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Should Acoustic Simulation Technology be Utilised in Architectural Practice? Does it have the Potential for BIM Integration?

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Abstract – The research presented in this paper, firstly, aims to convey the importance of our acoustic environment through focusing on the effects of undesirable acoustic conditions on cognitive abilities in spaces where cognitive performance is of the utmost concern, our learning environments. Secondly, it aims to investigate current state-of-the-art acoustic simulation methods, available platforms, and their levels of interoperability with architectural BIM authoring software. Structured interviews were carried out with 7 Irish architects and architectural technologists to determine if a disconnection between architectural design and acoustic performance exists and to identify the advantages and disadvantages of current workflows for acoustic performance evaluation. Additionally, industry opinions were gathered on whether it is measurable that our acoustic environments are at a disadvantage as a result of the apparent gap in available integrated acoustic evaluation solutions for a BIM-enabled design workflow, and finally to investigate industry demand for better integration of acoustic evaluation tools with BIM authoring platforms.

Keywords – Building Information Modelling, Aural Architecture, Psychoacoustics, Acoustic Simulation Technology, BIM Integration, Odeon Room Acoustics

I Introduction

We experience our built environment on many sensory levels, nevertheless, an overriding dominance of visual aesthetics in architectural design prevails. This pre-eminence of image greatly influences designers' decisions upon geometries, spatial proportion, and materials which may bear consequences for a mostly overlooked but nonetheless crucial aspect of our built environment, the acoustic environment.

Acoustic simulation tools have, for the most part, been considered by architects and designers to require levels of knowledge which lie beyond the purview of their expertise, deemed solely the apparatus of acousticians and acoustic consultants. In a sense this is true, acoustics is a deep and complicated field of physics requiring specialist knowledge and understanding to interpret the more involved parameters and intimate qualities of reflected and refracted sound. However, for the architectural designer, in depth analysis may not always be of necessity. Parameters which bear most significance on the quality of the acoustic environment such as Reverberation Time (RT), Signal-to-Noise Ratio's (SNR), the Speech Transmission Index (STI), and Sound Pressure Levels (SPL's) are among the most easily understood. Further to this, most acoustic simulation solutions provide the ability to listen to the acoustic environment of a proposed design, a process known as auralisation. This ability along with an understanding of basic acoustic principles can equip the designer with the means to evaluate the acoustic environment of a proposed design and enhance acoustic performance prior to construction. The most advantageous solutions would seek to leverage the power of building information modelling (BIM) through attaining a bi-directional exchange of building data between BIM authoring platforms and acoustic simulation software.

II Context of the Research

This research was carried out through a study of the current literature on the principles of Aural architecture, Psychoacoustics, and Building Acoustics. A literature review was then carried out to investigate the capabilities of current state-of-the-art acoustic simulation software and levels of interoperability with BIM authoring platforms and an evaluation of one of the leading software packages is presented. Structured interviews were carried out with 7 Irish architects and architectural technologists to determine if a disconnection exists between architectural design and acoustic performance and also to Identify the advantages and disadvantages of current workflows for acoustic evaluation and gather industry opinions on whether it is felt that our acoustic environments are at a disadvantage as a result of the apparent gap in available integrated acoustic evaluation solutions for a BIM-enabled design workflow.

III Objectives & Methodologies

Objective 1 To critically evaluate our relationship with our acoustic ecology, investigate how and why sounds affect us, and the impact it can have on our learning abilities.
Methodology Literature review on Aural Architecture (the human experience of sound within a space) and Psychoacoustics (our psychological responses associated with sound).
Objective 2 To investigate the causes of poor acoustic performance in buildings and what measures can be taken to mitigate these impacts.
Methodology Literature review on spatial acoustics (sound within space), noise & building acoustics (control of noise within space).
Objective 3 To investigate available state-of-the-art acoustic simulation technologies and current levels of interoperability with BIM authoring platforms.
Methodology A literature review on acoustic simulation methods is carried out to ascertain currently available acoustic simulation technology and the problems associated with attaining interoperability with BIM authoring software. An evaluation methodology is then used to critically appraise the practical use of a leading acoustic simulation program, the process for carrying out acoustic simulation, the results that can be obtained, and the benefits it could offer a BIM-enabled workflow if interoperability challenges can be overcome.
Objective 4 To critically examine current design approaches in architectural design for acoustic performance evaluation. To determine if there is a disconnection between architectural design and acoustic performance. To investigate opinions on the importance of the acoustic environment in learning spaces, whether acoustic analysis is deemed necessary for such places, and are these spaces at a disadvantage by the apparent gap in the availability of an integrated acoustic evaluation solution for BIM authoring software.
Methodology Thematic analysis using a hybrid approach of inductive and deductive coding and theme development will be used to pinpoint, examine, and record patterns of meaning from the data collected from structured interviews.

IV Literature Review

Aural Architecture

All sound seeks its expression in the medium of space [1]. Every space, be it natural or man-made, spawns an aural architecture. The acoustical characteristics of space are determined by its spatial geometry, surfaces, objects, and materials. What determines the aural qualities of a space is the human experience of these acoustic aspects [2]. Aural architecture is the properties of space which can be experienced through listening. It is the formation of a real and unreal place that produces the emotional/affective, behavioural, and life-related reactions of the sensitive living being [3]. Humans have a native ability to sense spatial characteristics through listening. This auditory spatial awareness is an evolutionary artefact [4], a part of our genetic inheritance found to be significantly associated with the complexity of geographical conditions and survival demands [5] allowing us to thrive in socially complex groups [6]. This ability allows us to navigate our surroundings, identify the location of sound sources, compensate for the influence of spatial acoustics on communications, and appropriate selection of a target voice amongst a number of voices [7].

Our perception of architecture is a multi-sensory experience [8]. However, design processes for the design of spaces other than those requiring high acoustic performance gravitate more towards conveying artistic expression through the visual [9]. Orienting itself towards the designers and their intentions and away from occupancy [10] without nearly as much consideration towards its sonic component, aural architecture [11]. This overriding pre-eminence of image over the actual multisensory experience of space diminishes the full design potential and limits the depth of its study [12]. While commentators from many different disciplines will agree on the pre-eminence of vision in architectural design, we can only ponder what has been lost as a result of this visual dominance [13]. Consequentially, ill-considered acoustic features such as geometry, proportion, and materials can promote undesirable acoustic conditions engendering a built environment that provides a saturated amount of poor-quality acoustic experiences in need of acoustic correction to be carried out in remedial fashion [2]. In the context of learning environments, a poor acoustically performing space fails to correspond to its function, potentially inhibiting our cognitive abilities [14], posing barriers to learning [15], and failing in its purpose.

Psychoacoustics

Over the past century, researchers have carried out several studies on the psychological, physiological, and academic effects of noise [16]–[20]. The landmark study by Morgan (1917) first established the effects that noise can have on cognitive performance. Results from his experiment, which studied participants attempting to learn new information in both quiet and noisy environments, found that the participants in a noisy environment showed a diminished attention span and were less likely to retain information than their counterparts.

Since this publication, many researchers have continued to demonstrate the negative effects of auditory distraction on learning abilities. Although the literature seems to lack broader theoretical frameworks that can explain how auditory distraction occurs, studies have found that Chronic noise exposure impairs cognitive functioning [21] and noisy environments can lead to reading problems [22], [23]. More recently Shield and Dockrell (2003) carried out an extensive literature review relating to the effects of noise which covered factors affecting speech intelligibility, annoyance, and the effects of environmental and classroom noise on academic performance. They found evidence that classroom noise levels can be high, particularly in rooms without acoustic treatment with the main detrimental effect of noise being the degradation of speech intelligibility [24]. Although there appears to be a shortfall of available literature of studies on adult learners, a considerable amount of research on speech intelligibility points to children who, being in the process of acquiring vocabulary, are most affected [25]–[27]. However, Woodford, Prichard & Jones (1999) contend that this effect may be greater in higher education due to an accelerated pace of presentation of material, high prevalence of mild high-frequency hearing loss in this age group [28], and higher use of open-plan study environments in higher education [29].

The Nature of Noise

Noise is a class of sounds perceived to be unpleasant, unwanted, or disruptive to hearing [22], [30]. From a physics standpoint, sound and noise are the same phenomena. Psychologically, sound is a sensory perception originating as a mental event evoked by physiological processes in the auditory brain [31]. It is through our subjective perceptual analysis of sounds do we label a complex pattern of soundwaves as being noise.

Background or ambient noise in learning environments are a combination of sounds emanating from outside of the building [32], from within the building, and from within the room [33]. The sounds of our anthrophony, biophony, and geophony [34] can act upon the building, entering the learning environment through open windows, poorly insulated windows, and the building envelope. Sounds from within the building can filter in through open doors and uninsulated partition walls [35]. The more immediate and distracting sounds emanate from within the room itself such as student activities [36] and HVAC systems [37], with sounds that contain intelligible language being particularly distracting [22].

Working with adult listeners, Bradley (1986) found that noise was the more significant factor affecting speech intelligibility. While quality of intelligibility is governed by room acoustics and noise control, it can be most clearly examined with the signal-to-noise approach or signal-to-noise ratio (SNR) [39] and the speech transmission index (STI). While STI is a measure of the intelligibility of speech degraded by additive noise and reverberation, the SNR compares the level of a desired signal (tutors voice) to the level of background noise. Favourable or positive SNRs denote that the signal is louder than the background noise. For example, the American Speech-Language Association (ASHA) found that to achieve a suitable SNR for children, tutors need to talk approximately 15 decibels (dB) louder than the background noise in the learning environment [40] while this figure can be as low as +6dB for adults listeners, although Bistafa & Bradley (2000) recommended that the SNR should be greater than +15dB. Assuming that the reverberation time is an optimal 0.4s to 0.5s an SNR of 25dB is ideal and 20dB being an acceptable value at 1m in front of the speaker [41].

Spatial Acoustics

The science of spatial acoustics is a complex subject due to soundwaves moving relatively slowly compared to that of light, sound having a far greater frequency range, and the wavelength of soundwaves covering a much broader range [6]. Soundwaves can behave in several ways in any given environment. The resulting spatial acoustics of a space is a compound of reflection, absorption, refraction, diffusion, and transmission [42].

Reverberation is one of the most significant acoustic properties of a space. It gives a room its specific character and is one of the most common sources of sound distortion affecting speech intelligibility in learning environments [43]. Reverberation is a build-up of numerous reflections or multiple discreet echoes which has the effect of allowing sound to persist in space even after the original sound source has stopped. Waves from the sound source will repeatedly bounce off reflective surfaces such as walls, floors, ceilings, and objects until it eventually loses energy or has been absorbed by materials with sound absorptive qualities [42]. This dense build-up of overlapping soundwaves affects speech intelligibility, masking and smearing the direct signal with reverberant speech energy [44]. According to Shield & Dockrell (2006), two main aspects make up the acoustic environment of classrooms: noise and reverberation. This appears to be quite reductionistic as Halmrast (2015) presents examples showing that standard room acoustic parameters such as the measurement of reverberation and signal to noise floor ratios do not reveal all interesting elements of perceived room acoustics. Stating that standardised measurement criteria might “mask” important information on the perception of room acoustics and their cognitive and psychoacoustic aspects [45].

BUILDING ACOUSTICS

Building acoustics is the science of extenuating noise in buildings with the aims of controlling the characteristics of sound within a room through reverberation reduction, mitigation of external noise intrusion through exterior building skin augmentation, and inter-room noise transfer mitigation [39]. A buildings’ acoustical characteristics can be influenced by several factors such as geometry, volume, sound absorption, the transmission and reflection characteristics of building materials, internal or external generation of sound, airborne and structure-borne sound [35]. According to Mareddy (2017), there are four basic principles of noise control:

- **Sound insulation:** prevents the transmission of noise via the introduction of a mass barrier of high-density materials such as brick, concrete, and metal.
- **Sound Absorption:** a porous material such as open-cell foams and fibreglass which absorb sound by converting sound energy into heat within the material.
- **Vibration damping:** A damping mechanism extracts the vibration energy and dissipates it as heat.
- **Vibration isolation:** prevents the transmission of vibration energy to a receiver by the introduction of a flexible element or physical break [46].

A high-performing learning environment relies heavily on an acoustic environment which affords a low noise floor and optimal reverberation times [47], benefitting the well-being and aiding the learning/teaching abilities of the students and the tutor [48], [49]. According to Gursel et al., (2009), achieving an optimally functioning building that fulfils the needs of the end-user necessitates identifying and quantifying the performance. The first and foremost concern in this approach is with how a building is required to perform and not with prescribing how it may be constructed [51]. Eastman et al., (2018) defines BIM as a modelling technology and associated set of processes to produce, communicate and analyse building models. As part of a company’s transition to a BIM-enabled company, leveraging acoustic simulation technology to analyse and optimise acoustic performance is the next coherent and essential step towards achieving high-performance buildings.

V ACOUSTIC SIMULATION TECHNOLOGY

Advancements in computational capacity and developments in acoustic simulation methods are creating new possibilities for acoustic design and analysis [53]. These advancements can enable the designer to predict the acoustic performance of a project before construction and capacitate a re-integration of acoustics in architectural design education and practice [54]. The development of integrated platforms that combine acoustic analyses and architectural modelling would allow for acoustic evaluations in early design phases and allow for greater collaboration among architectural and acoustic specialists [55].

The concept of computational room acoustic modelling was first envisioned nearly six decades ago when Schroeder (1962) presented his principal ideas at the 1962 International Congress on Acoustics. This paper laid out the methodology for what was much later to be called auralisation, the creation of audible acoustic sceneries from computer-generated data [57]. Early developments of this concept contained no audible components instead, it employed calculation strategies using pre-existing mathematical formulae such as the Sabine formula for reverberation time $T = 0.049(\frac{v}{A})$ and $E(t) = E(0)x(1-a)^{nt}$ to approximate sound energy travelling as a ray [58]. Since those initial ray tracing models, acoustic analysis and simulation software has evolved to provide more accurate predictions of complex acoustic phenomena such as diffraction and scattering [53], allowing practitioners to visually inspect spatial designs through superimposed acoustic heat-maps, reflection paths and their spatial distributions in time [59].

Although acoustic simulation technologies originally emerged from ambitions to interrogate architectural acoustic performance and enable the construction of acoustically better environments [60], there is an increasing number of applications found for fields such as archeoacoustics [61], cognitive research [62], game audio [63], virtual/augmented reality [64] and music research [65]. Many of these applications employ different types of analysis for various purposes and can also provide the possibility to generate binaural signals based on head-related transfer functions (HRTFs) added into the numerical signal chain [66] rendering the results for auditory perceptual evaluation [67]. This process of pre-hearing is known as auralisation, a term first coined by Kleiner et al.,[66] however modern vernacular expands the term to encompass both the process of acoustic simulation and the generation of its resulting binaural aspects [69].

ACOUSTIC SIMULATION METHODS

Techniques for room acoustic modelling can be categorised according to the underlying equation. The most accurate and insisted upon by research theorists are simulations that aim to solve the acoustic wave equation, a second-order partial differential equation describing the evolution of acoustic pressure as a function of position and time, or, the Helmholtz equation, representing a time-independent form of the wave equation [67]. The arduous task of solving these complex equations remains a key challenge due to the vast amount of computational and memory requirements needed [70] as such simulations can result in millions of values of sound pressure and/or particle velocity per cubic metre [71]. Due to this, analytic solutions exist only in some rare cases [67]. To improve upon computational efficiency, solvers need to apply some form of discretisation of space and/or time factors using discontinuous Galerkin methods [72]. In general, these are known as wave-based simulations which use such methods as the Finite Difference in the Time Domain, Finite-Element, Equivalent Source, and boundary-Element Methods [67], [73], [74].

Another approach to acoustic simulation and one most favoured among practitioners is geometrical acoustics (GA). Widely used in modelling mid and high-frequency behaviours of rooms, this approach is less computationally demanding, offering faster but less accurate results compared to that of wave-based techniques [60]. As stated by Miles [73], in practice, architectural spaces have far too many geometrical complexities to derive meaningful predictions of a sound field. Rather than performing painstakingly detailed estimates, it often suffices to estimate how the average sound levels are affected by changes in geometry and sound absorptive qualities of surfaces to provide guidance in design without the burden of complicated mathematics [73]. With GA methods, sound is assumed to propagate as rays and all phenomena caused by the wave nature of sound is neglected. These techniques have been in use for nearly 60 years since the influential works on ray-tracing by Krokstad et al., [74]. With later advancements these now include a family of methods such as ray, cone & pyramid tracing, the image-source method [76]–[78], beam-tracing [79] and techniques for modelling diffuse reflections such as acoustic radiosity [80] and the diffusion equation [81], [82] amongst others. All of these techniques have their strengths and weaknesses and models exist that aim to hybridise the strengths of each technique through combining ray-tracing with that of image source methods [83] and ray-tracing with the energy transition method [84].

VI ODEON ROOM ACOUSTICS

EVALUATION METHOD

The purpose of this evaluation was to determine the functionality, usability, and performance of one of the most widely used acoustic simulation software platforms. Although not interoperable with BIM authoring software, anecdotally, the author identifies that the merit of this evaluation lies in uncovering the capabilities of this technology, comprehension of the results and, the benefits it may bring once interoperability is achieved in the future. For this research, training was undertaken in advance through a study of the Odeon user manual and video tutorials provided on the Odeon website. A model created in Autodesk Revit was imported into the acoustic simulation software to investigate the workflow for translating BIM data into the acoustic simulation environment. The software was then operated using a room model supplied with the trial version for the following aims.

- To critically appraise the level of basic training needed to operate the software and obtain results.
- To assess the workflow for exchanging building data between Revit and Odeon
- To examine the process and additional manual input needed to ready the model for acoustic evaluation.
- To Investigate what types of analysis can be carried out and the format of results obtained.
- To investigate the level of knowledge needed to understand the results.

SCOPE & LIMITATIONS

Apart from the import of a Revit model, this evaluation used a room model supplied with the software. Due to limitations in gaining access to fully licensed acoustic simulation software, the following evaluation was carried out using a trial version of the latest iteration of Odeon Room Acoustics version 16. This trial version allowed for acoustic analysis to be carried out for evaluation purposes only. Limitations of this version restricted measurement results to the 1000Hz band and did not allow for the calculation of acoustical results on new/own geometries.

INTRODUCTION

Originally targeted at solving acoustic problems in concert halls and opera halls, the Odeon A/S company was established in 1984 as a cooperation between the Technical University of Denmark and a group of consulting companies to provide reliable acoustic predictions for both research in objective and subjective room acoustics and as a useful tool for acoustic consultants. The application has improved and extended its capabilities with each iteration to offer more reliable results, faster calculations, auralisation capabilities and more efficient methods of ray tracing, and improved calculation algorithms for sound scattering, early and late reflections and, sound transmission to name but a few. Released in June 2020, Odeon 16 is the latest version and is widely used by researchers [85]–[88] and consultants for its state-of-the-art calculation methods, accuracy, and ease of use.

Importing the Model

The starting point for the simulation is a 3D model of the room for which the acoustics are to be predicted. Geometry can be created within Odeon using the built-in parametric programming language and graphical extrusion modeler for cases where a 3D model is unavailable or to add more elements to an existing model such as acoustic diffusers or reflectors. Odeon also supports the import of .dxf, .3ds, .stl and .cad file types. To verify that building data can be properly imported, a simple model of a 22m x 16m classroom containing a door, windows and student desks were created in Revit is prepared and exported to .dxf making sure that solid geometry is exported as polymesh, an integer type in the .dfx file that Odeon will understand, and units set to millimetres.

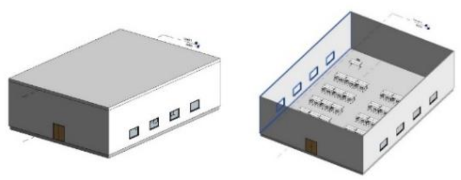


Figure 1. Interior and Exterior of the model prepared for export as a .dxf file from Autodesk Revit.

On importing the .dxf file, Odeon converts and creates a parametric file and shows several options for importing the file such as units, coordinate systems, and geometry gap tolerances. These were kept at the default settings. The import of this model, which included the furniture, had to be aborted after a two-hour wait time due to too many small details and polymesh triangles inherent in the furniture models which had slowed down the processing time considerably. A new .dxf file was exported from Revit, only this time the furniture models were excluded which allowed for import into Odeon almost instantly.

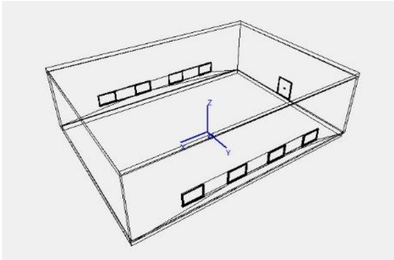


Figure 2. Graphical representation of the model in Odeon.

As this is a trial version of the software, the import of own geometries can only be viewed within the acoustic analysis environment. For the rest of this objective, a room supplied with the software was used to carry out the acoustic analysis.

Preparing the Model for Analysis

Once the geometry is imported (in this case a vendor-supplied room model was loaded) the first step was to set up the position of the sound source and receivers (the positions in the room for which the analysis will be carried out). Different types of sound sources in Odeon can be used to simulate sources in the real world such as array source for loudspeaker arrays, line source for longer sound sources such as pipes/ducts, and the multi-surface source which is practical for simulating noise intrusion through room boundaries. For this purpose, a single sound source was positioned centrally on the podium facing out into the room with a receiver placed at the rear of the room.

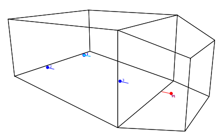


Figure 3. Room model example with the sound source (red) and receivers (blue).

The acoustical properties of the room were established by assigning materials with absorption and scattering coefficients to all surfaces in the model. These can be chosen from Odeon's material list or new materials can be created using the supplier's material data.
Once materials were assigned to each face of the model using the material library Odeon provides an instant method for estimating the average reverberation time (RT) in the room based on Sabine, Eyring, and Arau-Puchades equations. These are not the methods used in the actual analysis as they are less accurate but can offer an instant estimate of the average RT to help optimize material choices when designing for a specific RT.

When the room is prepared and ready for analysis the accuracy for the simulation must be set either using the suggested calculation presets or defining the impulse response length (depending on the RT of the room) and the number of late rays (result accuracy but also the amount of calculation time).

CALCULATION

Odeon derives a large number of acoustic parameters from both simulations and measurements. Many of which are calculated according to the ISO standard 3382, parts 1,2, and 3 for room acoustics. This is achieved by simulating the impulse response between the source(s) selected and the receiver(s). Different simulation methods are used in combination for optimal performance and precision including the Image Source Method, Early Scattering Method, Raytracing, and Ray-Radiosity Method.

RESULTS

The basic result of the calculation is the Room Impulse Response (RIR). This is the time history taken at the specified receiver location in the room, of the direct and reflected sound generated by the sound source. In Odeon the combination of RIR, sound source, and receiver are known as a point response. Point responses are the fundamental results of the detailed calculations/simulations. Simple room models may only require a single point response for analysis, however many point responses can be set-up for different combinations of sources and receivers. While the quick estimate tool is based on statistical formulae, the global estimate tool is based on raytracing and is useful for acquiring a first impression of the overall decay time and levels of absorption in the model. The following figures show a portion of the numerical and graphical representations of the results obtained from the simulation.

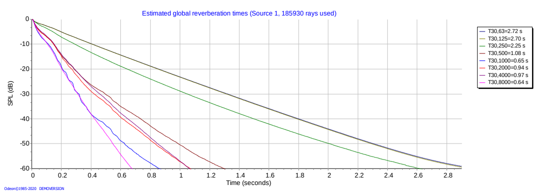
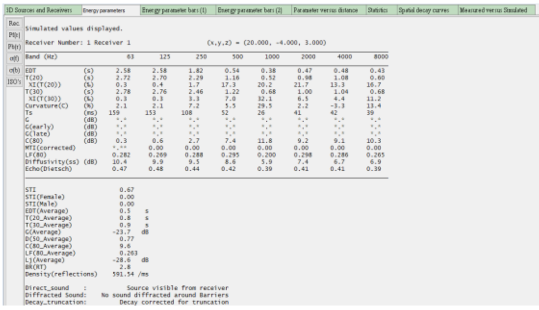


Figure 4. Estimated global reverberation times showing sound level decay curves for each octave band.



3D Sources and Receivers | Energy parameters | Energy parameter bars (1) | Energy parameter bars (2) | Parameter versus distance | Statistics | Spatial decay curves | Measured versus Simulated

Simulated values displayed.

Receiver Number: 1 Receiver 1 (x,y,z) = (20.000, -4.000, 3.000)

Band (Hz)		63	125	250	500	1000	2000	4000	8000
EDT	(s)	2.58	2.58	1.82	0.54	0.38	0.47	0.48	0.43
T(20)	(s)	2.72	2.70	2.29	1.16	0.52	0.98	1.08	0.60
XI(T(20))	(‰)	0.3	0.4	1.7	17.3	20.2	21.7	13.3	16.7
T(30)	(s)	2.78	2.76	2.46	1.22	0.68	1.00	1.04	0.68
XI(T(30))	(‰)	0.3	0.3	3.3	7.0	32.1	6.5	4.4	11.2
Curvature(C)	(%)	2.1	2.1	7.2	5.5	29.5	2.2	-3.3	13.4
Ts	(ms)	159	153	108	52	26	41	42	39
G	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
G(early)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
G(late)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
C(80)	(dB)	0.3	0.6	2.7	7.4	11.8	9.2	9.1	10.3
MTI(corrected)		*.**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LF(80)		0.282	0.269	0.288	0.295	0.200	0.298	0.286	0.265
Diffusivity(ss)	(dB)	10.4	9.9	9.5	8.6	5.9	7.4	6.7	6.9
Echo(Dietsch)		0.47	0.48	0.44	0.42	0.39	0.41	0.41	0.39

STI	0.67	
STI(Female)	0.00	
STI(Male)	0.00	
EDT(Average)	0.5	s
T(20_Average)	0.8	s
T(30_Average)	0.9	s
G(Average)	-23.7	dB
D(50_Average)	0.77	
C(80_Average)	9.6	
LF(80_Average)	0.263	
Lj(Average)	-28.6	dB
BR(RT)	2.8	
Density(reflections)	591.54	/ms

Direct_sound : Source visible from receiver
Diffracted Sound: No sound diffracted around Barriers
Decay_truncation: Decay corrected for truncation

Figure 5. Numerical values for each parameter at each octave band.

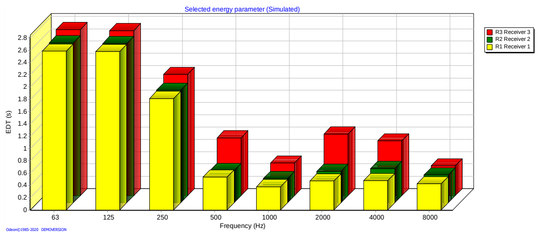


Figure 6. Bar chart showing sound energy per octave band for each of the three receiver positions.

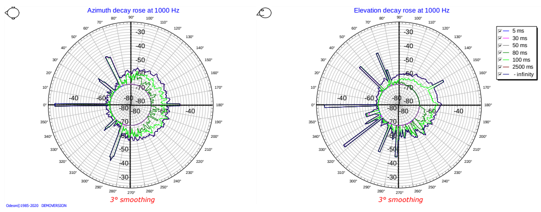


Figure 7. Rose chart showing the sound direction at different time intervals.

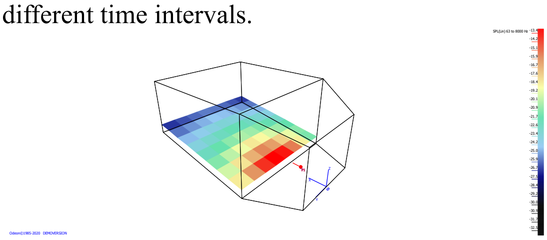


Figure 8. Grid response showing sound pressure levels for frequencies between 3Hz to 8000Hz.

CONCLUSION

The author found that the manufacturer's website provided a substantial level of support for training in both the operation of the software and the principles of room acoustics and that only a basic level of training was required to gather the above results. Useability was satisfactory although hampered by the use of ambiguous icons for various functions displayed on the somewhat outdated user interface. The application has powerful functionality for carrying out acoustic simulations and provides calculations for any required acoustic parameters. Due to Odeon's optimized algorithms, calculation/rendering times for this simple model were surprisingly short, taking only 12 seconds to produce the results but this time would be extended depending on the level of detail in the model. The application allows for the import of .dwg and .dxf files, among others, all of which contain geometrical data only and does not have interoperability with Autodesk Revit via IFC or any other means. Understanding and taking meaning from the results would, for some part, require further training, especially for the more involved parameters pertaining to ensemble conditions and the more intimate qualities of reflected/refracted sound. The most common parameters presented numerically such as STI, RT and SPL can be easily understood and provide the criterion which may be iteratively fine-tuned to meet required specifications via changes to materials and geometry. Along with providing numerical results, the acoustic environment may be portrayed both visually via colour coding the grid responses of multiple points of a chosen surface for various acoustic parameters and, through auralisation of the environment via applying the rooms impulse response to a chosen sound source and listening back at a specified location within the room. In conclusion, the application more than exceeded the authors' expectations in its ease of use, capability, and function for offering building designers useful feedback and insight into the acoustic environment of a given design and the multiple ways in which the results may be presented provides a useful means of communication amongst designers and to the client(s).

VII BIM INTEGRATION

As shown previously, the quality of our acoustic environments can have a great effect on our wellbeing, stress levels, cognitive performance, and overall comfort levels within a space. Providing the designers of our everyday spaces with the technological ability to assess the acoustical aspects of a proposed design can be operant in influencing designers to embrace acoustic design within their BIM-enabled workflow and pay greater attention to the effects of their design decisions upon the acoustic environment.

BIM is a working methodology built upon collaboration, interoperability, and coordination for attaining a digital representation of the physical and functional characteristics of a building project. This is achieved in BIM-enabled building projects worldwide through adhering to the concepts and principles laid out in the ISO 19650 set of international standards for the management of building information largely generated through BIM authoring platforms developed by vendors such as Bentley, Autodesk, Graphisoft, and Nemetschek.

The increasingly important role of building information modelling (BIM) to enhance performance-based design has, for many years, been an area in development. Extending this into the realm of acoustic performance simulation through integration with BIM authoring platforms would offer the designers of our built environment the ability to

- Leverage building data already inherent in the BIM model to populate the acoustic model.
- Interrogate acoustic performance in-house and within their design workflow.
- Allow designers to make more informed decisions when designing for acoustic performance.
- Allow the designers and clients to directly experience the aural implications of design decisions and make more informed choices, thus, avoiding the cost of over-specification and the consequences of under-specification.
- Help both architects and building owners to feel connected to the acoustical aspect of the design, enabling critical listening, opening up discussion of different acoustic treatments, design options and the overall sound of the space.
- Help the design team to come to an agreement on decisions that may have a significant impact on costs and aesthetics.
- Enable more control over the acoustic environment while improving upon workflow time and costs, culminating in higher acoustically performing buildings.

The most widely used BIM authoring software platform for architectural design in Ireland is Autodesk Revit [89]. Revit supports various design tools to improve project productivity along with available third-party solutions to extend its modelling capabilities. One of which, MagiCAD, a BIM solution for MEP, offers the ability to calculate the sound levels within a room although this has some limitations. Calculations are for sound levels emitted from air terminals only and use the Sabine formula method, a formula known for its accuracy varying wildly for rooms of different shapes and sizes and can only be relied upon for rough estimates at best. Besides this ability to gather a rough estimate of sound levels emitted from air terminals, there is a shortfall in available analytical tools to estimate BPS concerning acoustic performance. This absence of an integrated acoustic evaluation environment for Autodesk Revit is a major setback considering that the iterative nature of designing towards required performance requires the availability of methods and tools that can be easily used by designers that cover the selected performance criteria [90].

Currently, acoustic analysis must be carried out using standalone third-party software which does not come without its drawbacks. Most available acoustic analysis programs are developed for acousticians, thus, limiting accessibility for users who may only have a basic understanding of architectural acoustics. Even with significant practice and acoustic training, numerical metrics can be difficult to relate to acoustic phenomena and frequently fail to capture acoustical issues that can arise [91] although the more essential parameters along with results presented graphically and aurally offer greater accessibility and understanding.

According to Wu and Clayton (2013) and Jung et al., (2018), four sets of input data are needed for performing acoustic simulation: geometry (room volume, each face of the room and face area), finish materials (sound absorption coefficient at a series of octave band frequencies) sound source (position and power assuming it is omnidirectional) and audience (position in relation to the sound source). Due to interoperability issues [94], the current practice of transferring both geometric data from the BIM model to the acoustic simulation software is a unidirectional process requiring manual input to fix geometrical errors, simplify geometry and manually apply material properties which is time-consuming and prone to errors. This interrupt between acoustic environment reaction and design action provides a barrier in observing, understanding, and controlling the acoustic environment in the early design stages especially when compared to the intuitiveness and effectiveness of spatial and aesthetic design.

Curtailing the additional manual input needed through automating bi-directional transportation of both geometric and acoustical data between the BIM model and acoustic simulation environments such as Odeon, CATT-Acoustics, Comsol Multiphysics, and EASE, among others, is fundamental to facilitating the inspection of acoustical characteristics with little interruption of an iterative design workflow. A workflow that is dependent on initial acoustic analysis to be carried out and rapid "what-if" scenarios to be conducted.

Recognised as the official international standard for open BIM, Industry Foundation Classes (IFC) is a platform-neutral, open file format used to describe, share, and exchange relevant building data between different software applications and aims to provide the level of interoperability required to achieve BIM's full potential. However, in practice, IFC-based interoperability and data issues remain. Most of the commonly used state-of-the-art acoustic simulation software's are not interoperable with IFC, instead, they employ proprietary data schemas to represent the analytical model. Table 1 presents a summary of the current state-of-the-art acoustic simulation tools and their levels of interoperability.

Table 1

Linking acoustic simulation tools with Autodesk Revit.

SOFTWARE	INTEROPERABILITY	DRAWBACKS
COMSOL MULTIPHYSICS V5.5	Live link™ for Revit, Import of model geometry only.	Complex manipulation process within the Comsol analysis environment to define boundary elements, defeaturing, simplifying mesh elements, deleting element faces and assigning materials from built-in library.
ODEON V16	Supports DXF export from Revit. No IFC interoperability.	Some data may be lost in the transfer and re-modelling missing geometry such as windows and doors within Odeon can be cumbersome.Materials assigned within the simulation environment using Odeon's material database.
EASE V4.4	Supports DXF export from Revit. No IFC interoperability.	Model geometry has to be greatly reduced. Materials assigned within the simulation environment using the EASE material base.
CATT-ACOUSTIC V9.1	Supports DXF export from Revit. No IFC interoperability.	Imports model geometry only. Materials assigned within the simulation environment using Catt Acoustic material files.

In respect to the IFC Schema which was developed for procedural, contractual, and managerial purposes. Its use for the objective of acoustic simulation calls for a good deal of further development to extend its capabilities to include necessary data for acoustic analysis if the challenges presented by Mastino et al., [95] and listed in table 2 are to be overcome.

Table 2

Challenges for acoustic analysis in the field of BIM/IFC [95]

1. Appropriate Models	The models for acoustics analysis and simulation require explicit definition of the spaces (rooms and zones) and of their use, the clear specification of the exterior walls, the correct specifications of openings, etc. An IFC model should be represented not only visually but also at semantic level.
2. Appropriate Geometry	The analysis/simulation requires for acoustic spaces (zones and rooms) to be completely bounded by objects with known physical properties, taking into account how they are connected with adjacent spaces. This requires a direct connection between the perimeters of the spaces in the model, the objects correspondences along the boundary, the subdivision in homogeneous parts (homogeneous by the analysis criteria) of walls and slabs, checking that there are no gaps along the perimeter or, on the contrary, objects overlapping.
3. Integration with non-BIM Data	The correct integration of the necessary external data from external non-BIM sources must be appropriately associated with the BIM/IFC objects.
4. Correct definition of BIM/IFC objects	The model must contain details of the physical properties of the objects regardless of the detailed graphical representation level, because this is required by the analysis/simulation tools to determine their properties correctly.
5. Proximity Information	This is a kind of information supported by the IFC scheme, but not common for the CAD tools typically used to create BIM. Unfortunately, the acoustics analysis/simulation tools require such information; therefore if it is missing there is the need to be re-defined from building geometry.
6. Output Editing	The capabilities to edit the output that is, how "added" information should be properly associated/integrated into the BIM data to enable management, visualization and evaluation of results.

Research that has been undertaken over the last decade on approaches to linking BIM data with acoustic simulation software has pursued different approaches. Kim et al., [96] presented possibilities for integrated acoustic analysis, however, this approach was neither IFC-based and the analysis software used in conjunction with Autodesk Revit (Ecotect Analysis) was discontinued by Autodesk in 2015 [97]. Approaches using Dynamo, a visual programming tool that extends the power of Revit by providing access to the Revit Application Programming Interface (API) has been utilised for the extraction of both geometrical and acoustic data from the BIM model. A decision-making framework was developed by Aguilera et al., [96] using a dynamo script to extract data and calculate RT and airborne sound insulation. Erfani et al., [97] developed a Dynamo script that could extract information from both Revit and the open material database project OpenMat to calculate RT and visualise the results back in Revit through colour coding rooms within a plan view. A promising approach by [92] used the Revit API, C# programming in visual studio, and Direct X toolkit to develop a software prototype that could carry out automated analysis of RT and sound intensity levels while [100] used the API of Comsol Multiphysics to develop an algorithm to extract geometry, absorption coefficients and speaker location directly from the IFC file. Although none of these approaches allow for bi-directionality of data therefore whenever the building model is updated and a new IFC file is regenerated, the updated input data for the acoustic analysis has to be re-introduced and the process started over.

During the literature search, the author exhausted a wide range of keywords and could not find publications or current commercial software that could integrate enriched BIM data and acoustic simulation using a bi-directional system of data exchange and, to the knowledge of the author, connecting BIM with acoustic simulation remains a research issue. Based on the above findings, many proficient acoustic simulation tools are available but the ability to link other than geometrical data is missing. It seems that while efforts are being made to integrate acoustic analysis with BIM authoring software, more development work is required to overcome the challenges of extending the IFC schema, achieving improved functionality in reading and writing to the IFC file, and attaining a bi-directional exchange of building data.

VIII Interviews

Seven interviews were conducted with architects and architectural technologists from practices based around Dublin and Kildare. These practices were either using level 2 BIM, have some newer projects at level 2 BIM or currently making the transition to level 2 BIM. A semi-structured interview method using closed and open-ended questions was used to gather qualitative data. Requests for interviews and interview arrangements were conducted via email. The initial email provided information about the study contained in the research participant information sheet and upon agreement to take part in the study a further email was sent containing the interview questions and informed consent forms. Due to the current Covid-19 pandemic, all interviews were carried out using the Microsoft Teams collaboration platform at a time convenient to the interviewee. The interviews aimed to gain information and insights from people who are involved in the design of our built environments regarding current design approaches for acoustic performance evaluation, the disconnection of acoustic performance and architectural design, and industry need for acoustic simulation/BIM integration. For the following, the four architects will be listed as A01, A02, A03, and A04. The architectural technologists will be listed as AT01 and AT02 and the senior executive technician listed as SET01.

Presentation of Findings

All seven interviewees utilised Autodesk Revit as their main BIM authoring platform and had worked on projects where acoustic simulation had been implemented on contracts such as interior fit-out projects for major IT companies such as Facebook and Google, cinema design, conference centres, and housing schemes. Out of these, none had utilised acoustic simulation software in-house. 6 of the workflows for inspecting/evaluating acoustic performance directly involved an outsourced acoustic consultant, in the remaining case the responsibility was placed on the building contractor to carry out acoustic testing. The following table shows the responses when asked for their evaluation of this process.

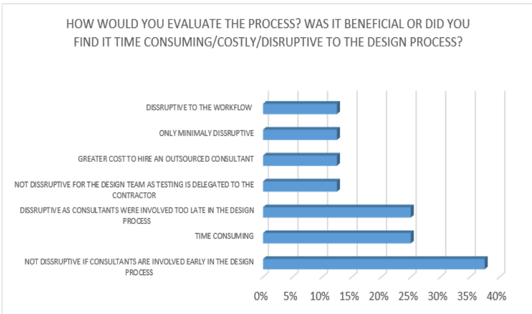


Figure 9. Evaluation of the current process for acoustic analysis.

When questioned on the significance of acoustic environments in learning spaces, A01 and AT01 believed they are important with the remaining 5 stating that they would have very high importance, citing the main factor being levels of concentration affected by poor acoustics owing to the incorrect use of materials and spatial design. Moreover, all of the respondents stated that acoustic analysis would definitely be a necessity for the design of such places.

When asked if they believe that there is a certain disconnection between architectural design and acoustic performance, all interviewees felt that this is the case with reasons for this being the architect's depth of knowledge of acoustics, with acoustics being a separate specialised field, and the lack of available integrated acoustic simulation software solutions. The gap in the availability of acoustic evaluation technology was felt throughout all interviewees. AT01 stated that acoustics would be more prominent in architectural design if this technology was available. A02 explained that many architects would feel that they have sufficient skills to know how a room may perform in smaller scale spaces through the specification of materials with acoustic reasons in mind but may not for projects that are "in the middle" such as classrooms. They would feel that they are making a heavy demand by asking a client to pay for an acoustic specialist to be consulted as the client(s) may believe that this should be covered by the architectural profession, so if the architect had access to a tool that could give them even a basic feel for how a space might perform, it would be enthusiastically welcomed.

All of the interviewees stated that our acoustic environments are at a disadvantage by the lack of an integrated acoustic evaluation solution for BIM authoring platforms and that having access to this technology would enable more informed design decisions made earlier in the design process and lead to better-performing environments. SET01 stated that this could lead to lowered design costs and that acoustic specialists may not need to be consulted so often.

A point raised by A02 was that, over the last 15 years, building standards have become somewhat tighter for housing projects regarding sound transmission between floors and apartment units. Architects currently rely upon technical details and manufacturers technical data to meet the required standards. A02 went on to state that this is an area where acoustic simulation software could provide a means of running sound transmission tests on a particular wall build-up to see if it meets building regulations and offer a way of seeing how this might be improved by changing materials and wall thicknesses. Figure 10 below shows the responses when queried on the benefits and drawbacks that they could foresee in the use of this technology.

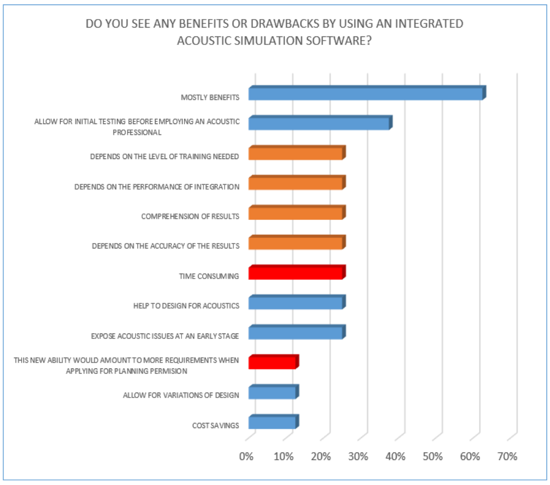


Figure 10. Benefits and drawbacks foreseen by using integrated acoustic simulation software.

All interviewees responded positively when asked if this software would then be utilised to evaluate spaces that may have previously been overlooked. A01 stated that it would offer better calculations for acoustic levels in these areas and AT01 raised the point that, depending on functionality, simulations may be set up to run analysis 'after hours' on many rooms as a time-saving measure. Current state-of-the-art acoustic simulation software can present simulation results in several ways, when asked what would be the most beneficial feedback that could be obtained for the designer SET01, AT02, A03 and A04 all agreed that the most beneficial of these would be quantitative values. As A04 stated, quantitative values are all you can accurately measure and write down in a specification so if your analysis is based on actual data you can measure this against the required performance specification.

Many of the interviewees were surprised that there is an ability to listen to the acoustic environment through auralisation. AT02 stated that although quantitative analysis would be the most important feedback, auralisation would be beneficial in being able to change materials and get real-time feedback on how the acoustics perform in the space. AT01 believed that auralisation would be the most beneficial as it would offer feedback on how different surface materials in the design behave and lead to better-informed decisions. A04 believed this ability would be valuable for more traditional buildings and that if you are getting into a much 'higher-order building', being able to physically listen to the acoustic quality of the space is probably important. A02 was of the opinion that the ability to listen to various design options of a room would be ideal and could also see that having the results displayed visually showing how the sound reflects and dissipates could be more beneficial to the architect as sheets of data and figures, while important, require a certain level of skill to understand but these can always be sent on to a specialist for interpretation.

Figure 11 shows the responses to the final question of the interview which was to ascertain what the main benefits would be by having the ability to investigate the acoustic environment of a proposed design within a design workflow.

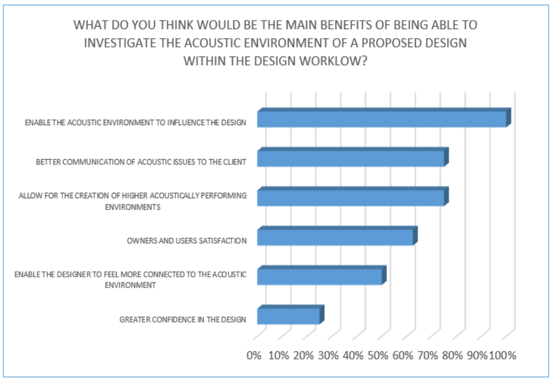


Figure 11. Benefits of being able to investigate the acoustic environment.

IX *Conclusion*

The acoustic environment is a crucial aspect of our multi-sensory experience of the built environment which suffers due to the pre-eminence of image in architectural design.

It is well documented that undesirable acoustic conditions can have a great effect on our well-being and cognitive performance. Our spaces for learning, which should provide an environment that promotes concentration and communication, often fail in their purpose due to the acoustic environment being overlooked or ill-considered at the design stages.

Factors such as high ambient noise levels, exterior noise intrusion mixed with excessive reverberation result in a poor acoustically performing environment, yet these factors may be extenuated using methods of exterior building skin augmentation, sound insulation, sound absorption, vibration isolation/damping, and the correct use of materials and acoustic treatment.

Achieving a higher acoustically performing building requires more attentive design at an early stage. This can be greatly assisted through adopting acoustic simulation technology as an essential tool in the design workflow although, in practice, factors such as time, cost, attitudes towards, or a lack of understanding of, the importance of the acoustic environment by both architects and clients may pose barriers in its uptake.

The findings suggest that acoustic simulation technology, although not being utilised directly by the designer, was deemed by all interviewees to be a necessity. They further suggest that a disconnection exists between architectural design and acoustic performance created in part by the lack of integrated acoustic evaluation technology and that the use of this technology would engender a greater prominence of acoustics in architectural design and lead to better acoustically performing environments.

With the appropriate training, current acoustic simulation technology is both accessible and capable of providing the means to evaluate acoustic performance. Granting designers the ability to make more informed design decisions will inevitably lead to better-performing environments and therefore acoustic simulation technology should be utilised in architectural practice. However, securing its place amongst the arsenal of tools available to the designers of our built environment can only occur with greater integration of this technology into a BIM-enabled workflow along with a deeper understanding of our relationship with our acoustic ecology on the part of the designer.

Unfortunately, this technology currently stands alone from any real integration with BIM due to challenges in attaining a bi-directional exchange of building data. Ensuring interoperability using the IFC format would require further development to combine building contractual and managerial aspects with that of physical and environmental data along with data required for the calculation of passive acoustic aspects. That being said, many researchers are currently making progress using various approaches to attain interoperability suggesting that the potential for integration between BIM and acoustic simulation technology may in time be realised.

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