Journal of Building Performance Simulation
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tbps20

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Published online: 19 May 2014.

Journal of Building Performance Simulation, 2015
Vol. 8, No. 1, 15–25, http://dx.doi.org/10.1080/19401493.2014.888594

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(*Received 9 July 2013; accepted 25 January 2014*)

Over the last decades, powerful prediction models have been developed in architectural acoustics, which are used for the calculation of sound propagation in indoor and/or outdoor scenarios. Sound insulation is predicted rather precisely by using direct and flanking transmission models of sound and vibration propagation. These prediction tools are already in use in architectural design and consulting. For the extension towards virtual reality (VR) systems, it is required to accelerate the prediction and simulation tools significantly and to allow an adaptive and interactive data processing during the simulation and 3D audio stimulus presentation. This article gives an overview on the current state-of-the-art of acoustic VR and discusses all relevant components in terms of accuracy, implementation and computational effort. With the progress in processing power, it is already possible to apply such VR concepts for architectural acoustics and to start perceptual studies in integrated architectural design processes.

Keywords: auralization; virtual acoustics; room acoustics; building acoustics; signal processing; simulation of sound propagation; real-time systems; virtual reality; immersive environments

Introduction

Architectural acoustics deals with sound in buildings and is usually subdivided into room acoustics and building acoustics. In classical room acoustics, optimal conditions for music perception and speech communication are the main goals. However, room acoustics also deals with other spaces today, such as foyers, workplaces, offices and classrooms, where optimum acoustic conditions include aspects of noise control, too. When it comes to sound transmitted between rooms in a building, not only the airborne sound insulation of the rooms' connecting structural elements must be taken into account but also aspects of the structure-borne excitation from, e.g. water installation, heating, ventilation or air condition systems in order to determine the building's overall acoustic performance. In principle, the acoustic performance can be predicted with various theoretical models such as analytical or numerical wave models, geometrical acoustics (GA) and statistical energy analysis (SEA). Input data are typically surface material descriptions such as absorption/scattering coefficients or impedances, as well as other architectural characteristics, such as room volume, surface areas or the thicknesses of building elements and their junctions. Today, all these data are usually encapsulated within the concept of building information modelling (BIM) (van Nederveen and Tolman 1992), which can be seen as a complete digital representation of the physical and functional characteristics of a building.

The era of computer-based room acoustics simulation began in the 1960s where Krokstad, Strøm, and Sørsdal (1968) published the first paper about the calculation of an acoustical room response by means of a sound-particle-based simulation technique. With the rapid development of computers and, thus, a significant increase of processing power, more sophisticated acoustical simulation methods were established and applied in the sound field analysis of rooms and buildings. Then, at the beginning of the 1990s, processor speed, memory space and convolution machines became powerful enough to allow room acoustical computer simulation and auralization even on a standard personal computer (PC) (Vian and van Maercke 1986; Vorländer 1989). Back then, simulation times ranged from hours to days to weeks. At about the same time, the first models for the apparent sound insulation of complete buildings were developed (Gerretsen 1979, 1986).

Since then, several improvements in the modelling algorithms, in binaural processing and in reproduction techniques were made (Kleiner, Dalenbäck, and Svensson 1993; Vorländer 2008). State-of-the-art commercial software for room acoustical simulation is only complete with an option for auralization via the sound card of the computer. The field of application has broadened vastly as not only music and the quality of concert halls, or other performance spaces, are to be evaluated but also

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the perception of general sound and noise. Therefore, building acoustics, automotive acoustics and machinery noise became areas of application, too. European standards – as the consequence of the European Union (EU) building construction directive – reflect the current state-of-the-art of scientific knowledge (European Standard EN, 2000). They are implemented in software for prediction (Gerretsen 1979) and auralization (Vorländer and Thaden 2000; Schröder and Vorländer 2007; Schröder 2011) of airborne sound insulation. In general, not only methods of GA (Vorländer 2008) or wave-based numerical acoustics such as the finite element method (FEM) (Zienkiewicz and Taylor 2000), the boundary element method (von Estorff 2000) and the finite-difference time-domain (FDTD) method (Botteldoren 1995) are suited to serve as basis for auralization but also analytic models and any kind of structural acoustics transfer path method. However, it should be noted that analytic models are not at hand for all configurations and structural acoustic transfer paths are, alone, not sufficient for auralization purposes. The key link between simulation and auralization is the representation of the overall problem in the time, frequency and perceptive domain, and the handling of sound and vibration by state-of-the-art signal processing (Vorländer 2008).

Another field of rapid progress is virtual reality (VR), which is – from a technical point of view – the representation and simultaneous perception of reality and its physical attributes in an interactive computer-generated virtual environment. Today, most VR-applications focus just on first-class visual rendering. Other modalities – if added at all – are presented just as effects without any physically based reference to real-world properties. However, it is a well-known fact that the visual perception is significantly augmented by matching sound stimuli (Gazzaniga, Ivry, and Mangun 1998). Especially in architectural applications such as a virtual walk through a complex of buildings, auditory information helps to assign meaning to visual information. Unfortunately, even simple scenes of interaction, e.g. when a person is leaving a room and closing a door require complex models of room acoustics and sound insulation. Important wave phenomena, such as diffraction at low frequencies, scattering at high frequencies and specular reflections have to be considered to enable a physically based sound field modelling. Otherwise, the colouration, the loudness and timbre of sound within and in-between the rooms will not be represented with sufficient accuracy. Hence, from the physical point of view (not to mention the challenge of implementation), the question of modelling and simulation of a realistic virtual sound is by orders of magnitude more difficult than the task of creating visual images. The main reason is the fact that sound in the full audio range must be simulated for frequencies and wavelengths covering three orders of magnitude (from 20 Hz to 20 kHz). This might be the reason for the delayed implementation of physically based 3D audio real-time rendering engines for virtual environments (Savioja et al. 1999; Funkhouser et al. 2004; Lentz et al. 2007; Schröder et al. 2010; Schröder 2011).

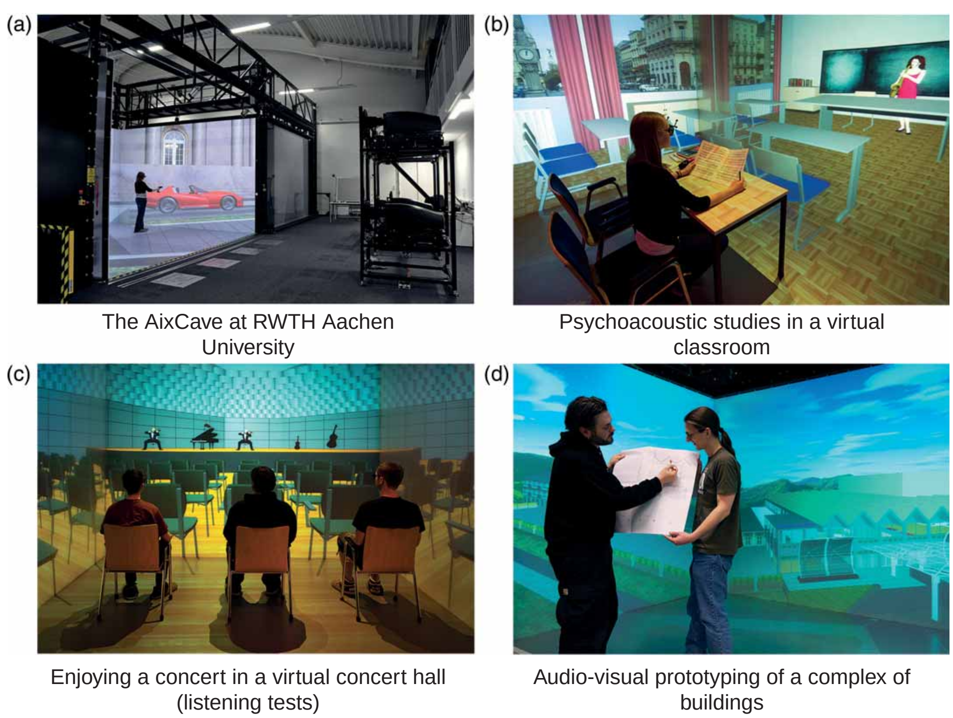

Figure 1. Immersive virtual environment at RWTH Aachen University that enables state-of-the-art physically based real-time auralization of the virtual scene.

The main purpose of the present article is to review the current state-of-the-art of simulation tools for room acoustics and sound insulation, and to discuss their application in real-time VR-systems for architectural acoustics (exemplary applications are shown in Figure 1). After a brief summary of the fundamentals of auralization with respect to signal processing and binaural technology, an introduction is given to room and building acoustics simulation. Besides the discussion of general problems, such as the acquisition and exchange of acoustic data or the construction of room models that feature an appropriate level of detail for acoustic simulations, established strategies of physically based sound field rendering are recapitulated. Here, special focus is given to sound insulation prediction models and room acoustic simulation methods based on GA. Finally, a closer look is taken at the most prestigious and challenging field of application for auralization techniques – that of VR, where aspects of real-time processing must be taken into account, too. Therefore, policies for data management, acceleration techniques and convolution are introduced and discussed in terms of accuracy, implementation and computational effort.

The fundamentals of auralization

Following the concepts of simulation in acoustics and vibration, the process of auralization can be described by (a) the separation of the processes of sound generation, sound propagation and sound reproduction into system blocks and (b) the respective representation of these blocks with tools from the system theory (Figure 2).

Digital signal processing

The signal processing part illustrated in Figure 2 shall be explained in more detail. The sampled source signal, $s(n)$, is called a “dry” recording. It contains the mono sound signal without any reverberation. The usual approach is a recording of the sound source at a given distance and in a given direction in an anechoic chamber. Also, the source directivity pattern must be taken into account. There are several ways to integrate directional sound radiation. For a sound source with time-invariant directional characteristic, a directional pattern can be taken into account in the simulation algorithm (Vorländer 2008). For time-variant sound sources such as wind instruments, for example, a multi-channel anechoic recording is a better approach. Accordingly, the whole auralization process is to be based on spatial data formats from the source via the propagation path to the audio reproduction system (Pätynen and Lokki 2010; Ben Hagai et al. 2011). The resulting signal after sound propagation in (between) rooms, $g(n)$, contains the characteristics of both the sound source and the transmitting system. Here, sound propagation within a room typically adds the phenomenon of reverberation to the source signal, while a listening event of sound transmitted through

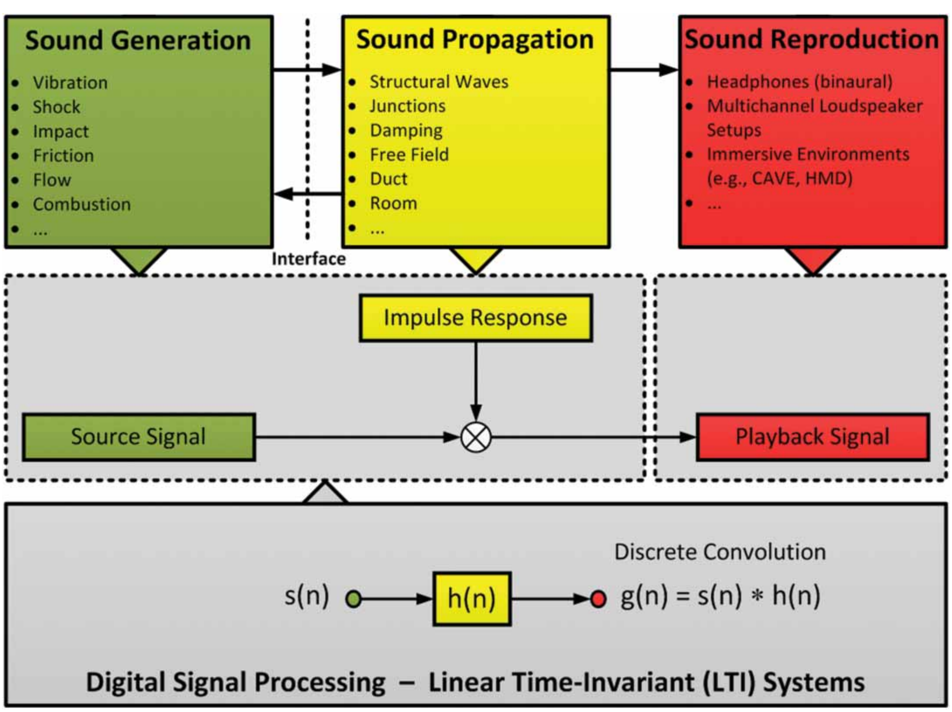

Figure 2. Generation and propagation of sound and its representation in the physics domain (top) and in the domain of acoustic signal processing (bottom). In the physics domain, the sound source characterization and the wave propagation can be either modelled or measured. The components will then be combined in a synthesis of source signals and impulse responses.

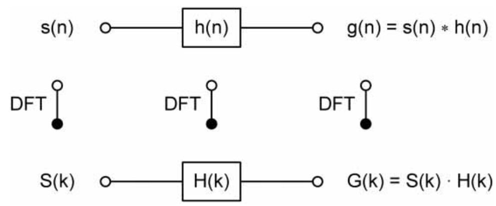

Figure 3. Convolution of audio signals in the time domain (top) or the frequency domain (bottom).

walls is characterized by a low sound pressure level and a dull sound (low-pass characteristic). The performance of a sound-transmitting system in terms of sound propagation physics is represented by the system's impulse response, $h(n)$. The sound signal at the receiver position is then achieved by convolving the original dry sound signal with the impulse response (the impulse response is usually represented by a digital filter). It is important to mention that after discrete Fourier transform the time-consuming method of convolution can also be efficiently performed in the frequency domain, because this domain reduces the mathematical operation of convolution to a simple multiplication (Oppenheim and Schafer 1975; Prandoni and Vetterli 2008). This interrelation is depicted in Figure 3.

Binaural technology

Similar to visualization, where 3D effects are strikingly more realistic than any 2D image or video, spatial hearing is a very important aspect of the human sound perception. In acoustics, the fundamentals of spatial hearing start with two major head-related processes that are (1) the physical diffraction of sound at the listener's head and torso and (2) the sound transmission from wave incidents on the listener from various directions. This sound transmission to the listeners' eardrums can be described by convolution filters as well, called head-related transfer functions (HRTFs) in the frequency domain and head-related impulse responses in the time domain (Figure 4). HRTFs are different for the angles of sound incidence, and they are specific for each individual person (Blauert 1996; Fastl and Zwicker 2007). Today, a large variety of HRTF-databases of dummy heads exist and promising methods for the rapid measurement of individual HRTFs are in progress (Dietrich, Masiero, and Vorländer 2013).

One might ask why the problem cannot simply be treated by using a mono signal, an equalizer and a headphone. The need for a more complex reproduction technique with a spatial representation is given by the fact that the human hearing extracts information about the sound event and the sound environment by the segregation of spectral, temporal

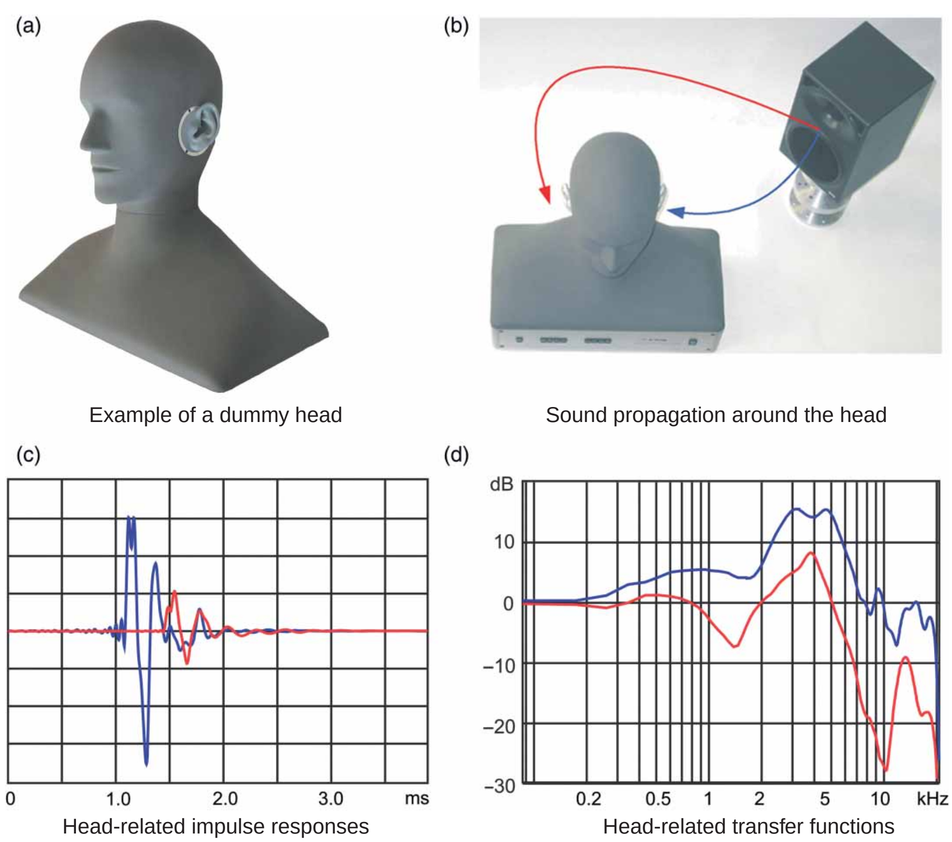

Figure 4. (a) Dummy head (b) in a listening position of a given sound incidence, (c) its head-related transfer function in the time domain and (d) its equivalent function in the frequency domain (magnitude shown), called HRTF.

and spatial attributes of acoustic objects. This, for instance, allows us to identify one speaker out of a cloud of diffuse speech (cocktail party effect Fastl and Zwicker 2007). In situations of noise emission, the spectral, temporal and spatial cues are extracted to judge the event as pleasant, annoying, informative or neutral.

Especially in rooms, humans are quite sensitive to the perception of sound in all its temporal, spectral and spatial aspects, which makes a realistic auralization in room acoustics quite a challenge. Source recording, sound propagation rendering and audio reproduction have to meet high-quality standards in order to convey a convincing auditory environment. In contrast, the two main perceptual cues in building acoustics are only (1) loudness and (2) spectral features of disturbing noise that is transmitted from other rooms of the building into the receiving room (low-pass characteristic). Hence, spatial (binaural) cues have lower priority and are just relevant for creating a plausible impression of the wave effect of sound transmission.

Room and building acoustic simulation

Today, acoustic computer simulations are applied in various architectural design processes with great success. Sophisticated simulation algorithms help to create information about both the room acoustics and the building acoustics already during the early architectural planning stage (an example is given in Figure 5). However, there are some major drawbacks at the moment that hinder a fluent workflow among different types of simulation tools, namely the acquisition and the exchange of acoustic data. In particular, the creation of computer-aided design (CAD) models that are appropriate for acoustic simulations always requires a certain expertise and understanding of how the underlying simulation algorithms work. Objects or surface corrugations which are not large compared to the wavelengths have to be taken out of the CAD model and replaced by a flat surface with adequate acoustic properties. This holds true also for chairs and audience seats. For the purpose of visualization, these elements are essential for a realistic impression. For the “acoustic view”, however, they are invisible. Accordingly, the room must be approximated by planes. The required level of detail is in the order of magnitude of roughly half a metre (Pelzer and Vorländer 2010). Second, the acquisition of standardized data that describe the acoustic performance of building parts is usually performed by experts and stored in one specific data format. Unfortunately, this makes a direct exchange of such data between different applications practically impossible since most tools rely on their own proprietary database formats. To overcome this issue, open database projects were founded, e.g. openMat (Pohl et al. 2012; OpenMat), openDAFF (OpenDaff) or Common Loudspeaker Format (CLF), which are free to use and support a detailed description of either surface materials or sound sources for the usage in acoustical simulation software. In a long-term view, all these shortcomings are expected to be solved by the consequent integration of detailed acoustic data into the BIM concept.

Room acoustics simulation techniques

From a psychoacoustical point of view, the impulse response of a room (in the following referred to as room

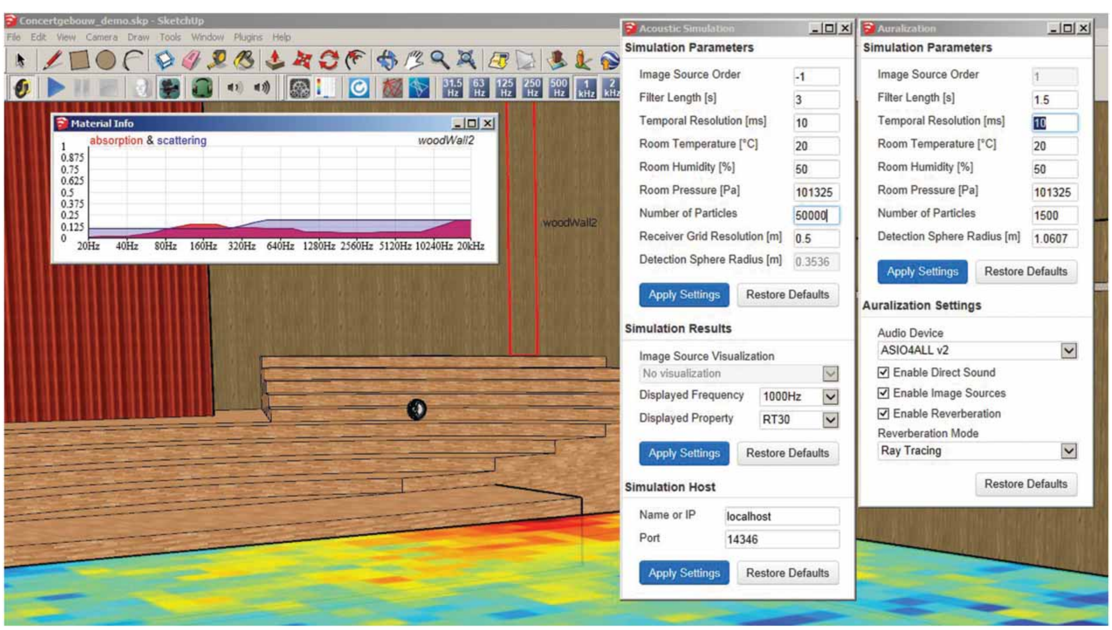

Figure 5. Room acoustics simulation of a concert hall and calculation of the respective room acoustical parameters using an easy-to-use plug-in for the CAD modeler SketchUp (Pelzer et al. 2013) that triggers the real-time room acoustics simulation framework RAVEN (Schröder 2011).

impulse response (RIR)) can be divided into three parts – the direct sound, the early reflections and the late reverberation. Following the human's perception of sound in a room, each part of the RIR features individual requirements. For instance, small deviations of timing and spectral information for the direct sound and early reflections affect the subjective sound source localization. In contrast, our hearing evaluates the late part of the RIR (late reverberation) with a much lower temporal resolution, where only the overall intensity by specular and scattered reflections in a certain time slot has to be energetically correct (Vorländer 2008). State-of-the-art room acoustics simulation algorithms therefore adapt to these psychoacoustical facts resulting in a significant improvement of both the overall simulation accuracy and the auralization quality. In the following, this will be explained in more detail by the example of the most commonly used room acoustics simulation model – that of GA.

Geometrical acoustics

Above the Schroeder frequency (Kuttruff 2000), room modes are statistically overlapping and the methods of GA can be applied. Until today, all deterministic simulation methods based on GA utilize the physical model of image sources (ISs) (Allen and Berkley 1979; Borish 1984), where each IS represents a specific sequence of specular reflections on the room's faces. The construction of RIRs from image-like models is straightforward: ISs are represented by corresponding filtered Dirac delta functions, arranged accordingly to their delay and amplitude, and sampled with a certain temporal resolution. Many variants of this type of algorithm have evolved, such as hybrid ray tracing, beam tracing, pyramid tracing, frustum tracing and so forth (Vorländer 2008), but they still remain to be image-like models. In general, ISs are good approximations for perfectly reflecting or low-absorbing surfaces in large rooms with large distances between the sound source, wall and receiver (Suh and Nelson 1999). However, round robin tests of room acoustics simulation programmes revealed the drawback of the IS-method, which is the incapability of simulating the important wave phenomena of surface and obstacle scattering (Vorländer 1995; Bork 2000).

Better results are achieved by hybrid simulation methods that combine ISs with stochastic simulation models, such as sound particle simulation methods (SPSMs) and radiosity (Figure 6). In contrast to SPSMs, radiosity assumes ideal diffuse reflections, i.e. the directional pattern of arriving sound is equally distributed over all directions and the energy decreases exponentially with time. This assumption is, however, too rough already for simple room geometries, such as long or flat rooms. This drawback does not apply for the Monte-Carlo SPSMs, often also referred to as stochastic ray tracing. SPSMs describe the sound field propagation as the dispersion of incoherent sound particles with an assigned frequency and amount of energy. Each sound particle refers to a spherical wave with

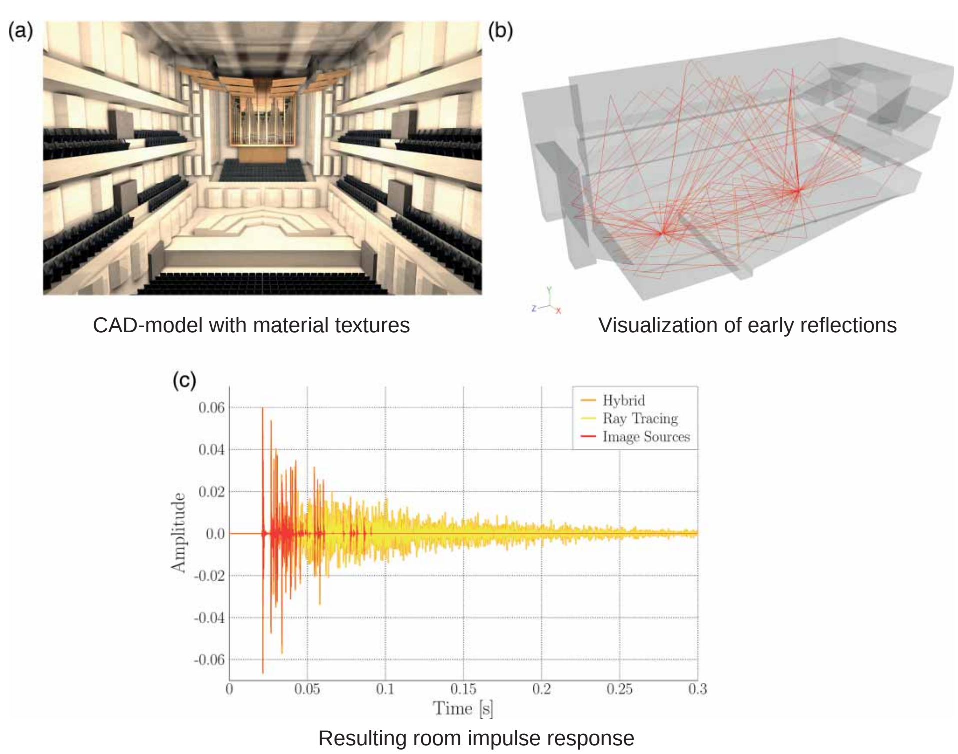

Figure 6. Simulation of a concert hall represented by (a) a CAD model for acoustic simulations, (b) the visualization of early reflection paths inside RAVEN and (c) the resulting RIR using the hybrid ISs and the ray tracing technique.

an infinitely small opening angle and decreasing intensity according to the basic $1/r^2$ distance law. In a room, each sound particle reflects off the room's faces a multitude of times, either in a specular or diffuse way, until the particle's energy is below a user-defined threshold. Volume receivers detect impacting sound particles and log their energy, the time of arrival and the impact angle resulting in a time- and frequency-dependent energy histogram. The size of both the histogram's time slots and frequency bands is based on the properties of human hearing, i.e. time slots are used with the size of a few milliseconds, and the overall frequency range is separated into (one-third) octave bands. In other words, SPSMs compute the low-resolution (temporal) energy envelope of the RIR. For high-quality auralizations, however, the temporal fine-structure has to be reconstructed, e.g. by using Poisson-distributed noise sequences (Vorländer 2008; Schröder 2011) as good approximations.

As a matter of principle, basic methods of GA fail to correctly simulate sound propagation from hidden sound sources to a receiver where the direct line of sight is blocked by other objects. The reason is that traditional methods of GA neglect the important wave phenomenon of sound diffraction since reflections are assumed to propagate only along straight lines. Several approaches exist for incorporating diffraction into deterministic and stochastic simulation methods, where the deterministic secondary source model by Svensson, Fred, and Vanderkooy (1999) and the uncertainty-based diffraction model by Stephenson (2010) have proven in various test scenarios to provide quite accurate results when integrated in methods of GA (Schröder et al. 2012).

Small rooms

For the acoustic rendering of rooms in flats and offices, or small rooms in general, methods of GA are not sufficient and wave-based models must be additionally taken into account, because relevant parts of the frequency response yield a significant modal structure below the Schroeder frequency (Kuttruff 2000). For example, a combination of the FDTD, or the FEM and GA is applicable. With extensive measurements and modelling of the acoustic characteristics of the wall, floor and ceiling materials, a good agreement between measured and simulated results can be achieved (Pelzer, Aretz, and Vorländer 2011; Aretz 2012). However, further investigations regarding the boundary and source representation, and the phenomenon of sound diffraction are necessary to improve the simulation accuracy. These shortcomings are a common problem in all acoustic simulation methods based on wave models (Vorländer 2013).

Sound insulation prediction models in building acoustics

In a typical room-to-room situation, the perceived signal of a listening event, for instance, music or speech "through the wall", is more quiet and low-pass filtered than in the single-room situation. A computer simulation should therefore give an authentic representation of loudness and colouration. In contrast to simulations inside a room, spatial effects have only a minor importance. Instead, specific primary sounds and a "diffuse" reverberant field can be assumed, which significantly simplify the simulation and auralization of sound insulation.

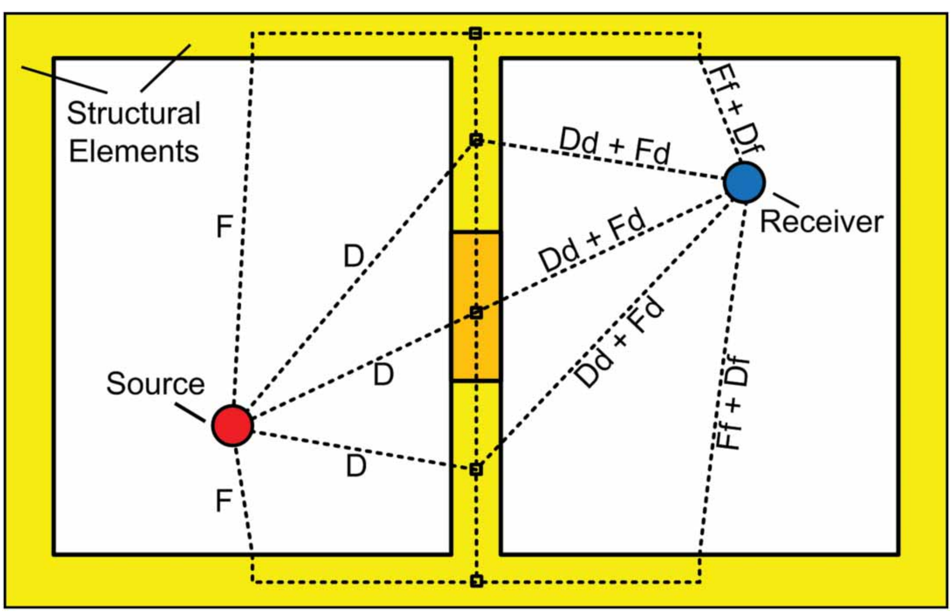

Figure 7. Sound transmission paths in two adjacent rooms including direct (D/d) and flanking paths (F/f) up to first-order junctions. Capital and lowercase letters denote sound paths in the sender room and the receiver room, respectively.

A well-suited method for the determination of the transfer function between the source and the receiving room must adequately cover these aspects. A physical model that is available for this task is the first-order SEA approach. Here, the sound energy is considered by its magnitude, its flow through the building elements, the energy exchange between adjacent building elements and the respective energy losses. Under steady-state conditions, the energy balance requires just knowledge of the mean energy, the mean losses and the coupling mechanisms of the systems. The basic publications which were used for the development of the European harmonized standard EN 12354 (European Standard EN, 2000) are papers by Gerretsen (1986, 1979). As an illustration, Figure 7 shows the energy paths for a typical room-to-room situation. The standardized sound level difference, D_{nT}, for example, can be calculated by adding all energy contributions from the direct and flanking paths. For each path holds that the sound pressure in the receiving room can be approximately described by the sound pressure source signal multiplied by a frequency-dependent factor. In the end, these components are filters related to the transfer functions between the source room and the radiating walls. With an appropriate model of the radiation path from the wall to the listener in the receiving room, the total signal can be obtained after superposition of the direct and flanking paths, and their contribution to the total reverberation can be added in order to achieve a plausible spatial sound with respect to colouration and level (Vorländer and Thaden 2000; Thaden 2005).

Real-time auralization

The method of auralization can be integrated into the technology of "virtual reality" as long as the auralization framework does not under-run the quality constraints given by human perception. In addition, latencies in the input–output auralization chain, for instance, from motion tracking, audio hardware, signal convolution and audio reproduction further reduce the maximum permissible computation time for both room acoustics and building acoustics simulations.

The task of producing a realistic acoustic perception, localization and identification is already a big challenge for off-line auralization and real-time processing is only possible with significant reductions of complexity. In particular, the modelling and handling of the room geometry has to be kept as simple as possible to reduce processing times, while simulations have to reach a certain quality. Here, physical and psychoacoustic evaluations usually help to find the space between simplifications and the period. In the following, data management and convolution problems are briefly discussed with respect to real-time processing.

Data management

One fundamental geometric operation in GA is the computation of intersection points of rays/particles with the rooms' faces. Just imagine the application of SPSM in a scene with many (more than 100) polygons, where thousands of particles have to be traced up to a high reflection order resulting in millions of intersection tests. In a naive brute-force approach, the polygons are listed in a serial order, and half of this list must be checked on average until the right candidate is found. Apparently, this is far too slow for real-time processing and more clever data structures have to be used. Spatial data structures, for instance, significantly reduce the complexity of such geometric operations by encoding the space in hierarchical or cell-like ordered subspaces, such as kd-trees and spatial hashing (Foley et al. 1996).

Another aspect is the data handling of dynamically coupled rooms, where the rooms' connections (in the following referred to as portals), such as doors, can be opened or closed at runtime. In the case of open room connections, the requirements for the simulation are very high due to a physically complex situation of bent decay curves and multiple reverberation times. Sub-division of the complex scene into rooms coupled by portals (Figure 8) has proven to be an appropriate way to optimize this rendering process (Schröder and Vorländer 2007; Schröder 2011).

Real-time convolution

In the early days of digital signal processing, at the beginning of the 1960s, the computational resources were far too limited to simulate the reverberation of a room in real-time by means of finite impulse response (FIR) filtering (convolution) with an entire RIR. Alternative artificial reverberation concepts were developed, which imitated the reverberation of a room and were appropriate for the hardware capabilities of the time.

Using partitioned convolution algorithms (Gardner 1995; Garcia 2002; Wefers and Vorländer 2012), real-time auralization of reverberant spaces can be realized by pure FIR filtering. Using current multicore PCs, a multitude of sound sources (e.g. a classical orchestra) can be simulated in real-time within a concert hall with more than one second of reverberation time (Schröder et al. 2010). In the simplest case, each sound propagation path (from one source to one listener) is represented by an individual RIR. The convolution engine processes the monaural audio signals of the virtual sources with these filters. For each listener, the signals of adjacent sound paths are summed up. As the sound propagation changes (e.g. movement or rotation of the listener), the room acoustic simulation is rerun and the filters, or parts of them, are exchanged. The non-uniform filter partitioning is chosen to support the required filter update rates for the application. Direct-sound and early reflection filters are updated with high rates (>25–100 Hz). For the diffuse reverberation tail, significantly lower rates (1–5 Hz) do not mostly diminish the perceived quality of the simulation, as the diffuse sound field changes slowly only with respect to a walking user for instance. A smooth changeover of filters without any audible artefacts is achieved by crossfading in

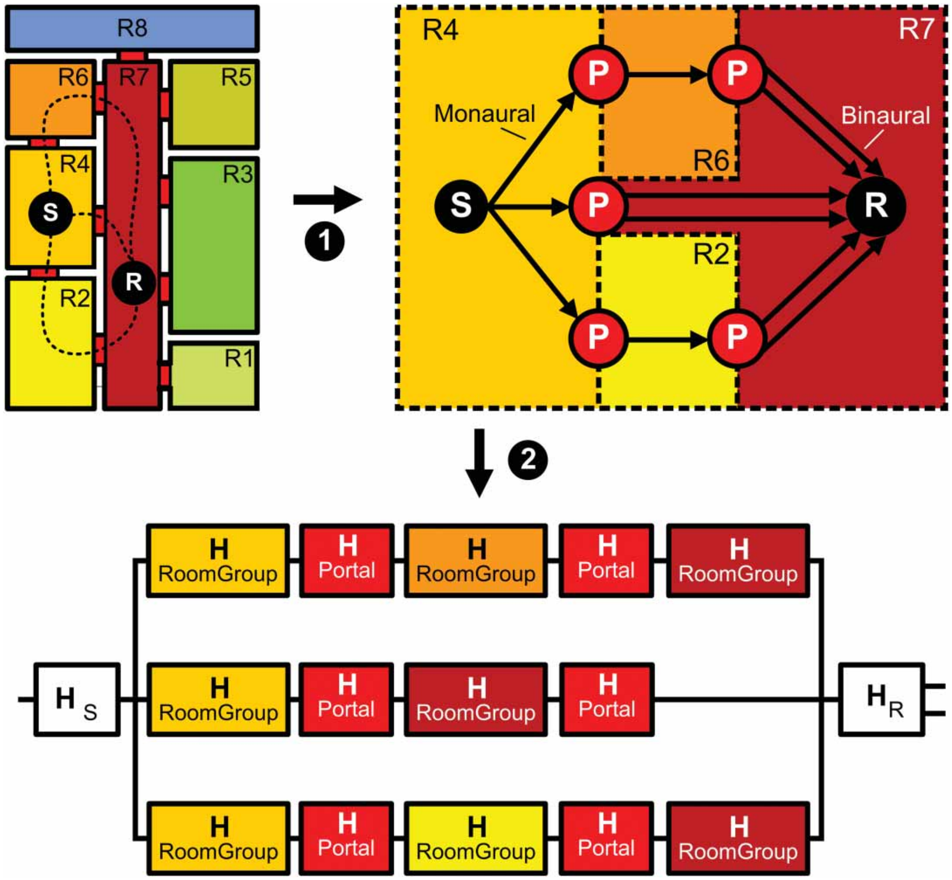

Figure 8. Example of tracking sound propagation paths throughout an office floor and constructing a corresponding filter network. Here, a sound source is located in room R4, while the receiver R is located in room R7. At first, all relevant propagation paths are determined and encoded in a graph structure (shown on the top left-hand side of the figure). In a subsequent step, this graph serves as a construction plan for the respective filter network (shown at the bottom of the figure) that represents the overall sound propagation from the source to the receiver. Source: Figure taken from Schröder (2011).

between the convolution results of the current and the next filter.

Unlike time-domain filters, partitioned frequency-domain filters are subjected to restrictions when it comes to assembling them into networks of filters (parallel and serial structures). Implementing an auralization filtering network (Figure 8) with individual, partitioned frequency-domain filters allows for a rapid change of individual parameters (e.g. opening/closing a door), but can easily lead to bottlenecks in the real-time processing, which eventually puts a strong limit on the possible number of virtual sound sources. When a large throughput (a multitude of virtual sound sources) is desired, the real-time filtering for each sound path should have the lowest possible computational requirements and consist of a low number of cascaded filters only. For comprehensive scenes, it is more beneficial to transform each filtering network into an equivalent single filter. This process is called filter rendering. Using advanced rendering strategies, which make use of memorizing intermediate results, also complex sound propagation and transmission scenarios can be auralized and interactively altered in real-time (Wefers and Schröder 2009; Schröder 2011). This, for instance, allows a user to perform a virtual walkthrough in a wide-range building environment, where he can open and close windows and doors.

Summary and outlook

After some decades of development in architectural acoustics simulation, a significant progress has been made indeed. This fact is related to the results of the activities in many groups working in the field of room acoustics and VR systems. The developed simulation programmes are successfully applied in numerous applications for room acoustics design. General user guides and user interfaces, however, are still uncertain and they do not provide a good basis for using a specific software. Software specifications differ particularly as regards the transition of early/late response modelling and the treatment and combination of specular and diffuse reflections. As long as the user is not sure how many sound particles shall be chosen, how the resolution of the geometrical CAD model is to be defined, how the scattering coefficients are found and the transitions order between early and late parts is chosen, uncertain results may occur. However, it is not a task of research to find out those differences. Instead, it should be clearly written in the user guideline of the applied simulation software.

For sound insulation auralization, research and development is still required. This is related to the fact that several approximations are made in calculating the total transmission loss including flanking transmission and the auralization of impact noise and equipment noise. These fields are not trivial at all to be included because of a lack of robust prediction models.

After all, however, VR concepts in architectural acoustics allow for new perceptual studies, investigations of well-being and annoyance and comfort in integrated architectural design processes.

References

Allen, J. B., and D. A. Berkley. 1979. "Image Method for Efficiently Simulating Small-Room Acoustics." *Journal of the Acoustical Society of America* 65 (4): 943–950.

Aretz, M. 2012. "Combined Wave and Ray Based Room Acoustic Simulations of Small Rooms." PhD thesis, RWTH Aachen University, Logos publishers, Berlin, Germany.

Ben Hagai, I., M. Pollow, M. Vorländer, and B. Rafaely. 2011. "Acoustic Centering of Sources Measured by Surrounding Spherical Microphone Arrays." *Journal of the Acoustical Society of America* 130 (4): 2003–2015.

Blauert, J. 1996. *Spatial Hearing – The Psychophysics of Human Sound Localization, Revised Edition*. Cambridge, MA: MIT Press.

Borish, J. 1984. "Extension of the Image Model to Arbitrary Polyhedra." *Journal of the Acoustical Society of America* 75 (6): 1827–1836.

Bork, I. 2000. "A Comparison of Room Simulation Software – the 2nd Round Robin on Room Acoustical Computer Simulation." *Acta Acustica United with Acustica* 86 (6): 943–956.

Botteldoren, D. 1995. "Finite-Difference Time-Domain Simulation of Low Frequency Room Acoustic Problems." *Journal of the Acoustical Society of America* 98 (6): 3302–3308.

Common Loudspeaker Format (CLF). Accessed February 2014. http://www.clfgroup.org/

Dietrich, P., B. Masiero, and M. Vorländer. 2013. "On the Optimization of the Multiple Exponential Sweep Method." *Journal of the Audio Engineering Society* 61 (3): 113–124.

von Estorff, O. 2000. *Boundary Elements in Acoustics: Advances and Applications*. Southampton, UK: WIT Press.

European Standard EN. 2000. "Standard Reference EN 12354-1:2000, Acoustic Properties of Building Elements and of Buildings. Building Acoustics – Estimation of Acoustic Performance of Buildings from the Performance of elements – Part 1: Airborne Sound Insulation between rooms (citation in OJEU(1)) 89/106/EEC (No)."

Fastl, H., and E. Zwicker. 2007. *Psycho-Acoustics*. 3rd ed. Berlin: Springer.

Foley, J. D., A. van Dam, S. K. Feiner, and J. F. Hughes. 1996. *Computer Graphics, Principles and Practice*. 2nd ed. Reading, MA: Addison-Wesley.

Funkhouser, T. A., N. Tsingos, I. Carlbom, G. Elko, M. Sondhi, J. E. West, G. Pingal, P. Min, and A. Ngan. 2004. "A Beam Tracing Method for Interactive Architectural Acoustics." *Journal of the Acoustical Society of America* 115 (2): 739–756.

Garcia, G. 2002. "Optimal Filter Partition for Efficient Convolution with Short Input/Output Delay." Audio Engineering Society, Convention Paper 5660, Los Angeles, CA, USA.

Gardner, W. G. 1995. "Efficient Convolution without Input-Output Delay." *Journal of the Audio Engineering Society* 43 (3): 127–136.

Gazzaniga, M. S., R. B. Ivry, and G. R. Mangun. 1998. *Cognitive Neuroscience: The Biology of the Mind*. New York: W. W. Norton.

Gerretsen, E. 1979. "Calculation of Sound Transmission between Dwellings by Partitions and Flanking Structures." *Applied Acoustics* 12 (6): 413–433.

Gerretsen, E. 1986. "Calculation of Airborne and Impact Sound Insulation between Dwellings." *Applied Acoustics* 19 (4): 245–264.

Kleiner, M., B. I. Dalenbäck, and U. P. Svensson. 1993. "Auralization – An Overview." *Journal of the Audio Engineering Society* 41 (11): 861–875.

Krokstad, A., S. Strøm, and S. Sørsdal. 1968. "Calculating the Acoustical Room Response by the Use of a Ray Tracing Technique." *Journal on Sound and Vibration* 8 (1): 118–125.

Kuttruff, H. 2000. *Room Acoustics*. 4th ed. Abingdon: Taylor & Francis.

Lentz, T., D. Schröder, M. Vorländer, and I. Assenmacher. 2007. "Virtual Reality System with Integrated Sound Field Simulation and Reproduction." *EURASIP Journal on Advances in Signal Processing*, Article ID 70540, 19 pages.

van Nederveen, G. A., and F. P. Tolman. 1992. "Modelling Multiple Views on Buildings." *Automation in Construction* 1 (3): 215–224.

OpenDaff. Accessed February 2014. www.opendaff.org

OpenMat. Accessed February 2014. www.openMat.info

Oppenheim, A. V., and R. W. Schafer. 1975. *Digital Signal Processing*. Englewood Cliffs, NJ: Prentice-Hall.

Pätynen, J., and T. Lokki. 2010. "Directivities of Symphony Orchestra Instruments." *Acta Acustica united with Acustica* 96 (1): 138–167.

Pelzer, S., M. Aretz, and M. Vorländer. 2011. "Quality Assessment of Room Acoustic Simulation Tools by Comparing Binaural Measurements and Simulations in an Optimized Test Scenario." Proceedings of the Forum Acusticum, Aalborg, Denmark.

Pelzer, S., L. Aspöck, D. Schröder, and M. Vorländer. 2013. "Interactive Real-Time Simulation and Auralization for Modifiable Rooms." Proceedings of the ISRA, Toronto, Canada.

Pelzer, S., and M. Vorländer. 2010. "Frequency- and Time-Dependent Geometry for Real-Time Auralizations." Proceedings of 20th international congress on acoustics (ICA), Sydney, Australia.

Pohl, A., D. Schröder, S. Drechsler, U. P. Svensson, M. Vorländer, and U. M. Stephenson. 2012. "openMat – an open XML-database for Acoustical Properties of Materials and Objects." Proceedings of the Internoise, New York City, USA.

Prandoni, P., and M. Vetterli. 2008. *Signal Processing for Communications*. EPFL Press, Lausanne, Switzerland. http://www.sp4comm.org/getit.html

Savioja, L., J. Huopaniemi, T. Lokki, and R. Väänänen. 1999. "Creating Interactive Virtual Acoustic Environments." *Journal of the Audio Engineering Society* 47 (9): 675–705.

Schröder, D. 2011. "Physically Based Real-Time Auralization of Interactive Virtual Environments." PhD thesis, RWTH Aachen University, Aachen, Germany.

Schröder, D., A. Pohl, U. P. Svensson, U. M. Stephenson, and M. Vorländer. 2012. "On the Accuracy of Edge Diffraction Simulation Methods in Geometrical Acoustics." Proceedings of the Internoise, New York City, USA.

Schröder, D., and M. Vorländer. 2007. "Hybrid Method for Room Acoustic Simulation in Real-Time." Proceedings of the 20th international congress on acoustics (ICA), Madrid, Spain.

Schröder, D., F. Wefers, S. Pelzer, D. Rausch, M. Vorländer, and T. Kuhlen. 2010. "Virtual Reality System at RWTH Aachen University." Proceedings of the international symposium on room acoustics (ISRA), Melbourne, Australia.

Stephenson, U. M. 2010. "An Energetic Approach for the Simulation of Diffraction within Ray Tracing based on the Uncertainty Relation." *Acta Acustica United with Acustica* 96 (3): 516–535.

Suh, J. S. and P. A. Nelson. 1999. "Measurement of Transient Response of Rooms and Comparison with Geometrical Acoustic Models." *Journal of the Acoustical Society of America* 105 (4): 2304–2317.

Svensson, U. P., R. I. Fred, and J. Vanderkooy. 1999. "An Analytic Secondary Source Model of Edge Diffraction Impulse Responses." *Journal of the Acoustical Society of America* 106 (5): 2331–2344.

Thaden, R. 2005. "Auralisation in Building Acoustics." PhD thesis, RWTH Aachen University, Aachen, Germany.

Vian, J., and D. van Maercke. 1986. "Calculation of the Room Impulse Response using a Ray-Tracing Method." Proceedings of the ICA symposium on acoustics and theatre planning for the performing arts, Vancouver, Canada.

Vorländer, M. 1989. "Simulation of the Transient and Steady-State Sound Propagation in Rooms using a New Combined Ray-Tracing/Image-Source Algorithm." *Journal of the Acoustical Society of America* 86 (1): 172–178.

Vorländer, M. 1995. "International Round Robin on Room Acoustical Computer Simulations." Proceedings of the 15th international congress on acoustics, Trondheim, Norway.

Vorländer, M. 2008. *Auralization - Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*. Berlin: Springer.

Vorländer, M. 2013. "Computer Simulations in Room Acoustics: Concepts and Uncertainties." *Journal of the Acoustical Society of America* 133 (3): 1203–1213.

Vorländer, M., and R. Thaden. 2000. "Auralisation of Airborne Sound Insulation in Buildings." *Acustica united with Acta Acustica* 86 (1): 70–76.

Wefers, F., and D. Schröder. 2009. "Real-Time Auralization of Coupled Rooms." Proceedings of the EAA auralization symposium, Espoo, Finland.

Wefers, F., and M. Vorländer. 2012. "Optimal Filter Partitions for Non-Uniformly Partitioned Convolution." Audio Engineering Society conference: 45th international conference: Applications of time-frequency processing in audio. Audio Engineering Society, Helsinki, Finland.

Zienkiewicz, O. C., and R. L. Taylor. 2000. *Finite Element Method Volume 1 – The Basis*. 5th ed. Oxford, UK: Butterworth-Heinemann.