatial decay of sound pressure per distance doubling in dB. This is usually compared with DLf, the spatial decay of sound pressure in free field conditions.

**Results**

Before interpreting the results, it should be mentioned that all three models did not have an equal mix of materials and consequently had different average absorption percentages per octave band. This is clearly visible in Figure 3. The reason is that the distribution of absorption along the length of the model is not homogenous, by truncating the model the average absorption was changed. However, the results are still comparable, as they were interpreted from the same area of interest.

**Simulation time**

An important consideration is the simulation time differences between the different model sizes. The Odeon software gives recommended minimum numbers of rays for each model for accurate ray tracing; this amount goes up with room size in this case study. Table 1 lists the simulation time per model in minutes (rounded down to one minute). The possible time savings for simulation time are substantial. If only a part of the long model is of interest a fixed number of rays can be used to simulate the acoustics. Using the same number of rays in the full model as in the “small” model returned similar results. Yet, the recommended number of rays was used for comparison because it is difficult to judge how many rays are sufficient.
The reverberation time was assessed based on an average over all receivers of the receiver plane or grid. Figure 4 shows that the differences in RT are quite significant for the glass material configuration.

The differences between $T_{30}$ of different sized models is larger when considering the small receiver plane (local) than the large receiver planes (general).

The reverberation times in Figure 7 were calculated with the Sabine formula, also considering absorption by the air. The differences between the model sizes are as significant for the glass variants as for the simulated $T_{30}$ values in figures 5 and 6. Medium ETFE values still match the simulated values relatively well. “Small” ETFE and “full” ETFE are significantly different from the simulated values.

The results obtained with Sabine’s formula are not accurate in general, except for medium ETFE.
distribution of absorption over the surfaces of the model is not homogenous and the shapes of the models deviate significantly from the shape of a cube. When using the sabine formula, perfect homogeneity and a cube shape are assumed because the formula does not contain any information on both of these parameters. In the case of the simulation, measurements are taken near the floor area, while with the Sabine formula one attempts to calculate the reverberation time for the whole volume.

**STI: Speech Transmission Index**

STI values were mapped over the entire large receiver plane. The results are grouped per material in Figure 10 and 11. Upon visual inspection there are no significant differences between the differently truncated models. There is only one difference at the left most edge of the large receiver plane, between “small-glass” on one hand and “medium-glass” and “full-glass” on the other. The STI value on the left most edge in “small glass” stays in the “poor” range while it transitions to “bad” in the medium and “full glass” models. However, the lowest value in this range is 0.27 while the threshold for “poor” is 0.3. This difference is equal to one JND for STI (Bradley et al., 1999).

**DL2**

DL2 or the spatial decay of sound pressure per distance doubling was derived for a path of receivers in the line of sight of the sound source in the simulation. Figure 7 shows this path in the geometrical model. ISO14257 requires to indicate if any object might be obstructing or be near to the chosen path of receivers. The path passes over a void in the space and over a glass guard rail near receiver 16.

![Figure 8: Distribution of receivers and source for DL2](image)

Figure 8 shows the curves for the A-weighted decay rate for the octave bands between 125 and 4000Hz. In both ETFE variants and glass variants DL2 (A)(125-4000 Hz) hardly varies, less than 1dB. Though the decay rate is slightly steeper for the “small” models, this is probably the effect of the end of the “small” model that is nearer to the source, and is 100% absorbing. The furthest receiver from the source is at 30m and this decay is only valid for this position in the space (considering how irregular the entire room is).

![Figure 9: DL2 curves for each model](image)

**G(average)**

$G$ values and DL2 curves strongly correlate, as both use the local sound pressure level in each point as a basis. Figures 12 and 13 give show the $G$ values averaged over the octave bands 63-8000Hz in a heat map in the area of interest (similar as STI values). The differences between degrees of truncations for the same material combination is negligible. Only near the left edge of the area of interest there is a zone of slightly lower $G$ values for the “small” model (compared to “medium” and “full”). $G$ values are higher for the ground floor (right from the speaker position). This is because the glass ceiling reflects more sound energy towards the ground floor (Figure 4 gives a clue of the height difference between the two floors”, which is about 7 m). In the ETFE models this energy is transmitted through the roof. ETFE cushions are a good tool to reduce late reflections at further distances from the source and are thus suitable for environments such as malls, or places for public transport where noise control and speech intelligibility at shorter distances are key.

A more accurate analysis per octave band could be performed, for the sake of this limited comparative study this was left out.

**Conclusion**

Three models, of which one was medium truncated, and one was strongly truncated, were compared in terms of 4 room acoustic parameters ($T_{50}$, STI, DL2, $G$), for two different material configurations. The difference in $T_{50}$ between the models was significant for the glass material configurations, the “small” glass variant was most significantly different in terms of JND’s (5% relative).

STI, DL2 curves and G(average) values were assessed spatially and were found to be only just significant for the left edge of the area of interest. Near the source
(approximately 15 m), no significant differences were found for any of the three parameters. Differences in $T_{30}$ are found to be relatively large between the different glass variants and relatively small between ETFE variants. For all other parameters, truncating the model did not have a significant influence. Though this difference in $T_{30}$ is probably due to the larger differences in average absorption between the glass models, a more precise analysis of the impulse response curves and analysis of other parameters such as $G_{ave}$ should shed more light on the reason for this discrepancy between $T_{30}$ and the other parameters.

It can be concluded that detailed modelling of the “small ETFE” and the “medium glass” truncations is sufficient to assess the room acoustic behaviour of the considered shopping mall, and that there is no need to include the further extremities of the mall in the simulation model. This conclusion can most probably be extended to other halls with similar absorptive properties. It can be expected that for spaces with less absorbing surfaces, larger parts of their volume need to be considered. More parametric studies are necessary to explore the possible benefits of truncating the models of other architectural typologies.

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**References**


Figure 10: STI per receiver in the three ETFE models

Figure 11: STI per receiver in the three glass models
**Figure 12:** G average per receiver in the three ETFE models

![G ETFE](image1)

- Small
- Medium
- Full

**Figure 13:** G average per receiver in the three glass models

![G glass](image2)

- Small glass
- Medium glass
- Full glass