Real-time Evaluation of Room Acoustics using IFC-based Virtual Reality and Auralization Engines

Documentation Report

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DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

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ISSN 1901-726X
DCE Technical Report No 286

Aalborg University
Department of Civil Engineering
Architectural Engineering

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Autumn 2019

Scientific Publications at the Department of Civil Engineering

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Published 2019 by
Aalborg University
Department of Civil Engineering
Thomas Manns Vej 23
DK-9220 Aalborg Øst, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 286

Recent publications in the DCE Technical Report Series

ISSN 1901-726X

DCE Technical Report No. 286

Contents

1 Introduction

Virtual Reality (VR) has seen increased use in recent years in the building industry for various simulation purposes. Through multiple studies, VR has proven to be an efficient tool for building design with user participation [1] [2], design of building evacuation signage [3] [4], the psychological aspects of building evacuation [5], and understanding decision-making and human behaviour [6]–[8] in a more cost effective way than real-life mock-ups [4] [9]. VR additionally provides an immersive communications platform for building designers, granting a better perceptual experience, which can improve decision-making [10].

Research and use of VR in the building industry, however, tend to focus only on building geometries [11], [12] and the visual aspect of VR [13]. VR is nevertheless not limited to presentation of the visual aspects. Use of sound and acoustic stimuli can enhance the visual perception and can sometimes be more important in VR than visual inputs [14] [15]. Use of VR with auralization is nevertheless not a common practice in the building industry.

Another topic receiving increased focus in the building industry is the indoor environment (IE), consisting of the thermal IE, atmospheric IE, visual IE and acoustic IE [16]–[18]. Increased use of 3D models and Building Information Management (BIM), has granted more possibilities for simulation of the IE. Simulation of room acoustics is, however, still mainly presented as graphs and tables, which can be hard to perceive without acoustic expert knowledge.

Computer simulation of room acoustics has been feasible since the 1990s. Before that, uncomplicated calculations and scale models were used to do acoustic analyses. Some acoustic problems can be solved using equations and scale models. More specific investigations in room acoustics are, however, often needed due to human's sensitive perception, in order to meet a desired acoustic performance [11].

Acoustic simulation of a room mostly occurs in acoustically challenging spaces, such as concert halls, train stations and theatres, often primarily focussing on music perception and communication through speech [11] [12], whilst standard rooms are designed based on acoustic demands set in the building regulations. The room acoustics of educational facilities, public buildings and homes are nevertheless also relevant to investigate [19]. An acoustic design that allows unwanted sounds, also known as noise, can cause interruption, irritation and lower performance of people working in the room [20] [21].

In some situations auditory perception is not finally understood, as sound disturbance is not necessarily based on a specific sound, but how the sound is perceived by the person hearing the sound [20]. A need for a better medium to evaluate the acoustic performance therefore arises. A method allowing better perception of sound, can be found in using auralization [11]. In this report auralization is defined in concurrence with Schröder (2011) as: *"Analogous to visualization… the generating of aural stimuli that corresponds to the current sound propagation throughout the simulated scene"* and *"the process of making an acoustic space audible, thus enabling listening to the space under design"* as defined by Kleiner, Dalenbäck and Svensson (1993).

Realistic auralization is very challenging to accomplish, as people (in this respect, building-designers, owners and end-users), have a very sensitive perception of sound [12]. Based on our research there is currently no complete tool, than the tool presented in this report, making it possible to consider the visual design and the acoustic dependencies of a room simultaneously, by combining VR and auralization.

This report, therefore, presents the process, findings and user-guide of the development of a real time Virtual Reality with Auralization system allowing building-designers, owners and end-users to *listen* to a design proposal and provide such people a better foundation for decision-making and a heightened ability to consider the acoustic IE during building design.

2 Methodology

Both theoretical and empirical data were collected as part of the research presented in this report. In this chapter, the methodologies used are introduced and explained. Methods used for testing the VR with Auralization system are introduced in chapter 4, describing the development of the system.

2.1 Theoretical data search

Theoretical data was collected through an initial literature search based the keywords: Acoustics, Virtual Reality, Auralization, and System Development. Through the initial search, key references were identified, which were then used in backward and forward snowballing [24].

2.2 Empirical data search

Empirical data were gathered using a wide range of methodologies, supporting several specific data needs for development of a combined VR with Auralization system and analysis of use and implementation of the system in a case study company.

An engineering company, hereafter known as the company, with branches in Denmark and Norway (and other countries), participated in the study. Six persons with expert knowledge in acoustics and building information management were interviewed over a period of 9 months, in order to understand how the case company works and to define or specify the needs of the system being developed. According to the contextual design method, used in this study, described by Holtzblatt & Beyer (1997) this is not a sufficient number of respondents to document a work-process. However, system testing and informal dialogs during project workshops, documented by the research team, provided additional data from five respondents. The five additional respondents also had the advantage of being able to compare the work processes following the implementation of the VR with Auralization system, with the current acoustic evaluation process used in the company, providing a better contextual understanding of the system with respect to the company.

All empirical data were gathered using qualitative methods. The interview method as defined by [26], allowing respondents to tell their story, and attain specific knowledge about work-processes and needs with respect to the tested system, as well as attaining background knowledge regarding the respondents' interactions [27]. The contextual inquiry method was used as a supplement to the interview-method, going through the processes: conventional interview, transition and wrap-up [25]. Contextual inquiry was applied as interview method, without using "Proper", due to time-restrictions during data gathering.

To analyse the data acquired from the respondents, the contextual design method was also used [25], applying the flow, sequence, cultural and artifacts charts, to visualise the context and data and work-flow of the company. Flow, sequence and artefact charts, from the contextual design method, were additionally used in interview as "wrap-up", in order to present the respondents with the answers they had given and allowed for specifying, correction or supplementing the data. Wrap-up was performed using e-mail documenting the data.

Testing, development and data gatherings were conducted in multiple iterations as shown in figure 2.1

Session-type	Participants	Number of participant
Internal system-test	Researchers and Developers	5
Informal User-Experience Test	Stakeholders, Researchers and Developers	11
Interview session	End-users and Stakeholders	3
Interview session	End-users	2
Internal System Demonstration	Stakeholders, End-users, Researchers and Developers	16
Informal User-Experience Sound-Distribution Test	Researchers and Developers	5
Sound recording	Researchers and Developers	5
Interview session	End-users and Researchers	3
Informal User-Experience Test	Researchers and Developers	5
External System Workshop	Researchers and Developers	17
Informal User-Experience Test	Researchers and Developers	5
Internal System Workshop	Researchers and End-users	8
Final System Demonstrationer	Reseachers, End-users, Project-Managers and Developers	17

Figure 2.1 Testing, data gathering and development sessions and type and number of participants during the development of the Virtual Reality with Auralization system.

All sessions are further described in chapter five, presenting how the system was developed.

2.3 Testing

Both internal and external system tests were performed, in order to test the usability of the system. The tests additionally created an opportunity for researchers and developers to discuss the system with both stakeholders and end-users, making it possible to fit the system to the exact needs of the users, benefitting the stakeholders.

All testing of the VR with auralization system involved a setup including the Oculus Rift CV1 head-mounted display (HMD) or the Oculus Quest (HMD) for the visual part and Seenheiser PC 363 and Bose QC35 ii, for playing the sounds during the real time auralization.

Different scenarios were used in the different sessions, allowing testing of realism and reliability of the system. The primary test scenario was a lecture room at the Department of Civil Engineering at Aalborg University. The lecture room in the tests, shown in figure 2.2, has a size of 94m^2 with four sound sources inserted

Figure 2.2 The lecture room's four sound placement locations in the real building.

into the scenario. The scenario was generated using a 3D model of the building, imported into the system using IFC.

In order to evaluate sound-transmittance through walls and windows, four different sound source-placement scenarios were tested, as shown in figure 2.3. This scenario allowed the test persons to walk around in the area in front of the sound sources and listen to different solutions of sound source placement, in order to

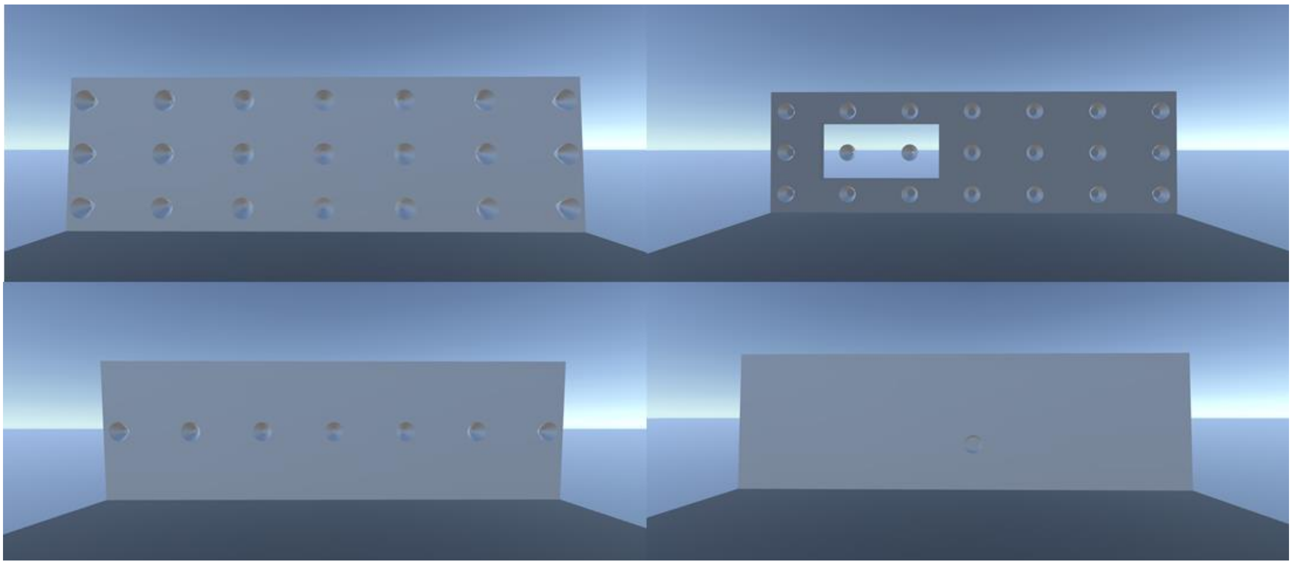

Figure 2.3 The four different test scenarios. Upper left: 21 sources. Upper right: 21 sources with window. Lower left: 7 sources. Lower right: single source, following avatar.

select a solution with a realistic sound-distribution.

A CAVE (Computer Automated Virtual Environment) designed by Epiito was additionally used during some of the workshops, showcasing how the system works through other mediums than HMD [28].

2.4 Recording setup

To do auralization it is imminent to have recordings in a high quality, with a known calibrated recording chain without influence of reverberation from surroundings. Such recordings of electronic systems and household appliances does not exist in any public database. A setup was, therefore, built at the Department of Electronic Systems, at Aalborg University, to facilitate the recording of anechoic sound-recordings.

The anechoic room used in this project has sound absorbing wedges creating a reflection-free environment down to approx. 65Hz.

Eight G.R.A.S. 40AZ microphones with preamplifier type 26CC were used in unison with an RME Mictasy sound card (44.1 kHz 24 bit) using a multi-track recording software on a PC.

Various entities (appliances and electronic equipment) were recorded, selected based on the sound-bits needed for doing auralization of typical one-family households. Each entity was placed in the middle of the anechoic room either on a sound absorbing material, or on a wooden board to account for a natural placement on e.g. tables, on top of a steel grate, with the microphones distanced at 500 mm, as shown in figure 2.4 and 2.5.

Figure 2.4 Recording sound of a projector in the anechoic room

Six different appliances and type electronic equipment were recorded. Two ventilations hoods were additionally recorded multiple times with different airflows. Sounds from a canteen-scenario and a construction site were recorded as well in their natural environments.

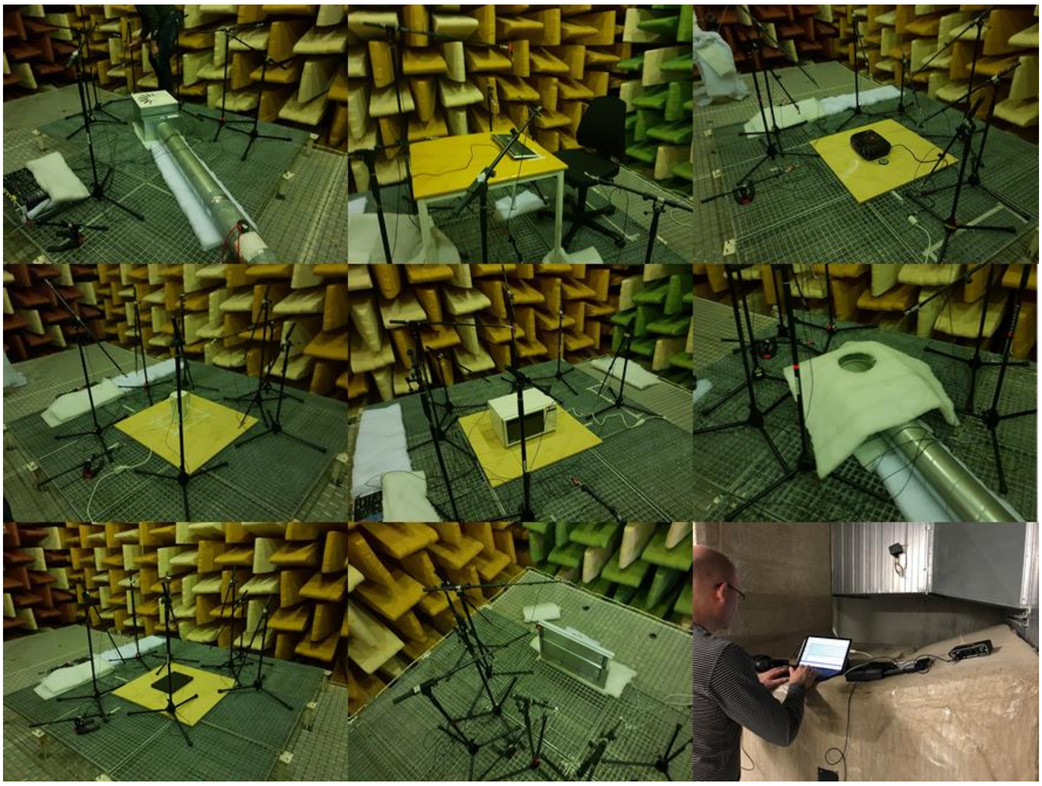

Figure 2.5 Pictures of all recording setups.

2.5 Structuring of the calibrated recording chain

This section explains how the chain of calibrated recordings without influence of reverberation is handled, from the recording is made in an anechoic room to it is imported in the Virtual Reality with Auralization system.

The system is calibrated using a maximum peak-level in the system, in this case the most powerful sound comprehensible by the system (e.g. 120 dB). Relative to this level, a sound-file is made using a calibration-tone of 94 dB, from which the system is calibrated, This means that the sound is played and the sound-level set for the headphones are measured and adjusted to 94 dB equivalent free-field-level. The voltage on the headphone-terminals are measured simultaneously, ensuring the ability to control the calibration using a voltmeter. The headphones used with the system and the frequency-response of the headphones needs to be equalized, making the system transparent.

The sound recorded in the anechoic room are conducted using calibrated recordings. This means the 94dB-level is fixed in the sound-files, which allows for adjusting of the sounds with respect to the 94 dB- level set in the system. An automatic adjustment is implemented in the sound import function of the system.

Accurate representation and distance dampening of the sound field in general is completely dependent on which auralization engine is used. If needed virtual measuring of sound levels is possible in the Unity Virtual Reality engine, through playing and recording a control sound in the Virtual space.

The level-adjustment and management of the recording chain is further described in chapter 4.2.

3 Case study

One of the major engineering companies in Denmark and Norway took part in development of the Virtual Reality with Auralization. The company made it possible to study how they work with modelling of buildings, and how they handle the acoustic design process. The company was studied through interviewing employees specifically working with 3D modelling and acoustic design.

Most building modelling in the company is done using Autodesk Revit supported by plug-inns and add-on-software, allowing detailed modelling, simulation and calculation based on the 3D building model. The design-flow of most projects, shown in figure 3.1, is usually based on end-user-demands and a design programme formulated by the building owner.

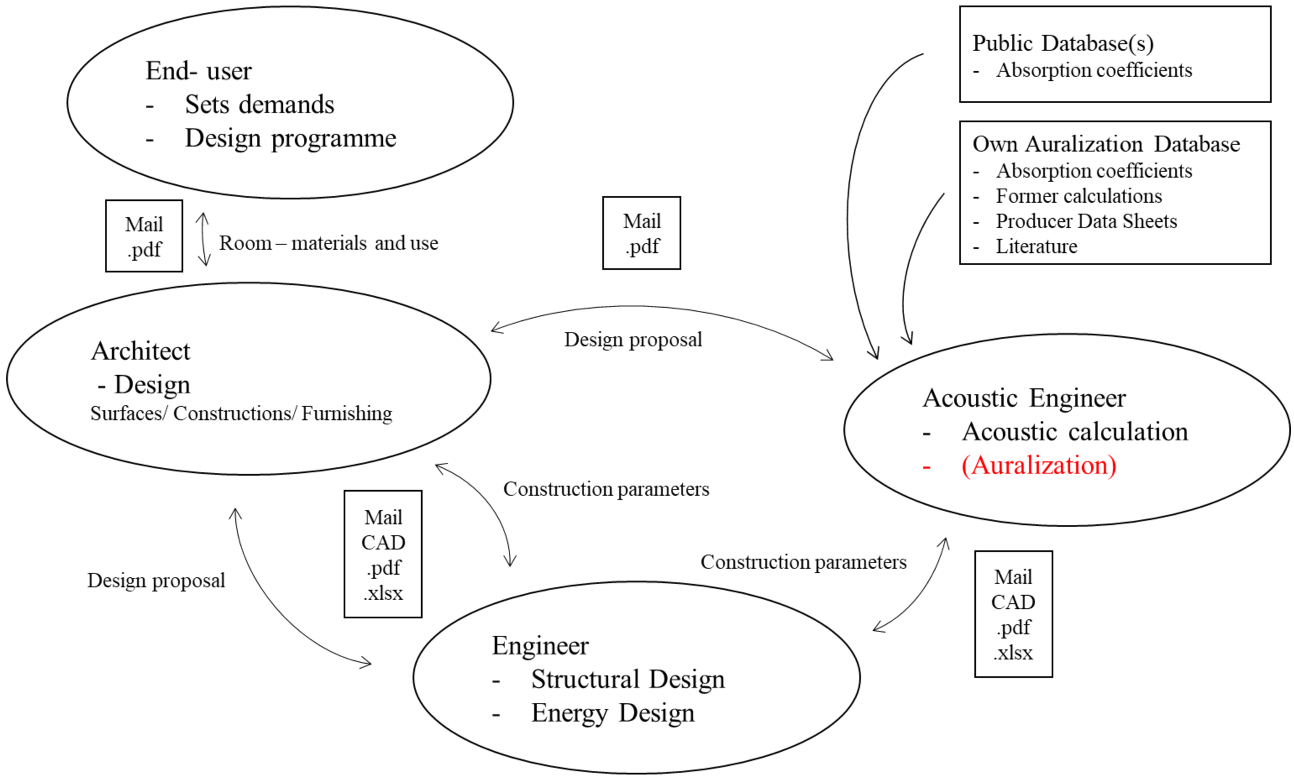

Figure 3.1 The current design-flow in the company

As shown in the figure, communication in the current design-flow involves use of various exchange-formats. E-mails and PDF's are in many design-projects the primary method for communicating design changes between designers and acousticians.

With respect to building information, the exchange-flow could be optimized through use of building information modelling principles, using a centralised model as the centre for communication and exchange. This process is described in depth in other publications, [6], [29]–[37], and is therefore not further elaborated on in this report. The process used by the company regarding data storage and exchange, could however be improved through the recommendations found in the referenced studies.

When designing room acoustics, the company's process involved designing the geometric space and evaluating it using national standards and best-practise acoustic values. Usually two or three scenarios are evaluated in design projects, however only the most acoustically challenging geometries. One of the primary factors defining, to what degree the acoustic design is evaluated, is determined by the buildings' type.

In the company's Danish branch-office, acoustic evaluations are based on calculations of reverberation based on absorption-coefficients catalogued in the company's own database. The database additionally store calculations and evaluations from earlier design projects. According to the respondents, standard-values are enough to ensure a high-quality acoustic performance in a room in most design-projects. Calculations of acoustic performance is therefore primarily done on big projects.

> *"It is only on major projects acoustic calculations are made. On smaller project only analysis by the people participating in the design-process is performed"* (Project-worker, Aalborg, 2018).

On occasion, building owners demand a higher level of acoustic performance of a room or building, which they specify in the design brief (also known as the design-programme). Building-owners, however, rarely ask for a higher level of acoustic performance than what is defined in the building regulations according to respondents from the Norwegian branch-office.

In Norway, a design-programme is mandatory using a national standard, used in all design projects the company carry out. A design-programme is optional in Danish design-projects and has no structure used by all in the industry. How the design programme is formulated and used in the Danish branch-office depends on projects' contractual specifications.

Most designs are selected based on dialog between different work-groups of designers in the company, combined with results from calculation and analysis-tools. To support the dialog, multiple documents and models are used, exchanged in various formats, including e-mail, PDF and CAD/ BIM formats (IFC, .rvt, .dwg, xlsx and .docx). The IFC format is used in the company, however mostly by the Norwegian branch.

Currently the company only uses auralization in rare situations, to understand the acoustic quality and the various acoustic dependencies of geometric challenging spaces, and to aid the presentation of a selected design to a client. The auralization used by the company is, however, not done in real-time and does not involve any immersive visualisation technology.

> "*When it comes to generating value on the projects, it is not something we are concerned with. With respect to visualisations, we* (Technical Installation Engineering) *do not have as much to win as the architects. However, being able to hear and simulate in Virtual Reality, with respect to both fire-safety, acoustics, airflow from ventilation-hoods and how changing of placement affects such, that would create value for us"* (Project-worker, Aalborg, 2018).

Owner and user-feedback is often relevant in design projects in selection of surface-materials. As changes to a surface-material affect the reverberation of a room, due to the materials' absorption-coefficient being changed, a visual link visualising the change, included in the use of auralization, can ensure people understanding the design better. However, respondents in the company did not find the visual presentation of

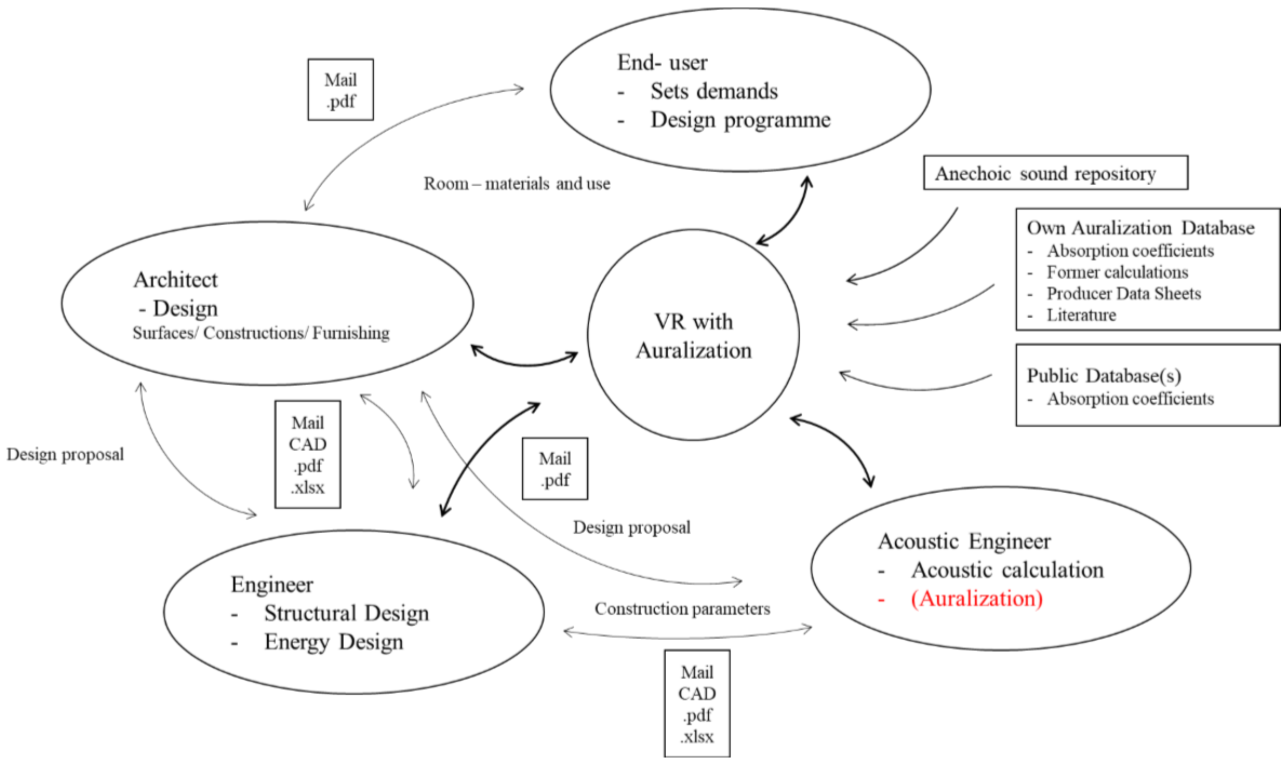

Figure 3.2 Design-flow of the virtual reality with auralization system used as the centre of communication.

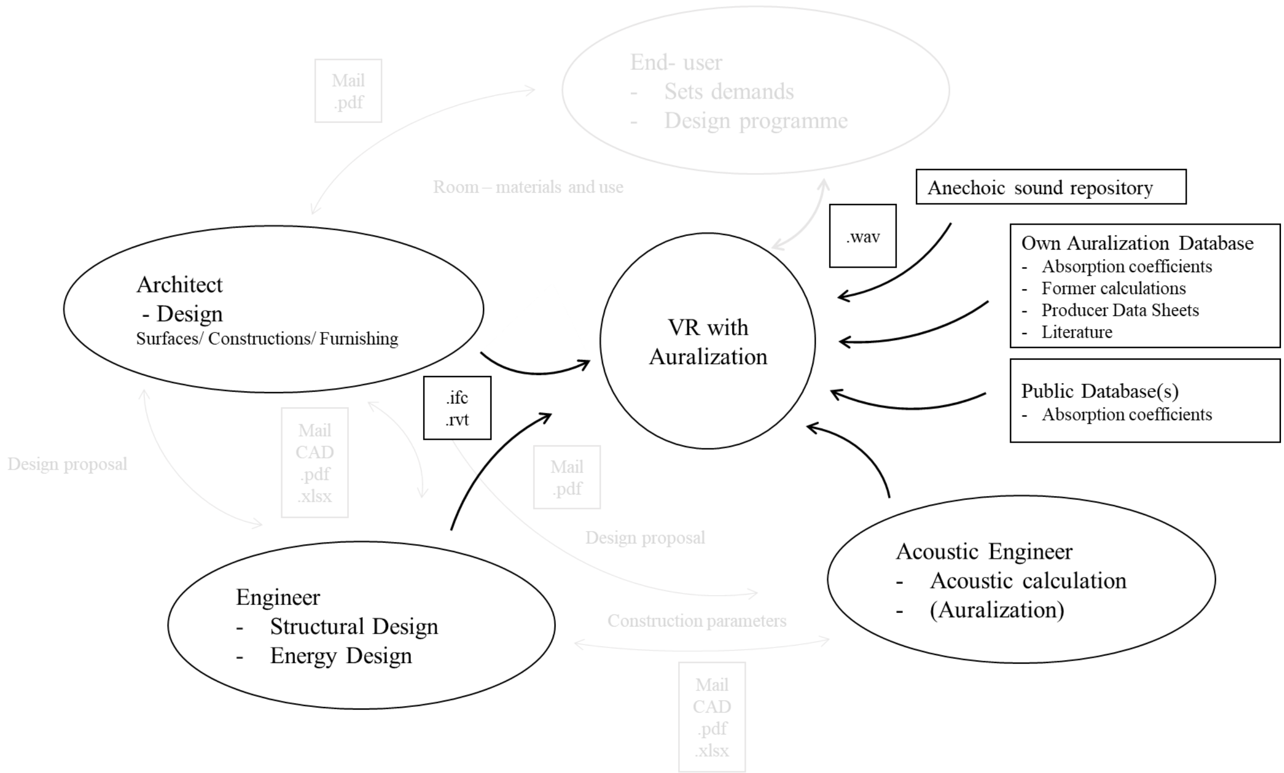

Figure 3.3 The scope of the system development and testing process.

geometry in VR as important as the realism of the auralization. This is in line with the conclusion of Pitt, M.; Goyal, S.; Holt, P.; Ritchie, J.; Day, P.; Simmons, J.; Robinson, G.; Russell (2005) stating that it would be wrong to assume that VR Environments must represent visual realism to be effective.

To support the current design-flow of the company, and provide an option to listen to a room under design whilst immersed into the environment visually, a Virtual Reality with Auralization system was designed. Rather than changing the design-flow of the company, the system is designed to be usable in the current flow, with only minor adaption needed in the branch-office in Denmark, with respect to use of the IFC format.

As shown in figure 3.2, the developed system is placed as the centre of communication in the room acoustics design-flow. In order to ensure functionality and realism of the system with immense focus on auralization, the scope of the study, as illustrated in figure 3.3, an iterative development and testing of the system were performed.

4 System-build

4.1 Software build for VR with Auralization

The system presented in the paper was developed in collaboration between Epiito A/S, COWI A/S and Aalborg University. The system is based on the Unity game engine, Epiito software and an auralization engine controlling sound- level and sound- distribution. It supports the use of the Industry Foundation Classes (IFC) format, which enhances its interoperability between multiple building and construction modelling applications in a non-vendor specific format [39]. The system is thereby usable for real time evaluation of room acoustics using IFC-based virtual reality and auralization engines as shown in figure 4.1.

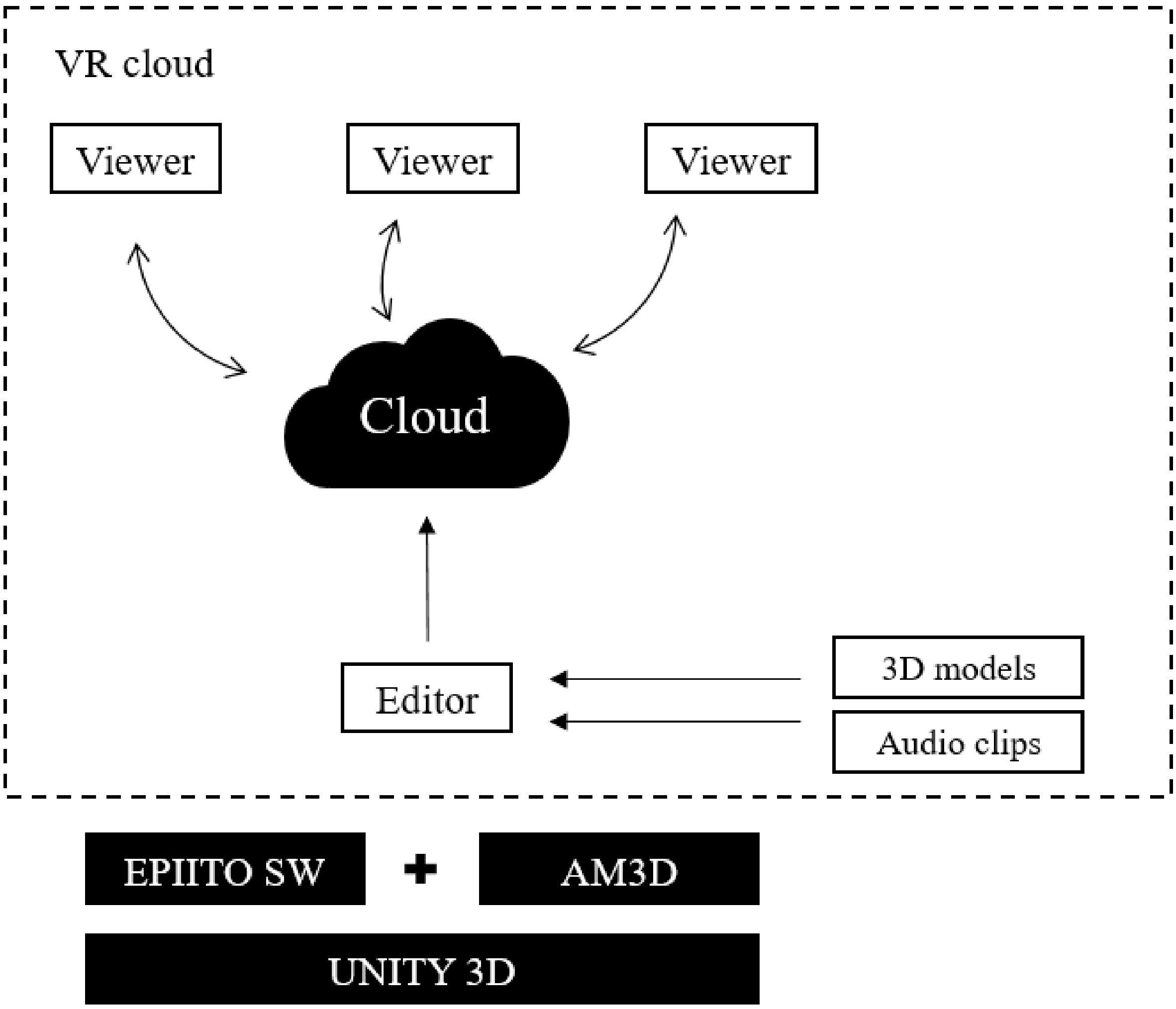

Figure 4.1 Flow model describing the system context

The Unity game engine supports use of the two auralization engines – Google Resonance Audio and AM3D spatial Audio, both allowing positioning of sound sources in a geometric room, and control of reverberation according to dimensions of a geometric room and its material properties. Both Google Resonance Audio and AM3D was tested and used in the project. Implementation details of the AM3D engine are unknown, and from a user's perspective, only one common (across frequencies) absorption-coefficient can be set. Resonance Audio is in principle open source, and some of the implementation details appear transparent. The main difference from a user's point of view is that Resonance allows for frequency dependent absorption-coefficients and definitions of new materials. From a perceptual point of view, the AM3D engine has a better true binaural reverb engine.

In both cases, absorption data and room dimensions has to be passed from the building model to the auralization engine allowing the engine to create the directional sound and the reverberation according to its internal algorithms.

When using the system it is possible to load in 512 sound sources simultaneously per user. The virtual environment (VE) is loaded from Epiitos cloud-service into the viewer, allowing each user to see the same geometries, but experience different auralization's', calculated based on the user's position in the scenario. The system additionally loads and unloads sounds depending on the calculated position of each user in the VE, ensuring only necessary sound sources playing, lowering stress on the system and the hardware.

4.2 Level-adjustment of calibrated recordings used for auralization

In this chapter, the process of selecting sound-levels and adjusting the sound levels is described in depth. The chapter, additionally, makes it possible to understand the settings behind the final sound output in the virtual reality with auralization system, and allows for adding more sound-files to the sound library insert-able in the system.

4.2.1 Selection of digital levels for the system using Unity

The system is calibrated using a maximum peak-level in the system, in this case the most powerful sound comprehensible by the system (e.g. 120 dB). If presumed a sinus-tone is played at this level, the root mean square (RMS) value will be $1/\sqrt{2}$ or -3 dB. The relationship between peak-level and RMS is called the crest-factor calculated: peak/ RMS. With peak-level set at 120 dB the sound level will thus be 120 – 3 = 117 dB sound level pressure (SPL)[1].

To use the system, sound files needs to be imported. In this report, we will use KeyboardA1.wav as an example in describing how this works. Each sound file has an associated calibration-file generated from calculated values in Matlab. A calibration example file: KeyboardA1.cal, is shown in table 4.1.

All values are normalised and refers to the maximum value of 1 (or 0 dB) in the sound file. In this example it is shown that the crest-factor of the signal is 45 - 9.4 = 35.6 dB. It is furthermore noticeable that the maximum peak-value of the file is -9.4 dB, indicating it is only possible to amplify the sound in the file by 9.4 dB (or a little less) if clipping and sound-distortion is to be avoided. It is additionally important to take account of all the files, which are imported, as a too low overall peak-level, can result in clipping and distortion of sound whilst playing in the system.

[1] Note that the $\sqrt{2}$ relation only relates to sinusoids. For other signals the crest-factor can be higher so it will not necessarily be possible to play signals with a RMS-value above 117 dB, without sound clipping, meaning the peak-values exceeds the maximum value playable in the system.

rms:	0.005613
dB_full_scale:	-45.5
peak:	0.337830
peak_dB:	-9.4
dBA_full_scale:	-53.9
EBU128LUFS:	-49.7
RecordingGain:	20.000000
dBSPL:	57.7
dBASPL:	48.8
94dBrms:	0.365058

Table 4.1 Contents of the calibration-file KeyboardA1.cal

4.2.2 Adjustment of sound levels

The value of a sound, specified in the last line of the .cal file (94dBrms) define at what level in the sound file (relative to 1) a 94 dB RMS calibration-tone would be. In this example it is: 0.365058. This value is equivalent to -8.75dB (20 Log(0.365058)). When the maximum RMS-level is set at 117 dB, we know that the calibration-tone-level in the file must be 117dB – 94dB = 23dB lower. It is, however, only 8.75dB – 3dB = 5.75 dB lower in reality. Hence the sound must be lowered by 23dB – 5.75dB = 17.25dB, in the file.
These calculations are implemented in the sound import module of the system.

4.2.3 Calibration of the absolute sound level in the headphones

This section is divided into two. Firstly, focussing on the calibration and adjustment process and secondly, how to control the system with respect to the use of headphones.

4.2.3.1 Calibration and adjustment

It is imminemt to detect the sensitivity of the headphones used, and the level must be adjusted in a way making, e.g. 94dB, the tone of reference in both the digital domain and the headphones. The adjustment must be done using the volume control on an analogue headphone-amplifier or in a similar way.

If the sensitivity of the headphone (dB re 20µ Pa/ V) is known, then it is also known which voltage should be measured from the headphone amplifier output, ensuring the proper sound level in the headphones. This is not always possible as in the case with the Bluetooth headphones from e.g. Bose. In such case, the sensitivity must be measured based on the headphones being fixed on a coupler allowing measurement of the calibration-level.

In order to relate the calibration-values to the reference-level of the sound-files used in Unity, the calibration tone must be played in the Unity-environment, setting the reverberation in the used room to 0, equivalent to an absorption-coefficient of the wall being 1. The listener must likewise be placed in the Unity-environment 0,5 meter from the sound-source, which was also the distance between sound source and microphone when the sound was recorded in the anechoic room.

If the binaural engine is used and the listener is facing the sound source playing the reference tone, the measuring must be free-field-adjusted according to ISO 11904-2[2].

The free-field-adjusted calibration value is used as the foundation for adjustment of the volume, as it must play at the same level as the reference-tone in the digital environment (e.g. 94dB).

4.2.3.2 Control of sound

When the playback system (headphone amplifier) is adjusted according to the description in section 4.2.3.1, it can be used for the calibration box, designed for the system, as shown in figure 4.2. The box functions by playing a 250Hz tone, following the same procedure as the calibration process. The box then shows the number representing the calibrated value. This value can then be recreated for the calibrated headphones by plugging them into another computer and adjust the sound volume until the box shows the same value. When headphone type is changed, the full calibration process must be completed anew. The calibration box simply functions as a volt-meter producing a number proportional to the voltage at the headphone terminals. This assures the same level in the headphones across different platforms (PC, tablet, phone, etc.).

Figure 4.2 Calibration box designed for calibration and level adjustment of the headphones used with the system

[2] If the listener in the Unity-environment can be made as a virtual ideal microphone, collecting sound from one spot without using the binaural engine, allowing the calibration to be conducted directly through measuring on a coupler. This method can, however, only be used if it is affirmed no additional adjustments are done to the sound mixing when sound is weaved through the binaural engine. This must be measured.

4.3 Hardware setup

In order to use the VR with Auralization system, multiple hardware is required. The system is compatible with most types of VR-viewers such as Oculus Rift and Quest as well as HTC VIVE (figure 4.3) and CAVE (figure 4.4).

Figure 4.3 VR-setup on trolley

Figure 4.4 CAVE setup: Test-persons navigate sensors, whilst listening to the room using over-ear-headphones.

Use of head-mounted-display's and CAVE demands relatively powerful computers. The system does however not demand much processing power, allowing the system to work also on smartphones (figure 4.5).

Another necessary hardware is high-quality over-ear-headphones. In the development and testing of the system Seenheiser PC 363 D and Bose QC35 ii headphones was used. Only over-ear headphones were used in the testing, as the absolute sound level is easier to control in such headphones.

Figure 4.5 VR-setup using a powerful laptop. The system can additionally be used with smartphones.

In order to have a reliable sound played from the headphones, they need to be calibrated, as described in chapter 2.5.

5 System testing

In this chapter, the system testing of the Virtual Reality with Auralization system is described. All sessions, c.f. figure 5.1, are presented to provide the rationale of the decision-making of the development of the virtual reality with auralization system[3].

No.	Session-type	Participants	Number of participant
1	Internal system-test	Researchers and Developers	5
2	Informal User-Experience Test	Stakeholders, Researchers and Developers	11
3	Internal System Demonstration	Stakeholders, End-users, Researchers and Developers	16
4	Informal User-Experience Sound-Distribution Test	Researchers and Developers	5
5	Informal User-Experience Test	Researchers and Developers	5
6	External System Workshop	Researchers and Developers	17
7	Informal User-Experience Test	Researchers and Developers	5
8	Internal System Workshop	Researchers and End-users	8
9	Final System Demonstration	Reseachers, End-users, Project-Managers and Developers	17

Figure 5.1 Testing sessions and number of participants during the development of the Virtual Reality with Auralization system.

5.1 Internal System Testing

Five respondents participated in the system testing, focusing on placement of sound-source and realism of the auralization. The respondents were all researches and developers in the project, with expert knowledge into how the system is designed, and the systems' limitations. This test was made prior to the recording of anechoic sounds.

The test was of the 94m^2 lecture room introduced in chapter 2.3. The informal listening test used, involved the respondents walking around in the virtual environment, listening to following four sounds:

- A projector (not recorded in an anechoic room).
- Speech (generic recording obtained on the internet).
- Sound from construction-site from open window (recorded from the outside of the real window).
- Sounds from neighbouring rooms through an open door (real recording, with low presence of reverberation).

5.1.1 Test-conclusion

The test revealed an imminent need for anechoic recordings and an ability to control the sound levels in the virtual environment better, in order to obtain a more realistic auralization. With respect to the generation of the virtual environment with auralization, testing showed a need for a more automated process for setting up an acoustic-space and perform sound-source placement, based on the IFC format.

5.2 Informal User-Experience Test

An informal user-experience test was conducted in the spring of 2018, allowing the stakeholders and some of the potential end-users of the system to try-out the system and provide the developers and researchers with an evaluation on the system from their viewpoint.

[3] It is important to note that some of the test-sessions described in this chapter, occurred as part of the development of the system, and that some of the results regarding anechoic recordings and calibration have already been described in chapter 3 and 4.

Eleven respondents participated in the test-session, both with and without prior knowledge of the system. The respondents were, additionally, a mix of people with and without acoustic expertise, allowing the developers and researchers to acquire data regarding the systems functionality for non-experts.

After having been immersed into Virtual Reality, the respondents participated in informal interviews; allow both questioning and answering as well as discussion of the system functionality and usability.

5.2.1 Test-conclusion

Interviews with the respondents revealed that further research and analysis of sound-source placement and sound distribution from said sources was needed. A key concern for some of the respondents were sound-transmission between and from neighbouring rooms, and how such sound-transmission can affect realism of the system, depending on how the problem is resolved.

The respondents also indicated that a manual system-setup for sound-source placement and sound-level control would be hard for acoustic non-experts to handle, and that an automated process was needed.

The testing also revealed a need for a better understanding of the work processes in the case-company and its branches, as the interviews showed that concerns regarding the use of the virtual reality with auralization system were different between respondents from different branches.

5.3 Internal System Demonstration

Another test-session was conducted in the autumn of 2018 at the Danish headquarter of the case-company, as shown in figure 5.2. The session had 16 participants including researchers and developers as well as stakeholders and potential end-users.

Figure 5.2 Stakeholder using virtual reality with auralization for the first time

The test showed how virtual reality can create a “wow-effect” due to fascination of the technology. The system-demonstration and discussion that followed revealed that both stakeholders and potential end-users were able to see a potential use for the system in generating value on design projects, for both acoustic non-expert, end-users and internally in the organisation for communication on design-projects.

5.3.1 Test-conclusion

The testing showed how different respondents reacted to virtual reality and intuitiveness differentiates from person to person. Especially stakeholders participating in the system demonstration found it difficult to navigate the system and required more instruction and aid than participants used to working with 3D modelling or using gaming technology privately.

The session resulted in positive comments and evaluations by stakeholders and potential end-users. It furthermore allowed developers to attain better understanding of where to improve the setup with respect to usability and intuitiveness.

5.4 Informal User-Experience Sound-Distribution Test

Based on results presented in chapter 5.2 a test session was conducted, testing how to programme sound-source placement and movements in virtual reality using the Epiito software. In order to evaluate sound-transmittance through walls and windows, four different sound source-placement scenarios were tested, as shown in figure 2.3. Four respondents tested the sound distribution in four different scenarios, shown in figure 2.3.

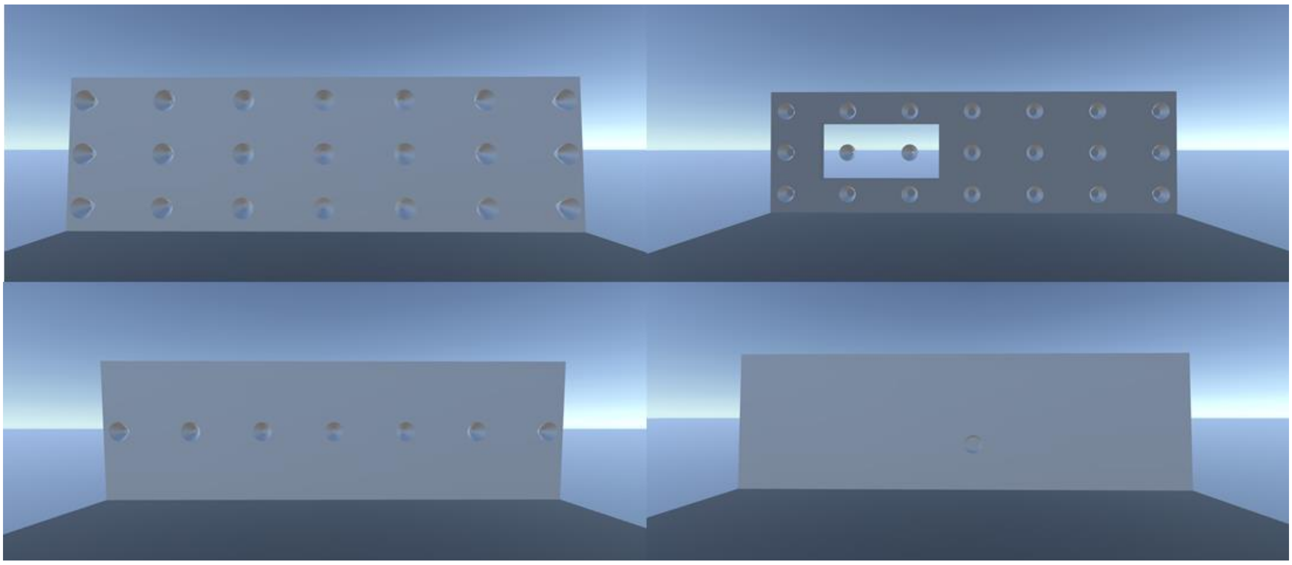

Figure 2.3 (re-inserted) The four different test scenarios. Upper left: 21 sources. Upper right: 21 sources with window. Lower left: 7 sources. Lower right: single source, following avatar.

The sounds used in the test were all without presence of reverberation. Only developers and researchers participated in the testing, however, with different levels of acoustic knowledge.

The forth scenario in the test was concluded to provide the most realistic experience of sound in virtual reality and the solution distributing sound most evenly when moving around in a virtual environment.

5.3.1 Test-conclusion

A sound-source placement solution was selected with the sound source following the user in virtual reality allowing a realistic experience and an even sound-distribution. It is important to note that sound-sources are loaded into the virtual reality with auralization system for each user (viewer), making sound and sound-distribution unique to each player.

5.5 Informal User-Experience Test

As preparation for the external system workshop described in next chapter, an informal user-experience test was conducted with participation of researchers and developers of the virtual reality with auralization system.

The testing was done to ensure functionality of the system after update of the system regarding:

- Sound-source placement
- Sound-distribution method
- Generation of spaces based on the IFC code, allowing acoustic spaces in the virtual environment to be generated automatically.
- Automatic registration of building components (ventilation hoods, electronic equipment etc.).

To test the system-changes a generic 3D model of a building in IFC was opened in the virtual reality editor and used for testing the automated functions creating the acoustic space, as shown in figure 5.3.

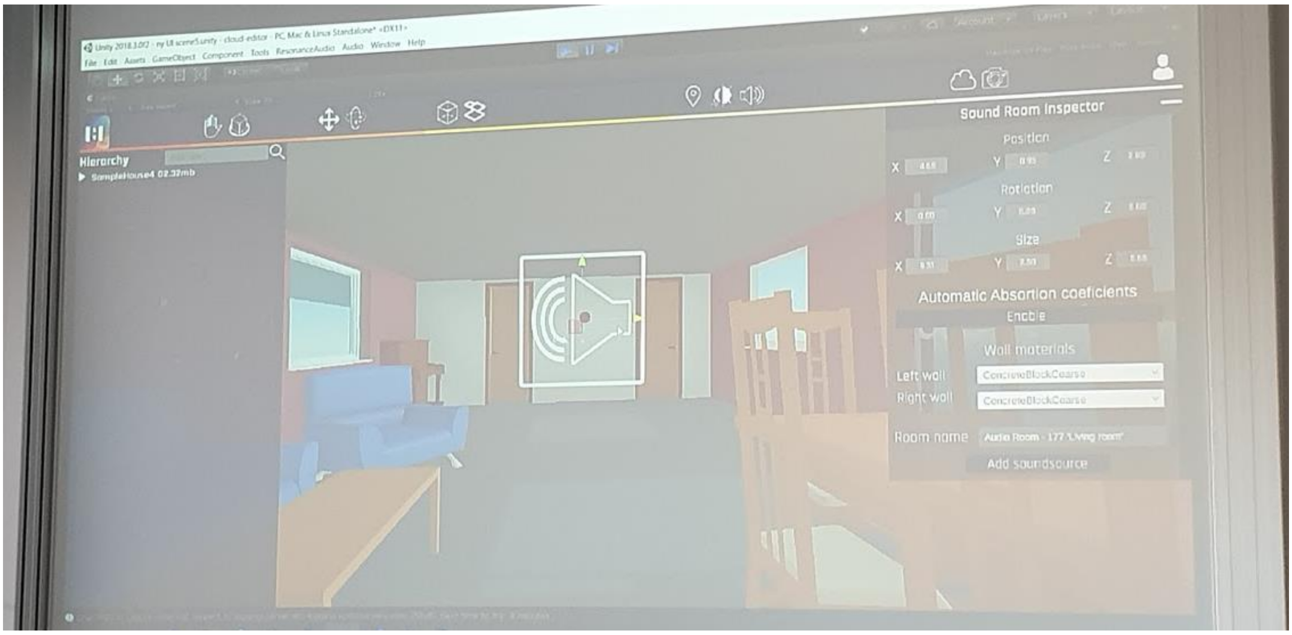

Figure 5.3 Test scenario with acoustic room generated based on IFC read.

In addition to testing the system in virtual reality with auralization using head-mounted display and over-ear-headphones, the system was tested in CAVE.

5.4.1 Test-conclusion

The test revealed that all improvements of the system based on earlier tests were functioning and that virtual reality with auralization worked using both head-mounted-display and in CAVE, however limited in CAVE due to noise from the projectors viewing the virtual environment.

5.6 External System Workshop

In order to test the system with independent groups of respondents, the system was demonstrated and tested at the 7th Regional International eCAADe Symposium in Aalborg, Denmark. Seventeen respondents participated in the workshop, testing functions and system-use.

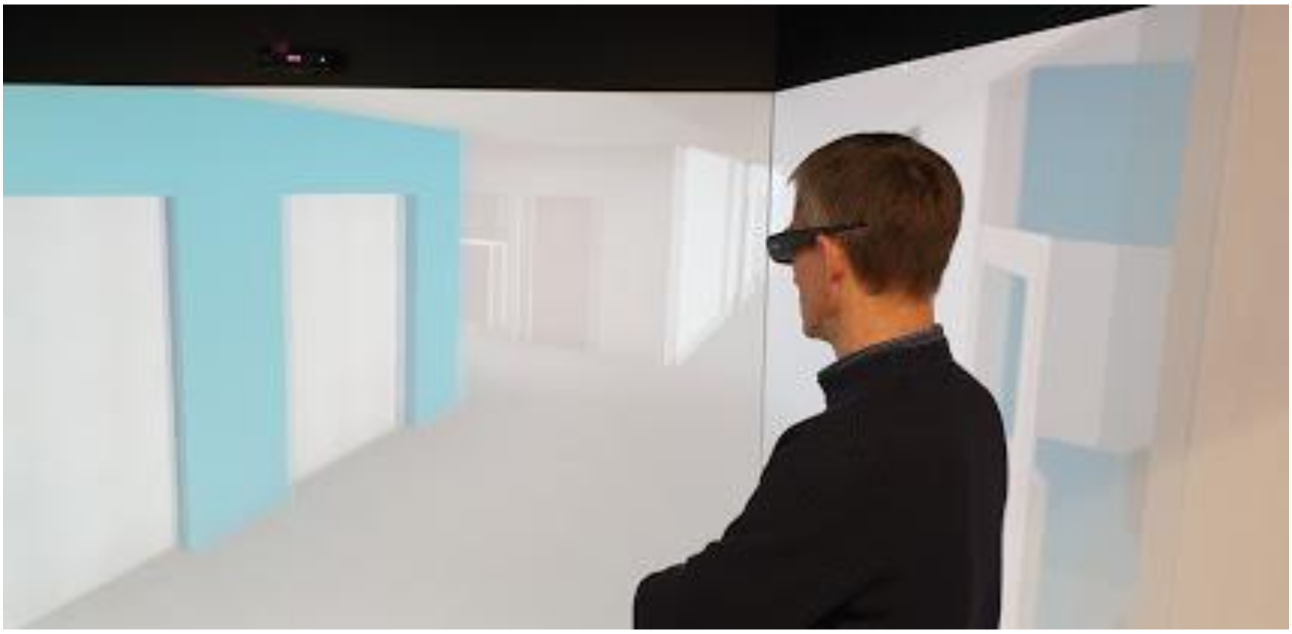

Figure 5.4 Test of functionality of changes to the virtual reality with auralization system in CAVE.

The workshop started with an introduction to the system and the theories behind the design of it, as shown in figure 5.5. Respondents were then allowed using the system, going from generating a virtual environment (VE) based on a 3D model in IFC and place sound sources to the VE and adding anechoic recordings to said sound sources. The respondents were additionally able to interact visually with each other, as the workshop had three connected systems set up. Two of the system set up were HMD and the third was CAVE.

Figure 5.5 Developer presents the design and functionalities of the system.

Some of the respondents with knowledge regarding virtual reality, auralization and room acoustics were impressed with how easy the system is to use.

> *"The systems we, made for more complex geometries must render over-night, and sometimes longer, so this system is very fast in comparison"* – Respondent from workshop, 2019.

The fact that other virtual reality systems with auralization can handle geometries that are more complex is important to acknowledge when comparing such tools with the system presented in this report. Discussion with the respondents at the workshop, however, revealed that a need for systems to aid decision-making with respect to acoustic performance of a room is needed when acoustic non-experts must make decisions.

The test-sessions made it possible for the respondents to try the system viewed through both head-mounted display and CAVE, as shown in figure 5.6 and 5.7.

> "*The CAVE has a great "wow-factor" but it seems like the head-mounted display solution works better, and it looks better"* – Respondent from workshop, 2019.

Ahead of the workshop respondents were invited to bring their own 3D model in the IFC format, as both researchers and developers wanted feedback regarding the system's usability and intuitively. However, none of the respondents brought any model. The lecture room scenario used in previous test-sessions was there used again during the workshop.

5.6.1 Test conclusion

The test revealed that the user-interface of the system needed to be streamlined, making it easier to navigate the system. The participating respondents found the system to be a trustworthy representation of reality, and sounded realistic. Using CAVE for immersion into the virtual environment, however, proved challenging

Figure 5.6 Respondents gets introduced to the system viewed through head mounted display.

with respect to hearing the sound played through headphones, as the noise from the projectors viewing the VR made too much noise.

Figure 5.7 Respondents are immersed into the virtual environment using CAVE.

5.7 Informal User-Experience Test

After presenting the system at the workshop, as described in the previous chapter, updates were made to the system, automating some setup-processes and streamlining of the user interface. Researchers and developers of the system then tested the new implementations to ensure functionality of the system before presenting an updated version of the system to respondents from the company.

5.8 Internal System Workshop

In the summer of 2019, an internal system workshop was conducted, allowing researchers, developers and end-users chance to evaluate the system and participate in discussion regarding the system before the systems' final demonstration. Respondents with and without acoustic expertise, as well as project-managers and project stakeholders participated in the workshop. Two of the respondents had not previously seen or tried out the system.

Some of the respondents with acoustic expertise had concerns regarding distancing in the system and advocated for implementing a measuring function in the system.

> "*We need to have the distance to a sound source available and it would be nice if we could measure distances whilst being in the virtual reality*" (Respondent from the workshop with acoustic expertise).

Another concern raised by the respondents was the use of IFC as primary exchange format, as none of the test persons working with acoustic design on a daily basis had knowledge of the use of IFC. The concern was, however, diminished by one of the other respondents working as project- executive in the company explaining that the Norwegian branch of the company has completed its implementation of IFC whilst Denmark is working towards it.

Figure 5.9 A respondent, with guidance from one of the system-developers, setting up a virtual environment in the virtual reality editor.

During the workshop, the system was tested on both system setup and the virtual reality with auralization resulting from the setup. Head-mounted display was the primary medium for viewing the virtual environment, whilst setup of the system was done using a monitor as shown in figure 5.9. Mobile phone based virtual reality with auralization was also demonstrated. The solution was, however, not tested at the workshop, as the calibration method for mobile phones has not yet been completed.

Even though the system was described as interesting and funny to use, not all comments were positive, seen from the developer's point of view.

> "*It is very funny to try this. But you really need to consider if it has any application in our work"* (Respondent from workshop with acoustic expertise).

5.8.1 Test conclusion

The workshop and the comments given by the participating respondents showed that the scope and purpose of the system needed to be explained better to potential users of the system with acoustic expertise. The respondents did not fully understand that the system is made with intention of improving acoustic design of common and geometrically unchallenging room, and that users without acoustic expertise are intended as the primary i users of the system.

5.9 – Final System Demonstration

The final demonstration of the system was conducted with 17 people participating, nine of whom were potential end-users both with and without acoustic expertise. The testing involved having respondents working together in groups, immersed into Virtual Reality using both head-mounted display (HMD) and CAVE, as shown in figure 5.10 and 5.11. The demonstration differentiated from previous tests and workshops, as the HMD used was the Oculus Quest, and not Oculus Rift, allowing respondents more movement during immersion. The scenario used in the test-session was the lecture-room scenario also used in most of the previous tests, allowing respondents whom had participated multiple times during the development and testing cycles of the system, to be able to compare the experiences they had had with the system.

Figure 5.10 Developer introducing use of head-mounted display and controllers to respondent.

Figure 5.11 Respondents are introduced to the CAVE and how it works.

After having tried both the HMD and CAVE version of the system, the groups were asked to evaluate the system and answer an open-questioned questionnaire, allowing the respondents a chance to give a final evaluation of the system and as a group reach a conclusion with respect to the system, after in-depth discussions.

When asked about what context the system could be usable in for the case company the respondents named multiple possibilities.

“The system can be used as a tool for selling, design, communication, value engineering and quality assurance in HVAC” (Respondent group 1).

“The tool can aid the requirement steps and help define thresholds for the client” (Respondent group 3).

The comments from the respondents were aligned with the developer’s intentions with the system. The answers given by some of the respondents, however, indicated that the purpose of the tool were not understood by all, and that some of the respondents believed that the tool was also design to support decision-making in geometrically challenging rooms.

“The tool could support us in design of Metro stations with many noise-sources. It must be large projects the system is used on, in order to drive it. The system must be able to handle other scenario-analysis to give a holistic result for prioritisation on the client’s side.” (Respondent group 2).

The answers given by the respondents in the questionnaire revealed that using virtual reality through HMD has both benefits and disadvantages. *“Using the VR- headset results in losing a direct (personal) connection with a client. Hardware is a limitation and so is the occurrence of motion-sickness”* (Respondent group 1). Respondent group 2 adds to this:

“*It needs to work convincingly and in a quiet environment.”* (Respondent group 2).

The third respondent group additionally emphasised that the developers and stakeholders of the system needs to be realistic about the limitations of the system and ensure alignment of expectations to the system.

Even though the use of HMD were mentioned as one of the system’s limitations, the respondents did find it as a method adding benefits to the experience of the virtual environment.

“PC (viewed VR, rd.) *is an alternative, but HMD definitely adds value”* (Respondent group 1).

“You get submerged into the virtual environment, especially the directional aspects.” (Respondent group 3).

Respondent group 2, furthermore, added that CAVE is a better environment with respect to the virtual environment in their opinion. It is, however, not favourable in acoustic designing.

The final step of the questionnaire was for the respondents to name which improvement they would like the system to have.

“The ‘box’ geometry limitations should be removed, and players immersed into the same environment should be able to chat. The sound/ noise library should also be elaborated on. Another feature that would be nice is being able to export the reverberation-time spectrum, to convince authorities about sufficient speech quality. Refurbishment assignments including 3D photos and different acoustical mitigation pleasures would additionally be nice to have.” (Respondent group 3).

Respondent group 1 also named expansion of the sound library as one of the key improvements the system would benefit from. They additionally called for the system to be open for testing by people, to find flaws and improvement-necessities before the system is released commercially.

Figure 5.12 Respondents immersed into virtual reality using HMD.

Respondent group 2 only had one improvement suggestion, being the ability to see a visual representation of sounds being played in the virtual environment.

Other suggestions for improvement names in the questionnaire were real-time audio analysis possibilities, real time design including material selection and collaboration with other industries within the system.

One of the respondent groups also requested a start-up manual for users starting to use the system. Such manual will be released with the consumer edition of the system.

5.9.1 Test conclusion

Based on the comments from the respondent groups, the virtual reality with auralization tool is both realistic and usable for design of room acoustics. However, as intended, the system does not support auralization of geometrically challenging rooms like train stations, concert halls or airport terminals etc. What is now needed is testing of the system without influence of the developers or stakeholders of the system, in order to find flaws and bugs in the system.

The system used for the final system demonstration was not the consumer-ready edition of the system; hence, some of the functionalities in the system were not completed. In addition, the user manual was not made available for the respondents, as it has yet to be produced.

6 Conclusion

This chapter highlights important questions for the case-company to answer when implementing the virtual reality with auralization system in addition to describing focus areas in further development of the system.

As established throughout the report, the scope of the developed system is design-projects including room acoustics of geometrically unchallenging designs. Most buildings consist of such rooms, but are often overlooked in the design-phases regarding evaluation of room acoustics. The tool is hence designed to simulate such overlooked designs, allowing acoustic non-specialists to listen to the room under design, using existing 3D models in the IFC format.

Using the tool, provides the company an opportunity to deliver better acoustic design-solutions to their clients, without the high costs, usually generated from doing advanced acoustic simulations on design-projects. The company will additionally be able to sell acoustic evaluation as a service in all projects, and thereby have a possible financial earning from implementing the system, on top of being able to deliver better solutions to their customers. It is important to note that the simplified real-time acoustic simulation the system provide is not intended to be the solution for acoustically challenging designs such as: train and metro stations, concert halls and airport terminals, which are types of projects usually being evaluated by acoustic experts.

It must be emphasised that the system is made for acoustic non-experts and only allows users to define absorption-coefficients and to control design and placement of sound-sources.

Possible future development is expected to include:

- Communication between users in a multi-user setting of the virtual environment.
- Improved possibilities of handling sound from adjacent rooms.
- Alignment of user-interface with related tools.
- Direct connection between the VR with Auralization system and BIM-authoring tools.

Anechoic sound-recordings have been made as part of the projects, and will be made accessible with the system. Additional sounds must, however, be recorded making the system usable in more design-projects.

Through this report, containing the documentation of the rationale for the developments and results from testing the system, and the in-depth description of the recording, management and control of the anechoic sound and the sound-levels. The report additionally serves as a case study, which can guide future development and other system development research.

Acknowledgements

We would like to extend our gratitude to the COWI foundation for financing parts of this research. We would also like to thank all the respondents from the case company as well as respondents from other architectural, engineering or construction companies. Finally, we would like acknowledge the participation and contributions from the participators in the project COWI A/S, Epiito A/S and the Department of Electronic Systems at Aalborg University.

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This report presents the data which the papers: **Realistic Real Time Simulation of Room Acoustics using Virtual Reality with Auralization** [13] and **Designing Room Acoustics using Virtual Reality with Auralization** (Swanström Wyke, S.; Svidt, K.; Christensen, F.; Bendix Sørensen, J.; Mithun Fadnes, T.; Lund Jensen, R.; 2019 (*Un-published*) are based on, as well as other un-published data from the research project: **Virtual Reality in Design, Construction and Operation,** at Aalborg University.

Disclaimer: The study presented in this paper was conducted with participation of one of the key engineering companies in the Danish building industry, as both respondents and project stakeholders. The conclusion might, therefore, be primarily directed in said companies' interest. We, however, believe that both the research and the developed VR with Auralization system has application in the industry generally as well.