CASCADE: A NOVEL COMPUTATIONAL DESIGN SYSTEM FOR ARCHITECTURAL ACOUSTICS

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ABSTRACT

Computation of sound propagation in enclosed spaces is needed for a variety of purposes such as noise exposure in industrial spaces, acoustic privacy conditions in open-plan office settings, and speech intelligibility in auditoriums. In this context, the present paper offers a twofold contribution: First, the concept of a prototypical computational environment (SEMPER) is described in which the informational basis for performance simulation is derived from the structurally homologous general (architectural) building representation without additional user intervention. In other terms, modifications to the building design are automatically mapped into the underlying model of performance analysis, thus enabling the user to rapidly and efficiently perform simulations of sound propagation in enclosed spaces from the early stages of design to the final (detailed) design solution. Second, the underlying computational approach to the acoustical simulation is outlined. The sound propagation model (CASCADE) is essentially a hybrid stochastic one that combines features of sound particle concept and statistical energy distribution analysis.

1 ON SEMPER

Objectives

SEMPER, a prototype of an active multi-aspect prototype design environment (Mahdavi 1996a) is being developed primarily in accordance with the following system requirements:

- Consistent and coherent multi-aspect modeling of the fundamental physical processes (relevant to the building's performance) throughout the building design and development phases.
- Seamless and dynamic communication between various simulation models and a shared object-oriented space-based building representation.

SEMPER includes modules for energy simulation, thermal comfort analysis, air flow modeling, HVAC system analysis, lighting, acoustics, and life-cycle analysis. The focus of this paper is CASCADE (Mahdavi 1996b, Mahdavi et al. 1996), the acoustics module within the SEMPER environment.

Simulation Approach

In the past, various computational design evaluation concepts have been suggested (and partially implemented) to cater for the dynamic (temporal) transitions in the design process and the associated changes in the quantity and resolution of available information. A traditional concept relies on a problematic assumption implying the appropriateness of "simplified" models for (the less "complex") early design and detailed simulation for the (more "complex") later stages of design. As to the nature of the relevant physical phenomena involved in the building performance (e.g. sound propagation inside spaces), the early design schemes do not imply lesser levels of complexity than the more detailed ones. The relevant difference for the simulation process lies rather in the resolution of the specifications of constitutive building components both in terms of geometric and "behavioral" properties. For example, the realistic prediction of the sound field, even for a most simple L-shape room, typically involves a non-uniform reverberant field, non-specular reflection, non-isotropic source emission, and diffraction phenomena. Thus, even the initial building model, although ill-defined (in terms of component specification), should be evaluated based on simulation methods that rely on a "first-principles-based" modeling of the fundamental physical processes involved. In fact, CASCADE, the sound propagation module in SEMPER, combines features of sound particle models and statistical energy distribution analysis. The sound field build-up phase of the simulation relies on generation and emission of virtual "phonons" leading to the determination of the excitance pattern of room enclosure elements. The sound field is then "collapsed" for arbitrary locations of receiver using the probabilistic reflection patterns of the excited enclosure elements.

Seamless Dynamic Communication within the SEMPER Environment

The integration of detailed simulation methods and CAD systems is complicated by the fact that the building representation needed for detailed simulation methods does not adequately match the representation used in commercially available CAD systems. For example, detailed acoustical simulation methods require the definition of spaces. Almost all currently available commercial CAD systems rely on building representations that do not include spaces. A space-based CAD system would provide a representation that is practically homologous to the building representation schemes needed for most detailed performance simulation routines (Mahdavi 1996a). Here, the term "homologous" implies that the two representations have information structured in a manner such that they can be mapped into each other without geometry interpretation. SEMPER demonstrates this by dynamically linking the buildings general representation (essentially a shared object model with methods that can activate a topology kernel for geometric operations) with structurally homologous representations of the simulation modules (essentially the domain object models). These two components, together with the user interface and a database (for the encapsulation of data on building components, materials, layers, and units) constitute the overall architecture of SEMPER as schematically illustrated in Figure 1.

Figure 2 illustrates both the general object-based building representation in SEMPER and the derivative object model in CASCADE. While the former entails an object model that is shared across multiple simulation domains, the latter is specific to the acoustic application. The above described system architecture allows for the effective homology-based mapping from the shared building representation to that of a specific domain (cp. figure 3). The shared building representation embodies topological information and associative labels pointing to semantic information (mainly material properties) in the system's database. Therefore, it has knowledge of architectural spaces as well as their constituents (enclosure elements) and their relationships (adjacencies, shared walls/roofs, etc.). CASCADE receives this information and utilizes it as the underlying informational basis for the acoustic representation. This process involves the association of two surface layers with each enclosure, opening, attachment, or partition element. The surface layers embody information on acoustical behavior such as frequency-dependent absorption coefficients (including - if available - reflection directivity patterns), surface roughness, and transmission coefficients. These surface layers are subsequently segmented into smaller grid elements to facilitate the numeric computation of indoor sound field.

Note that the acoustical model in CASCADE is automatically generated from the general architectural representation and that subsequent changes in design (as reflected in the shared object model) are directly mapped into the acoustical model without the necessity for any user intervention. In other terms, as the design progresses, the resolution of acoustical model increases, resulting in a more detailed analysis. This provides "on-line" simulation feed-back to the user while eliminating the need for explicit definition and updating of the underlying simulation model.

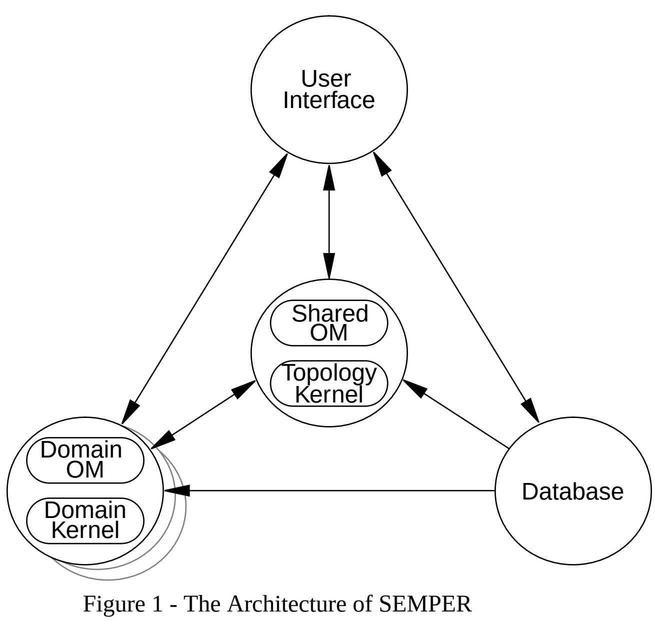


Figure 1 - The Architecture of SEMPER

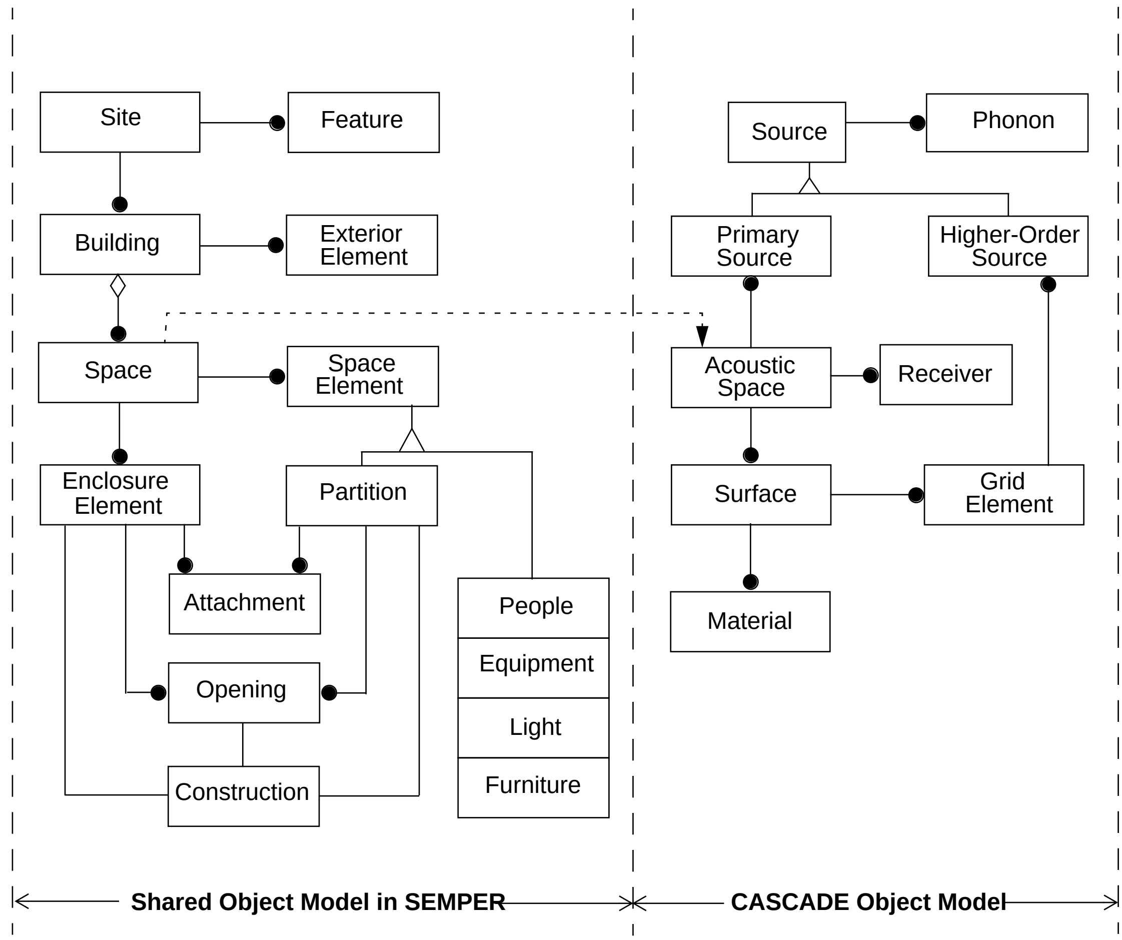


Figure 2 - SEMPER's shared object model and CASCADE's domain object model

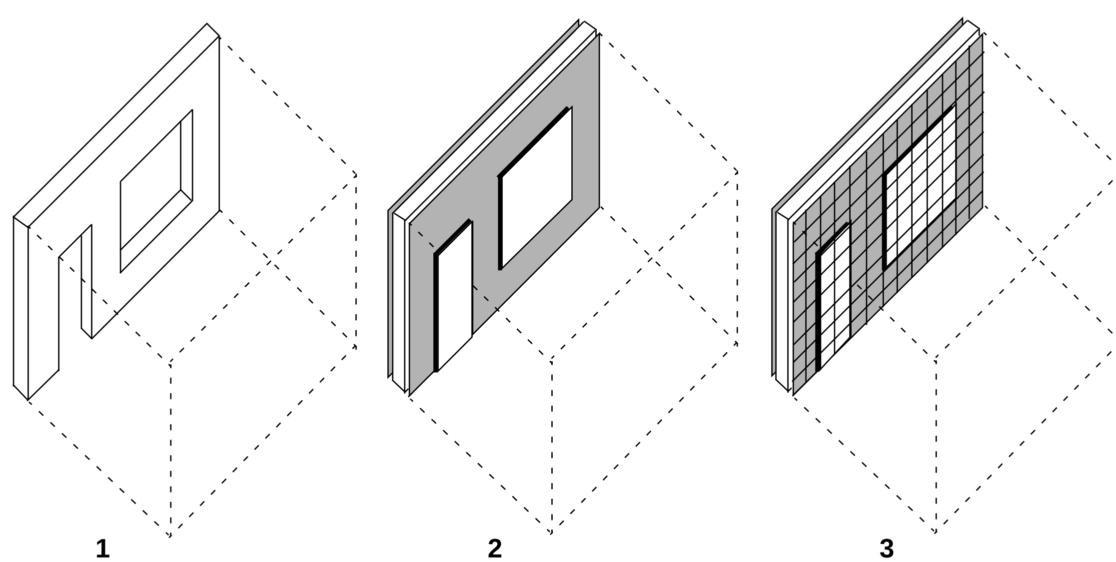


Figure 3 - Demonstrative illustration of the derivation of the CASCADE's acoustically relevant building representation from the general architectural representation in SEMPER (1: representation of an enclosure element in SEMPER; 2: CASCADE's "enrichment" of the enclosure element with acoustically relevant surface layers; 3: Segmentation of surface layers in grid elements for numeric computation purposes in CASCADE)

2 ON CASCADE

Overview

CASCADE's overall computational process is illustrated in figure 4. It involves the derivation of the acoustic model, the emission of virtual sound particles (phonons), the discretization of room surface elements and the generation of higher order sources, definition of the room surface system, definition of the receiver system, resolution of the room sound field for the receiver system, and the derivation of the acoustic performance indicators.

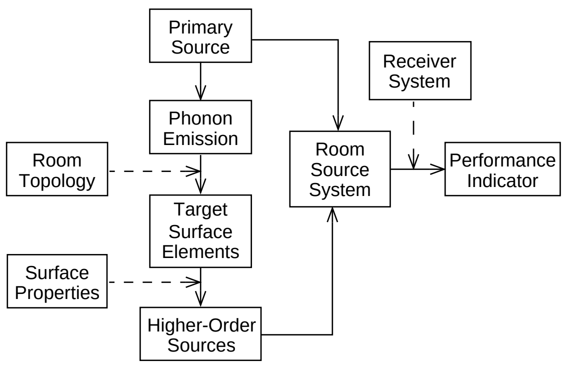


Figure 4 - Schematic illustration of the computational process in CASCADE

Derivation of CASCADE's Object Model

As stated earlier, once the building design is communicated to SEMPER by the user and the shared object model is generated, the necessary simulation model for the prediction of sound propagation is automatically derived by SEMPER's acoustic module, CASCADE (Mahdavi 1996a). This procedure involves the "enrichment" of the underlying shared object model with acoustically relevant representational schemes (element surfaces, finite grid elements, etc.) and material properties (absorption coefficients, reflection patterns, roughness, etc.).

Building Representation

CASCADE's simulation model geometrically defines spaces with their enclosure elements and partitions, all of which may have openings (doors, windows, etc.) and/or attachments (acoustically distinctive layers attached to the surface of primary enclosure elements or partitions within the space). The main elements of the representation are the surfaces of these enclosure elements and partitions.

To allow for detailed numeric computation, the surfaces are divided into smaller grid elements. These have associations to acoustic properties such as absorption coefficients and reflection patterns which are read from the database. To facilitate the generation of the finite grid elements for a room surface, a local coordinate system is established for that surface ($\zeta = 0$). Therefore a 3 x 3 transformation matrix M is associated with each surface and the global coordinates (x, y, z) are converted into local ones (ξ, η, ζ):

$$\begin{pmatrix} \xi \\ \eta \\ \zeta \end{pmatrix} = M \cdot \begin{pmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{pmatrix} \qquad \text{Eq. 1.}$$

In this equation, x_0, y_0, z_0 are the coordinates of local origin in the global system.

The grid elements can be conveniently aligned to the axes of this local coordinate system. To determine if a grid element is within a non-orthogonal room surface, the coordinates of the grid center are examined. A grid element is considered for numeric computation if its center is within the surface boundaries. A similar strategy is applied in dealing with openings and attachments. If a grid is located within an opening or attachment, it will be associated with the corresponding material and surface properties (absorption coefficients, reflection patterns, roughness, etc.).

Algorithmic Requirements Profile

The underlying model for the computation of the indoor sound propagation in CASCADE was developed to be coherent (first-principles-based) and consistent (applicable to various stages of design). Furthermore, it was designed, from the outset, in a manner to be effectively integrated within the multi-aspect SEMPER environment. A review of existing simulation approaches led to the conclusion that an approach that would utilize features of sound particle methods and the Monte-Carlo method would adequately respond to these requirements. Particularly, the statistical nature of sound particle emission and propagation modeling could allow for variable degrees of computational investment depending on the variable nature of design information which itself is a function of the design stage.

Sound Field Build-up

First, phonons are generated from the primary sources. A phonon denotes in this context a virtual sound particle that is emitted from a sound source in a certain direction and with a certain amount of acoustical energy. A primary source is defined with its acoustical power, directivity pattern, location, and aiming direction. The simulation can be carried out for virtually any number of primary sources. For the calculation of the reverberation time, a standard source with a default location in the space may be used.

The directivity pattern of primary sources and considerations pertaining to the Monte-Carlo method are used to determine the number of phonons that are emitted in a specific spatial direction (Mahdavi 1996b). The overall energy of all phonons corresponds to the acoustical power of the primary source. These phonons are traced to surfaces with which they collide. Each collision creates a higher-order source. Along with the location of this new source, an associated temporal marker and the spatial direction of the specular reflection are recorded for the relevant finite grid element. The acoustical power of the higher-order source is computed based on the energy of the incident phonon and the absorption coefficient of the relevant finite grid element. The directivity pattern of this virtual higher-order source (i.e., the effective reflection pattern of the surface) is determined based on the frequency of the incident sound, the surface size and its roughness. This reflective behavior is represented in terms of (Gaussian) probability functions. The assumption is that for each surface and at each frequency, the magnitude of the reflective energy is maximum for the direction of the specular reflection and proportionally decreases with increasing angles of deviation from this direction. If a surface is specular reflector, the Gaussian pattern is highly directional. Diffuse reflectors are represented *via* less directional Gaussian patterns (cp. figure 5).

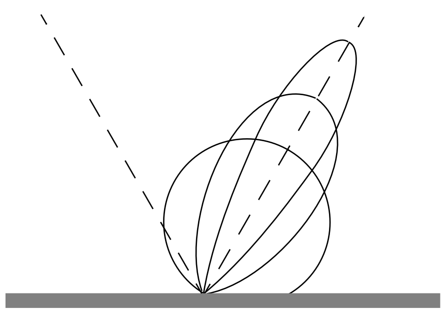


Figure 5 - Illustration of typical surface reflection patterns

In the current implementation, the relative energy of the reflected sound in a given direction is a function of its deviation angle from the direction of the specular reflection. Subsequently, the probability $P_{(\theta)}$ of a phonon being reflected in an angle θ (angle of deviation from the specular reflection) is computed as a function of θ and b (a parameter that describes surface's reflective behavior) according to the following equation:

$$P_{(\theta)} = \frac{1}{\sqrt{2\pi} \cdot b} \cdot e^{-\left(\frac{\theta^2}{2 \cdot b^2}\right)} \qquad \text{Eq. 2.}$$

The parameter b is a function of the frequency of the incident sound f and the characteristic frequency f_u:

$$b = m \cdot \left(\frac{f_u}{f}\right)^n \qquad \text{Eq. 3.}$$

In this equation, m and n are two empirical constants. For a parallelepiped, f_u can be estimated based on the speed of sound c, room dimensions W, L, H, and the angle of incidence ϕ:

$$f_u = \frac{c}{\cos^2\phi} \cdot \frac{W \cdot L}{(W + L) \cdot H^2} \qquad \text{Eq. 4.}$$

To summarize, in the sound field build-up phase, phonons are traced from primary sources to room surfaces through multiple reflections thus generating a large set of higher order sources distributed across surface grid elements. While the distribution patterns of the primary sources are given by their directivity, the distribution patterns of higher-order sources are derived based on the incidence angle of the arriving phonon as well as the acoustical characteristics of the surface elements. Higher order sources have different delay times due to difference in their "history" (cumulative travel paths). The delay times decide at which points in time the higher order sources become activated. When the distribution of the higher order sources is accomplished, the sound field can be derived based on this multiple-order source system. Note that this sound field build-up phase does not require the knowledge of the receiver positions.

Sound Field "Collapse"

The receiver system may be defined in many ways. The user can query for the attribute of a certain performance indicator (e.g. sound pressure level) at a single point in the space. Alternatively, a flexible-density grid of reference points can be specified. After the sound field build-up phase of the simulation, the total sound field can be treated as a distributed source system that includes all the primary and higher-order sources. For each receiver point that is specified, the contribution of energy from the total source system is computed by using the directivity/reflection patterns and temporal markers (i.e., the delay times) of each source. As to the higher-order sources, the magnitude of their effect on a receiver depends on the deviation angle of the source-receiver line from the direction of the specular reflection. If obstacles (e.g. partitions, furniture elements, etc.) are found between a source and the receiver, modifications are made to the sound field due to the diffraction effect.

When this procedure is completed, each receiver has registered an acoustical event sequence that contains information on a series of sound intensity levels and corresponding arrival times. From the information embodied in this sequence, all pertinent acoustic performance indicators are derived (e.g., sound pressure levels, reverberation time). For example, the sound pressure level (L_p) is derived as the sum of individual components of the event sequence (L_{pi}) as registered at a specific receiver point within an appropriate time window:

$$L_p = 10log\left(\sum_{i=1}^{n} 10^{\frac{L_{pi}}{10}}\right) \qquad \text{Eq. 5.}$$

The reverberation time can be derived from the event sequence as well. This involves, however, the simulation of a large order of inter-reflections between the room surfaces. We apply the least linear regression method to obtain the reverberation time. Suppose the reverberation decay curve is a linear function such as $L_p = at + b$. Based on a set of event component levels and their arrival times (L_{pi}, t_i), the least square regressive approximation yields:

$$a = \frac{\sum_i^n L_{pi} \cdot t_i - \frac{1}{n}\sum_i^n L_{pi}}{\sum_i^n t_i^2 + \frac{1}{n}\sum_i^n t_i} \qquad \text{Eq. 6.}$$

Given the decay rate a, the reverberation time T_{60} is given by:

$$T_{60} = -\frac{60}{a} \qquad \text{Eq. 7.}$$

In summary, as the sound field is "collapsed", the total effect of the sound field is derived for each receiver point, based on the contributions from the primary and higher-order sources scattered across the room surface grid elements. Note that in this second phase, the phonons are not explicitly utilized. The emissive energy, the distribution pattern, and the location of all primary and higher order sources are already established at the end of the first phase, so that the acoustic performance parameter (such as sound pressure level) at receiver points can be simply obtained by the energetic summation of all contributions from this multiple-order source system.

Diffraction

While collapsing the sound field for a particular receiver point, the contributions from primary and higher order sources that are not "visible" from that point are modified based on the source power and directivity, geometric constellation (source-obstacle-receiver configuration), and the sound frequency. For example, for an isotropic point source S (with a sound power level $L_{W,S}$) at a distance r from the receiver R (see figure 6), the resulting sound pressure level (for frequency f) at R ($L_{p,R}$) can be obtained from the following equation:

$$L_{p,R} = L_{W,S} - 10\log(4\pi r^2) - \left(17.6 + 10\log k + 10\log\frac{f}{500} + 10\log\frac{\vartheta - 25}{65}\right) \qquad \text{Eq. 8.}$$

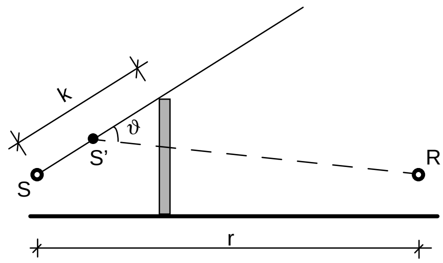


Figure 6 - Illustration of the geometric factors in diffraction modeling (S' is a reference point halfway between S and obstacle's highest point)

3 CASE STUDIES

Predictions and Measurements

Gibbs et al. 1972 include the documentation of measured and predicted sound pressure levels due to an isotropic sound source in a 4.4 x 3.08 x 2.27 *m* test room (cp. figure 7). In one experiment the absorption coefficient (at 2000 Hz) of all room surfaces except a side wall was 0.27. The side wall's absorption coefficient was 0.88. We modeled the same test room in CASCADE assuming that all room surfaces were diffuse reflectors. The results (relative sound pressure level iso-lines) are illustrated in figure 7, together with both Gibbs et al. 1972's measurements and their predictions based on a source image method. CASCADE's results display reasonable agreement with measurements despite the rather simplistic diffuse reflection assumption.

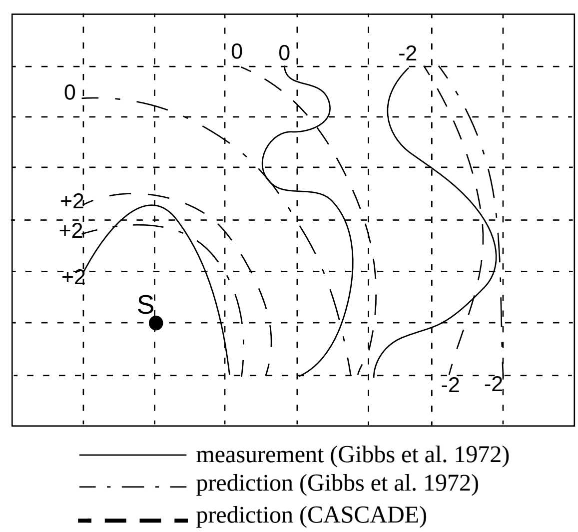


Figure 7 - Predicted and measured relative sound pressure level iso-lines

Some Parametric Studies

To further illustrate the capabilities of CASCADE, a second series of preliminary simulation studies was performed using a 6 x 4 x 3 *m* space as the test room. Four configurations of room surface absorption coefficients were considered (cases 1 to 4 as documented in table 1). Room surfaces were modeled as diffuse reflectors. The virtual source was assumed to have an isotropic directivity pattern. The source location remained the same throughout the simulations as indicated in figures 4 to 8. The test frequency was assumed to be 500 Hz.

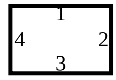
In addition to modeling the sound propagation for cases 1 to 4 using CASCADE (cp. figure 9 to 12), case 1 was also modeled using a simplified method assuming a uniform reverberant field (cp. figure 8). Note that the total absorption of cases 1 and 2 are equal. Likewise the total absorption of cases 3 and 4 are equal. The motivation behind this arrangement was to demonstrate CASCADE's behavior while modeling non-uniform distribution of absorbing surfaces, a circumstance that cannot be modeled *via* simplified approaches.

The simulation results (relative sound pressure level iso-lines at 500 Hz) are shown in figures 8 to 12. The reverberation times for each case were also computed (using both Sabine's and Eyring's equations as well as CASCADE) and are included in table 2.

The comparison between the predictions of the simplified method and those of CASCADE for case 1 (cp. relative sound pressure level iso-lines in figures 8 and 9) displays a good agreement, although CASCADE predicts a slightly weaker reverberant field at room periphery. The predicted values for the reverberation time are also very close, particularly those calculated by the Eyring formula and CASCADE (cp. table 2).

As to the issue of the spatial distribution of sound absorbing materials, figures 9 and 10 clearly demonstrate that the high sound absorbing end wall of case 2 (note the absorption coefficient for wall 2 in Case 2 as included in table 1) does have a measurable effect on the overall sound distribution pattern in the test room. A comparable effect can be observed while comparing cases 3 and 4 (figures 11 and 12). In the latter cases the rather high room average absorption leads to inaccurate estimation of the reverberation time using the Sabine formula. A better estimation can be obtained for case 3 using the Eyring formula. CASCADE's prediction is in this case practically identical with Eyring's. However, as the results for cases 3 and 4 indicate (cp. table 2), for a room with a highly non-uniform distribution of absorbing materials (note particularly the absorption coefficients for floor and ceiling in Case 4 as included in table 1), CASCADE's results can significantly deviate from those obtained by the Eyring formula.

Table 1: Test room case descriptions with absorption coefficients at 500 Hz

	α wall 1	α wall 2	α wall 3	α wall 4	α ceiling	α floor
Case 1	0.19	0.19	0.19	0.19	0.19	0.19
Case 2	0.10	0.90	0.10	0.10	0.10	0.10
Case 3	0.34	0.34	0.34	0.34	0.34	0.34
Case 4	0.10	0.10	0.10	0.10	0.90	0.40

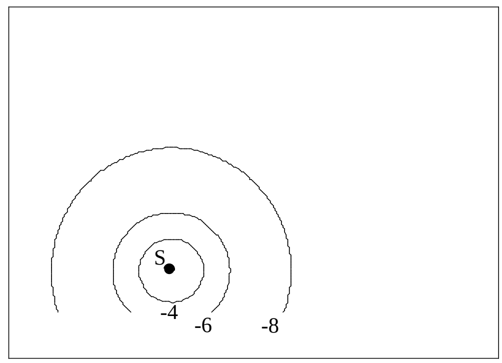


Figure 8 - Sound distribution in the test room (case 1) as predicted by the simplified method

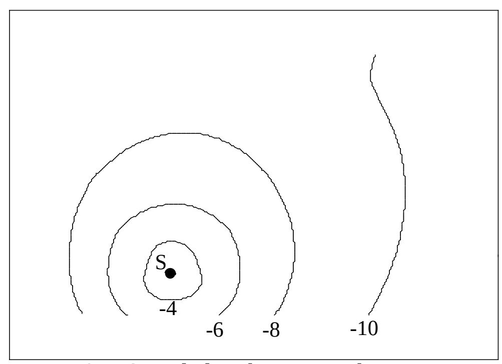


Figure 9 - Sound distribution in the test room (case 1) as predicted by CASCADE

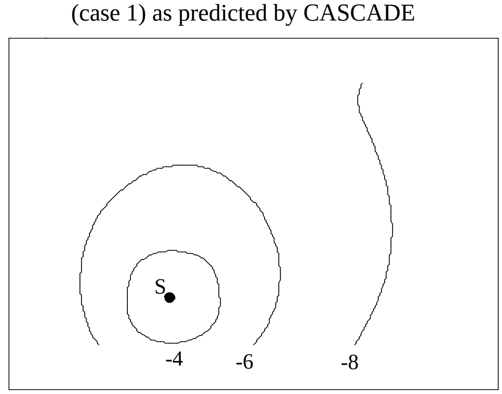


Figure 10 - Sound distribution in the test room (case 2) as predicted by CASCADE

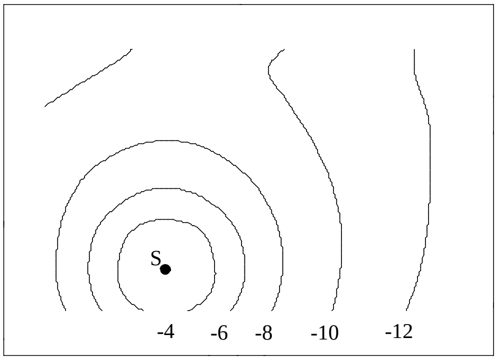


Figure 11 - Sound distribution in the test room (case 3) as predicted by CASCADE

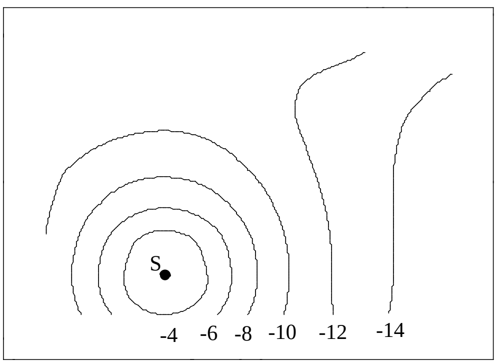


Figure 12 - Sound distribution in the test room (case 4) as predicted by CASCADE

Table 2: Predicted reverberation times (s)

	T_{60} Sabine	T_{60} Eyring	T_{60} CASCADE
Case 1	0.58	0.51	0.51
Case 2	0.58	0.51	0.67
Case 3	0.32	0.25	0.25
Case 4	0.32	0.25	0.13

4 CONCLUSION

An indoor sound propagation model (CASCADE) is dynamically linked to a shared object-oriented space-based architectural representation, so that changes in design are dynamically mapped into corresponding modifications in the homologous domain representation of the acoustical model. This is achieved without user intervention and geometry interpretation. The paper has thus provided a proof of concept for incorporation of a detailed, reliable and consistent acoustical simulation methodology (phonon-based stochastic sound field modeling) within an integrated multi-aspect design support environment (SEMPER).

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