Investigating A Novel Approach for Optimising Indoor Room Acoustics using Parametric Digital Twins

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CONTENTS

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1 INTRODUCTION

The atmosphere of a space shapes our experiences, ranking the highest in what people are looking for in a good venue [1]. This combined with 60% of respondents avoiding noisy places, and over half of the population experiencing heightened sensitivity to background noise, shows there is a real need to have good atmospheres and sound in public spaces. This problem is recognised by significant players in the industry, such as Jaguar Land Rover, investing £150M in acoustics research to benefit mental health and wellbeing [2].

Mumbli is a start-up company also tackling this area, focused on improving people's hearing wellness by helping venues such as cafes, restaurants and coworking spaces improve and monitor their acoustics, and enabling users to find venues they want to go to based on their sound qualities.

Mumbli is supporting this Masters project to help them achieve their mission, with this work focusing on improving venue acoustics.

2 PROBLEM STATEMENT

Mumbli has found that improving the acoustics of venues is often challenging. Currently, the primary option is to install absorption panels to reduce Reverb Time, RT, as this is usually what makes a place sound "bad". Venue operators often want to install such panels, but may not have sufficient budget, or suitable location to install, or it may clash with their aesthetics. Sometimes there might be budget for half the recommended number of panels, but little knowledge on how to make the best of fewer resources. Mumbli is facing all these scenarios and is now looking for a way to computationally optimise indoor acoustics that accounts for these objectives and constraints and can be offered as a service to venues.

There are likely many ways to approach this. A literature review will focus on comparing a variety of these methods and explore the latest work in these fields, to identify both the best existing solutions and opportunities for novel work. At this stage, the review will focus on the core which is the acoustics modelling. Creating digital models of indoor spaces and optimisation architectures will be explored in the next phase.

3 Literature Review

3.1 Room Acoustics Background

3.1.1 Sabine and Eyring

From 1900 through 1915, Sabine worked on predicting the RT of concert halls [3]. Sabine's equations calculate T_{60}, the time in seconds for a sound to decay by a factor of 1000, or -60dB.

$$T_{60} = \frac{0.161V}{A + 4mV} \quad (1)$$

Equation (1) shows how T_{60} is proportional to V volume of the room, inversely to A total sound absorption (sum α absorption coefficients multiplied S areas), and constant m sound energy losses for traveling through air. Eyring (1930) also proposed a different method of calculating A [3].

These methods, while very simple, are both used today commercially for sound treatment installations [4] [5] [6]. Treatment providers calculate how much absorption surface area must be added to achieve a desired RT. These models neglect many acoustic properties and can be bettered by taking an approach which takes room geometry into consideration.

3.1.2 Geometrical Acoustics

Geometrical Acoustics, GA, uses geometric observations and laws to estimate the acoustic properties of a space, with concert halls being some of the earliest practical examples [7]. Sound is considered as rays emitted from a source, with paths traced up to a receiver [8]. GA can be used to estimate impulse responses (propagation of sound pressure) and time-energy characteristics (decay of sound energy) [9], where each peak on the impulse response represents a reflection path.

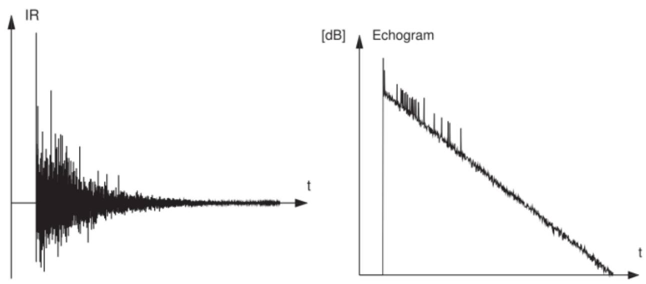

Figure 1: Impulse Response (left) and Echogram (right) [9]

GA: Image Source Methods

ISM gets its name from using virtual "images" of the sound source reflected in the room boundaries to create reflection paths. Figure 2 shows an emitter (left, red) and receiver (right, blue) and the four 1st order reflections, one for each wall, and their "virtual" sound source.

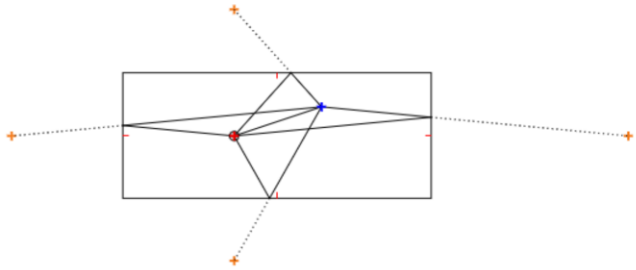

Figure 2: Interactive demo of imagining method [10]

This method was first conceived by Carslaw (1899), realised with the shoebox room example by Cremer (1948), and used for calculating sound pressure as a function of time by Mintzer (1950) [9]. However, this method only considers *specular* sound reflections, where angle of incidence equals angle of reflection.

GA: Ray Tracing

Sound reflections can also be *diffuse*, where a ray reflects at a "random" angle. Real materials exhibit both properties, and the ratio of specular to diffuse reflections is the *scattering coefficient*. Ray tracing is a *stochastic* method where the emitter emits rays in random directions, whose paths are traced for a defined number of reflections. If a ray intersects the receiver volume, it is registered to create similar outputs to ISM. The reflection types can be probabilistically simulated using the scattering coefficient [9].

This method dates to Allred and Newhouse (1958), with Krokstad et al. (1968) then using ray tracing to create time-energy responses of a rectangular room. Kulowski (1982) proposed using a standard deviation measure of convergence at intervals to judge when enough rays have been cast [9].

GA: Diffraction

Diffraction occurs when sound waves bend around a sharp edge, for example around a pillar or a narrowing between two rooms. This is not accounted for in GA's assumption that sound travels as a ray, but can be approximated by detecting these edges and treating them as edge sound sources themselves [9]. Professional Ray Tracing software such as CATT have this functionality available [7].

3.1.3 FEM & BEM

Finite Element Methods and Boundary Element Methods are physically based (solving the wave equation) and differ in that FEM discretises the domain volume whereas BEM discretises the domain boundary [11]. These are the most accurate methods [12], accounting for diffraction and low frequency modal responses, but quickly increase in computation complexity especially at higher frequencies. Commercial implementations exist in products such as the Acoustics module in COMSOL [13] and the free software FreeFEM [14].

The accuracy and computation time depend heavily on the order of the polynomial functions to solve, p, and the mesh size, h. Algorithms can be used to optimise these methods including adaptive mesh sizes around complex geometry, and adaptive polynomial orders, increasing accuracies in selected elements [15].

3.1.4 FDTD & FVTD

Finite Difference Time Domain and Finite Volume Time Domain methods differ from FEM/BEM by using a finite difference in place of the derivates in the wave equation, removing computational complexity [11].

FDTD methods were first applied to room acoustics by Botteldooren (1994) and have been extensively developed by Bilbao (2013) [12] and his PhD student Hamilton (2016) [16].

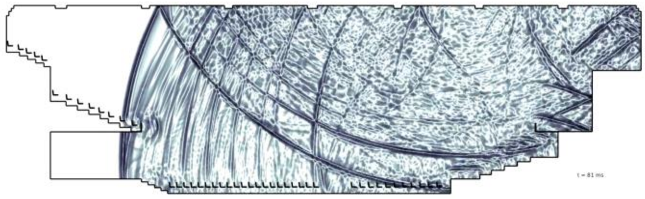

Figure 3: 2D Wave simulaton of a concert hall [17]

Figure 3 shows a simulation from Hamilton using these methods in a 2D concert hall.

3.2 Room Acoustics New Works

From improved wave-based models to machine learning methods, exploring the cutting-edge and developing landscape will help shape the direction of this project and make sure it works on novel, relevant problems.

3.2.1 SEM

The Spectral Element Method is a variation of FEM/BEM using different underlying functions, which, according to Ainsworth and Wajid (2009), makes the method *"particularly attractive for the efficient numerical simulation of wave phenomena"* [18].

Llopis et al. (2021) propose an extension of this by using Reduced Basis Methods, RBM, to speed up the repeatability of SEM [19]. RBM takes parametrised room models and uses an initial stage to generate a problem-dependant basis. For subsequent runs with different room configuration input parameters, the basis can be used to reduce the dimensionality of the problem, speeding up computation.

3.2.2 Optimisation Models

Multi-objective optimisation in architecture

Agirbas (2021) presents an optimisation model for building design which accounts for acoustics, claiming to be the first [20]. The model uses objective functions maximising annual daylight, speech clarity (C50), and floor area. Furniture was not considered, and materials kept constant, with building dimensions parametrisable and constrained.

The model was made in Rhinoceros [21], a 3D modelling software with a visual programming language. The Grasshopper plug-in [22] allows for parametric modelling of the room. Other add-ons were used for modelling daylighting and acoustics, all part of a complete, parametric system, Figure 4.

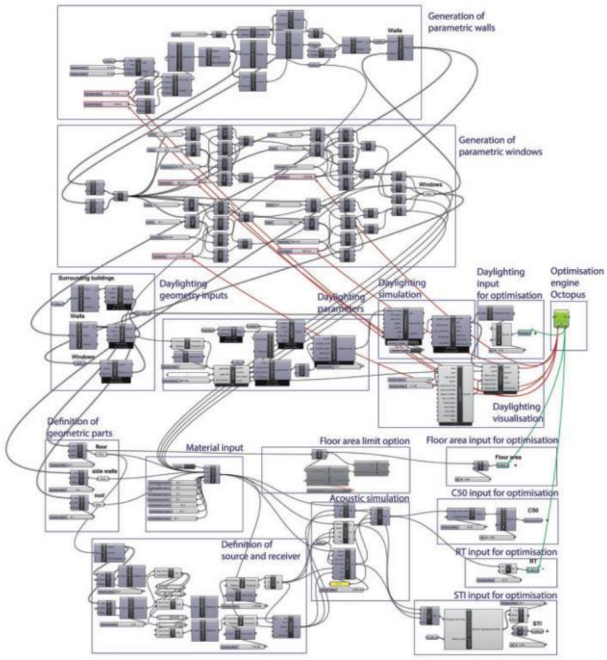

Figure 4: Node script network for the model [20]

The Octopus add-on multi-objective optimiser [23], based on a genetic algorithm, was able to take initial setup conditions and produce more optimal building designs, with better C50 and daylighting values.

Optimisation of absorption placement

The optimisation of acoustic absorption panel placement is generally non-linear as discussed by Saksela et al. (2015) [24]. Their study turned this into a linear problem by eliminating the "spatial" variables. The walls were discretised into tiles with absorption coefficients. A least-squares method then found the optimal distribution of absorption coefficients. Spatial information can then be extracted by identifying which wall sections required the greatest coefficients as visualised in Figure 5, offering "plausible" results [24].

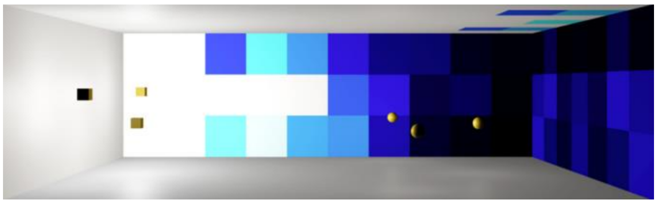

Figure 5: Absorption coefficients, white (0) to deep blue (1), emitters (cubes) left, receivers (spheres) right

3.2.3 Machine Learning

Image2Reverb

ML methods look to skip entirely the process of modelling a room to calculate RT. Image2Reverb [25], is a model to estimate RT from a photo of the room. Image2Reverb uses deep convolutional networks based on GANSynth that take an image input and produce an impulse response. Their work found promising results, with "plausible" auralisations generated from the model's impulse responses.

Predicting Acoustic Indicators

Yeh and Tsay (2021) built a Gradient Boosting Decision Tree (GBDT) model to estimate RT60, SPL difference, C50 and C80 from basic geometric measurements of the room [26]. In their tests, this exceeded the accuracy of Sabine and Eyring models.

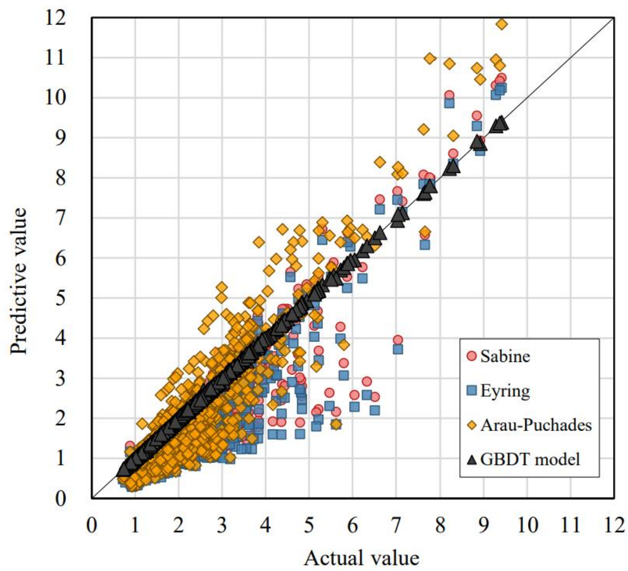

Figure 6: Scatter plot of RT [26]

In Figure 6, the "Actual value" represents RT evaluated in Odeon, serving as ground truth, and "Predictive value" is the time predicted by the models shown. Training data comes from a procedurally generated dataset of 800 cuboid rooms, also made in Rhinoceros [21]. Room dimensions, window placement, and acoustic treatment placement are all parametric variables. The absorption coefficients were obtained from datasheets and refined using Odeon's "Genetic Material Optimiser", an algorithm used to automatically adjust the coefficients such that the model prediction matches a measured ground truth [27].

3.3 Summary and Learning

As discovered in the review, the research landscape is constantly evolving, with continued research into FDTD, SEM, and potentially more models to come. Therefore, the **optimisation layer developed should be modular** and able to operate on different acoustic models as they develop. Initially, the well-established method of Ray Tracing will be used, the most accurate of the faster GA family.

However, there seems to be far less work in implementing these models in optimisation methods. It is interesting to note Odeon's own recommendation to use "trial and error" [28] when using its GA software, manually changing parameters until the simulation delivers desired results. Existing optimisation studies target specifics such as room shape, or absorption panels. This project therefore aims to be a **highly generalised** optimiser with the scope to handle **massively multivariate room models.**

Expanding on this, it may also be worth looking at **alternative ways for improving room acoustics** which, as identified so far, have not been explored by other studies. For example, does rearranging the furniture change the acoustics? Does changing the direction of people talking impact speech intelligibility? Therefore, furniture and other objects will be included as variables to be optimised. This might give venues the option to improve their acoustics "for free" by just modifying their existing space, or help venues make the most out of the treatment they can afford, financially and spatially.

It is also interesting to observe the different approaches taken for generating parametric room models, such as the use of Rhinoceros, and the methods used to **reduce the parameter space**, such as approximating acoustic panels as discretised walls with absorption coefficients. These will help inspire optimisations within the project.

In almost all work studied, the same few evaluation metrics were used such as RT60 and C50. With Mumbli's diverse range of client venues and a wellness focused mission, other evaluation metrics should be explored, such as more **perceptual models** like speech intelligibility discussed in [29] and [30].

A supplementary full breakdown of objectives and measurable outcomes is given in **5.**

4 PROJECT PLAN

The acoustic simulator CATT Acoustics will be used extensively in this project. The Audio Experience Design team has access to this software for at least the duration of this project.

Access to venues will be required to take test measurements. This will be provided through project partners Mumbli, who have confirmed access to at least 5 venues. Use of this data in this project falls within the already agreed terms between Mumbli and the venues.

Acoustic materials (e.g. absorption panels) may be required to test predictions. These should be provided through Mumbli as part of their acoustic treatment of venues. However, if no material is available, other methods of validation may be used. This could include replicating a tradition Sabine based acoustic treatment in CATT Acoustics and comparing these predicted results to the predicted results of this project's "optimised" proposal, to assess the ability of the optimiser against a baseline.

No part of this project will be disrupted in the case that Mumbli chose to end their involvement. New venues may need to be found in this case.

No human trials are not foreseen at this stage.

5 SUPPLEMENTARY: ACTIVITIES BREAKDOWN

Aim	Measurable outcome	Term
User friendly way to create 3D models of a room	Create a schema of required information for the model and create a template for collecting this data on a site visit to a venue. 3D models may be made in Blender to make use of its Python API in later steps, with templates and custom scripts written to accelerate the creation process. Data such as material properties will be stored in the 3D file as metadata. Constraints such as usable ceiling space can be modelled as empty geometry (e.g. bounding boxes, which do not get included as geometry on export)	T1
Parametrisable permutations of the model	Parameters and constraints will be defined in the metadata for each object in the model. A list of parameters can then be automatically generated to define a valid permutation of the room. A function will take an input list of new parameters and transform each object in the model accordingly. Parameter lists can be passed in either manually or via scriptable commands.	T1/2
Export to acoustic software	Scripts will be written to export the model in the appropriate format for the acoustic software, in this case, CATT. This will enable the desired acoustic qualities to be evaluated using the pre-set simulation environment.	T1
Run acoustic simulation	The acoustic simulator will need to be set up for the needs of this project. Parameters such as type of solver, number of ray bounces etc will need to be defined, most likely from experimental data to decide the best setup for the project, for example deciding a trade-off between time and accuracy.	T2
Calculate perceptual values	Existing perceptual models in MATLAB / Python will take the output values from the simulation and compute additional desired metrics.	T2
Optimisation function	Exact implementation yet to be decided. The input parameters for the room model and the output metrics from the simulation and perceptual models will be passed into the optimiser function. As an example, a genetic algorithm may be used where multiple random rooms are evaluated and the best few chosen. These parameters will spawn a new child generation of room models, with the parameters being passed back into the Blender model which will create the new rooms for evaluation and so on. Other algorithms will be explored and evaluated; this will be the focus of the project.	T2/3
Alternative methods of optimisation	Inspired by the literature review, other methods will be explored in the optimiser. For example, approximating absorption panels as a grid of tiles over a surface with absorption coefficients to be optimised using solvable algorithms such as least-squares. Methods like this could decompose the optimisation problem and reduce the dimensionality, making it easier to find optimal solutions.	T2/3
Validation	Case study venues through Mumbli's connections will be used to validate this project. Practical measurements will be taken as baseline for the venue. The room will then be modelled and optimised using the methods created in this project. A proposed acoustic treatment plan will be generated and implemented in real life. New measurements will be taken and compared to the predicted results. This can be repeated for more venues, if possible, as further validation. Evaluation can be quantitative and qualitative, for example taking both RT60, C50 values and customer surveys about the sound and atmosphere before and after acoustic treatment. Validation will also be done against the "default" option to answer if this model's acoustic treatment is better or better value for money than what would be recommended by the installation company / Sabine equations.	T3

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