Parametric Acoustics: Design techniques that integrate modelling and simulation

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Abstract
Architectural design is done entirely in computer-aided design (CAD) systems, and most CAD models are also done in 3D. Beyond CAD, parametric design software is now both popular and accessible to architectural students and practitioners. The most popular parametric system, Grasshopper (GH), is customizable and supports a rich ecosystem of plugins including many types of building performance simulation, including acoustic simulation. Architects often ignore sound and part of the reason for this is a complete lack of sound in architectural design software. Parametric modelling presents an opportunity to integrate sound into architectural design, and at earlier design stages. This opportunity addresses challenges of interoperability and file exchange as modelling and simulation happen within one system. In this paper, we review recent research utilizing parametric modelling combined with acoustic simulation and identify a way of working we call "parametric acoustics". We further identify nine techniques that can leverage capabilities of parametric modelling and integrated acoustic simulation.

Keywords: Architectural acoustics, parametric modelling, room acoustic simulation, optimization, performance-driven design

1 Introduction

In the past 30 years there has been a dramatic shift in contemporary architectural practice from design using paper drawings to computer software. Now all buildings are designed using computer-aided design (CAD) systems, and most today are modelled in 3D. With developments in CAD and building information modelling (BIM) software most architects create virtual models of their buildings from early design stages. In the last 20 years we have also seen the development of parametric design software created specifically for architects. [1] Grasshopper (GH) is probably the most popular of these parametric design systems and is widely used in architectural education and practice. As it supports the creation of custom plug-ins, there now exists a rich ecosystem of building performance simulation applications that run natively within this parametric design environment. [2] One of these plug-ins, Pachyderm, computes room acoustic performance. [3]

While acoustic performance is a component to all architectural projects, it is most often calculated by acoustical consultants, who are not involved in all projects. Acoustic consultants use specialized simulation software such as Odeon and CATT, and these simulation software's require geometry to be created natively or imported from architect's CAD files. This is an onerous design workflow, see Figure 1, as designs are created in many different media, by different people, and files need to be translated to go from one person or media to another. The time-consuming nature of this process, together with the fact that acoustical consultants are not always brought onto the design team in early design stages means that acoustic design considerations do not have a chance to influence early form investigations, and acoustic performance is often relegated to a remedial action later in the design stage.

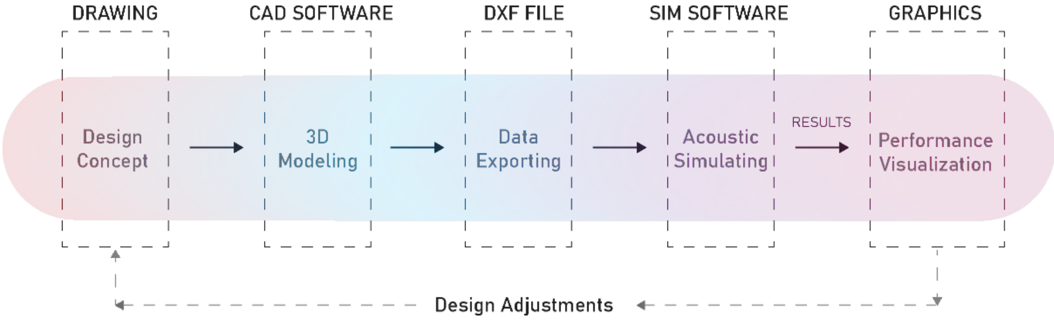

Figure 1 – A standard architectural acoustics workflow

This research project begins with the proposition that there is an inherent opportunity that lies within new parametric design and simulation software that enables acoustical performance to be brought in earlier in the design process. We call this new way of designing for sound and space, "parametric acoustics." In the parametric acoustics workflow, designs do not need to be translated as design logic, modelling, and simulation is done within the same environment – within the "parametric script", see Figure 2. We believe that this revised workflow makes it easier and faster to carry out acoustic simulation, and it will greatly increase the formal and aural possibilities that designers will be able to explore.

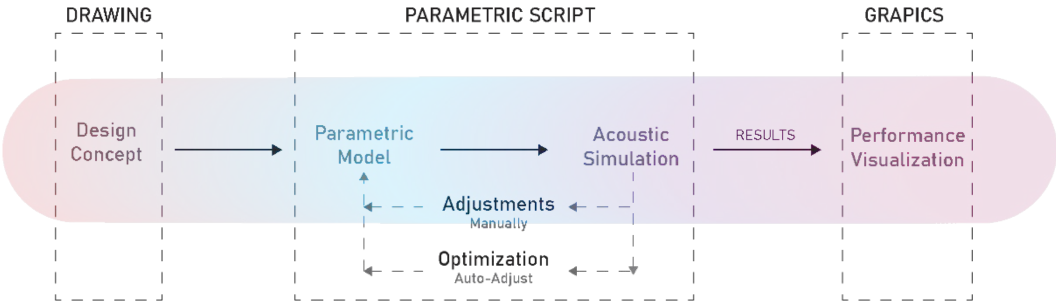

Figure 2 – A parametric acoustics workflow

2 Background

In the early 2000's, most architects still relied on their intuition and past experiences to begin the early designing phases of a project, often through the fundamental method of trial and error to try and meet required project requirements. In the case of acoustics, only when a clear design was established were other acousticians consulted to analyze and help optimize performances metrics. This post-design consultation approach could lead to cost increase and limit potential solutions due to installation challenges. [4]

However, this mentality started to slowly change in the 2000s, with the introduction of new parametric software designed specifically for the building industry, and one of the first parametric programs was *GenerativeComponents (*GC*)*, developed by Robert Aish. [5] GC was developed and user-tested by members of the Smartgeometry (SG) community, a computationally-adept group of architects and engineers who were interested in integrating parametric modeling as part of their design workflows. [6]

In conventional modelling, parts of a model are easily added, modified, or erased, but these parts have no relation to each other, and so changing designs is difficult which limits exploration and restricts design. [7] In parametric modelling, the designer establishes relationships and builds a design through this series of relationships. As this requires more thought to develop the logic of the design, parametric design can take more time initially, but it makes reworking designs very fast. [7] In architecture, parametric modeling often refers to “propagation-based systems” [1] which is based on the idea of constraints where the user selects and establishes the relationship between parts, which together build up into cohesive system that remains consistent throughout changes. [7] By leveraging computational power, parametric modeling can quickly iterate through different design changes within the defined constraints within the algorithm and remain consistent to the entire framework. [7] Through parametric modelling, architects are now able to leverage complex mathematical formulations to optimize building designs using simulations such as structural analysis and daylight studies. These powerful new tools enable architects and engineers to integrate performance from early in the design process. This performance-driven geometry approach has started to become the primary driver for design explorations for architects and academics. [8] [9] [10]

David Rutten, a developer for McNeel’s Rhinoceros 3D CAD software began to develop a parametric visual scripting plug-in, *Explicit History,* in 2007*,* which was the precursor for the now well-established GH parametric design software. [11] For the building industry, GH has popularized parametric modeling more than any other comparable platform due to its easy-to-use graphical user interface (GUI), and open development environment. The advancements of parametric modeling rapidly led to the creations of many popular GH plugins for structural (Karamba3D), daylight (DIVA, Ladybug) and energy (Honeybee) analysis purposes.

In architecture, acoustic qualities can have direct impact on how people experience and perform in a space. [12] The strategic placement of absorptive, diffusive, and reflective materials is utilized to tune the soundscape of architectural spaces. [13] This is particularly important in auditoriums or concert venues where acoustic performance is the primary programmatic function. However, sound is component to all architectural design, and so all architecture should have some consideration of acoustic performance. In many cases, acoustic solutions are often implemented as an addendum. Acoustic simulation tools that ran natively within CAD software remained unknown until the introduction of Arthur van der Harten’s Pachyderm Acoustic Simulation, which uses a standard raytracing (RT) algorithm. [3] Prior to Pachyderm, only few architects trained in acoustics had the skillset to write custom computer programs in CAD that could carry out acoustic simulation. The introduction of Pachyderm has introduced a new territory of design in architectural acoustics. Architects and engineers are now able to both utilize acoustic simulation based on RT methods, and leverage the benefits of parametric modelling, to design better sounding architecture.

3 Methods

Various design-minded acoustic engineers, and technically focused architects have begun to leverage the abilities of parametric modelling combined with acoustic simulation to develop form-driven architecture. This renewed interest by practitioners has presented an opportunity to investigate the state-of-the-art, [14] and report on how building designers are integrating these tools in their design workflows. [15] A literature review was conducted using a set list of keywords and searched both the University of Toronto database as well as CUMINCAD, a resource of established architectural conferences and journals. We manually filtered to a final list of 40 publications for review. In our analysis of these papers, we noted commonalities, differences, and unique approaches the works, such as workflows, software, custom scripts, and acoustic simulation methods. These findings were categorized into core strategies that we defined and discussed in further detail. This paper builds off a comprehensive study of acoustic performance-based design carried out by Badino et al. [8]

4 Results

We recognize that using a literature search of only academic papers, it is not possible to produce an exhaustive list of all recent projects that combine parametric modelling and acoustic simulation; however, clear observations about the state-of-the art can be made from the data. Table 1 summarizes the results of the literature search, and a few key observations emerge from it: first, Rhino and GH are by far the most popular modelling tools with which to carry out parametric acoustic explorations; second, while Odeon appears to be the most widely used acoustic simulation software, it is almost always used to verify the results of the parametric modelling approaches, and the most common simulation approach that is integrated with parametric modelling is the development of custom acoustic performance calculators; third, the most common algorithmic simulation approach is ray-tracing; fourth, projects seem relatively evenly split between music venues and other program types; and fifth, that surprisingly few optimization software's are used.

[i]	Software: CAD Modeling			Software: Visual Scripting		Software: Coding Language		Software: Program	Software: Acoustic Simulation							Methods					Plug-ins					
	Rhinoceros	MicroStation	Not Specified	Grasshopper	Dynamo	Visual Basic	Python		CATT	COMSOL	Odeon	Pachyderm	Matlab	Reflex AFMG	Custom \ other	FEA \ FEM	FDTD	RT	PatternSearch	BEM	Galapagos	Octopus	Custom GA	Kangaroo 2	Snail	KUKA|prc
[16]	✓			✓				Meeting Room			✓							✓								
[17]	✓	✓		✓				Meeting Room			✓	✓	✓	✓			✓	✓		✓						
[12]	✓			✓			✓	Meeting Room			✓			✓	✓		✓	✓		✓						
[10]			✓					Midsize Office																		
[18]	✓			✓				Multi-use RM				✓						✓								
[19]	✓			✓				Fabrication Lab.		✓					✓	✓		✓				✓	✓		✓	
[20]	✓			✓				Industrial Hall			✓							✓								
[21]			✓					Open-plan room			✓							✓								
[22]	✓			✓			✓	Scatter Wall																		
[23]	✓			✓				Hanging Canopy					✓		✓		✓		✓							
[24]	✓			✓				Concert Pavilion							✓						✓					
[25]		✓				✓		Concert Pavilion			✓				✓			✓								
[26]	✓			✓				Music Hall	✓				✓		✓			✓	✓							
[27]	✓			✓				Music Hall										✓								
[28]	✓					✓	✓	Music Hall							✓	✓		✓					✓			
[29]	✓					✓		Music Hall																		
[30]	✓			✓				Music Hall			✓							✓								
[31]	✓			✓				Music Hall			✓							✓						✓		
[32]	✓			✓				Auditorium							✓			✓								
[33]	✓						✓	Auditorium	✓									✓								
[34]			✓					N/A						✓				✓		✓					✓	

Table 1 – Modelling and Simulation Tools and Methods

A closer reading of these projects was undertaken to discover common parametric acoustic techniques. Beyond listing software or the mention of "custom" tools, many authors did not go into detail on the specifics of the logics of their modelling and simulation techniques. So, to identify techniques we not only used the papers summarized in Table 1, but added reflections upon our own practice [12] [17] [25] [21] [35] [36] to gain deeper understanding of the design workflows. We have identified nine techniques that can be useful to designers using a parametric acoustic workflow, see Table 2.

ID	Classification	Description	Index
1	**Reflection Mapping**	Counting rays that are reflected	[12] [16] [17] [18] [19] [20] [21] [25] [26] [27] [28] [30] [31] [32] [33] [34]
2	**Complex Geometry Generation**	Complex Geometry Generation for Diffuse Surfaces	[2] [12] [20] [23] [25] [29] [30] [37]
3	**Geometry Exchange**	Preparing geometry export settings to be imported in another program for validation, etc odeon/comsol.	[17] [31] [23] [29] [31]
4	**Material & Geometry Mapping**	Measuring and comparing reverberation time	[36]
5	**Optimization**	Using Genetic Algorithms / Machine Learning/ Deep Learning, etc…	[24] [28] [19] [9]
6	**Digital Fabrication**	Exporting complex geometry for standard fabrication tools. File to factory process. Enables the fabrication of much more complex geometry which could benefit acoustics	[23] [31] [29] [38] [20] [22]
7	**Drawings & Visualization of Sound**	The graphical export options available within programs	[9] [32] [30] [27] [39] [30]
8	**Exploring Design Space**	Looking at multiple acoustic parameters in relation to parametric geometry	[9] [26] [22] [33] [25] [12]
9	**Spatial Performance**	Not only point solution, or room-level solutions but gradient map of heterogeneous performance	[9] [40] [29] [38] [16] [18]

Table 2 – Nine Parametric Acoustic Techniques

4.1 Reflection Mapping

Reflection Mapping is one of the most popular methods used when combining parametric modelling and acoustic performance considerations. Basically, this technique maps sound as a ray as it traverses a 3D geometric model using a reflection model of angle of incidence equals the angle of reflection. This method can be extended and developed into a full raytracing simulation or can be simply used to map acoustic reflections. This method can visually output the path of sound from source to receiver, and different reflection orders can be studied. Because of its simple geometric rules, fast calculation times, and easy visualization it is a popular approach. Peters [25] describes a simple approach where first reflections from a parametric ceiling were mapped onto an audience and so design options could be judged by how many reflections hit the audience and how evenly distributed these were; Shtrepi et al., [34] used Iron Python to write a custom RT component inside GH to output qualitative analysis data using Reflection Mapping and quantitative analysis through the visual inspection of polar distribution from the reflected energy generated.

4.2 Complex Geometry Generation

A second common use of parametric modelling is the generation of complex surfaces that produce sound scattering. In Peters [12] a complex surface was generated to diffuse sound in a small meeting room. This was done to remove distinct flutter echoes and create a more even, diffuse sound field. Using geometric relationships between size and frequency [2] different options were studied. Reinhardt et-al., [20] used mathematical models to link form and materiality for sound scattering. A KUKA KR6 was used to fabricate randomized approaches where 35 foam disc samples were robotically milled through a range of random non-predictable patterns in GH with a focus on surface depth and frequency range.

4.3 Geometry Exchange

While acoustic simulation can be carried out within a parametric acoustics workflow, often these models are supported by acoustic simulations using specialized simulation packages such as Comsol, Odeon, and CATT. Parametric acoustics can generate geometry in the correct format for easy export/import. In Alambeigi et-al. [16] FabPod project, Odeon was used to study the effects speech privacy on the Fabpod geometry created in GH. Through numerous simulations, they decided on using Speech Transmission Index (STI) and Speech Clarity (C50) as the two key parameters to analyse for speech privacy. Reinhard et-al., [20] generated geometrical models in GH and conducted acoustic simulation in Odeon to investigate the acoustic consequences on performative structures. By working in both Rhino and Odeon, the team was able to exchange ideas and knowledge with an interdisciplinary team of structural engineers, acoustic designers, and architects.

4.4 Material and Geometry Mapping

Wallace Sabine first defined the reverberation time as the relation between space, surface, and material. This straightforward relationship can be encoded into a parametric model. If the absorption coefficients are known and the parametric model is able to compute volume and area, the reverberation time (RT) as predicted by the Sabine formula can be calculated. In 2011, Peters' paper [36] computed the RT for classrooms in a school using this method. In Bonwetsch et al., [38] a robotic arm was used to 3D print Polyurethan material into coil shaped diffusion panels that resulted in noticeable in differences in acoustic performance as flutter echoes and standing waves were eliminated.

4.5 Optimization

Parametric modelling is often used in combination with genetic algorithms (GA) methods to optimize complex geometries for acoustic performance. It is important to note that optimization is not restricted to just GA's but can also refer to other methods such as Artificial Intelligence, Machine Learning or Deep Learning. In terms of GA's, Galapagos is an optimization solver in GH; there are other optimization plug-ins available for GH, such as Octopus. In Foged et-al., [24] Galapagos was used to orient 200 reflector panels to maximize reflection mapping and optimize manufacturing of these panels for laser cutting machines. In Giglio et-al. [19], a multi-objective evolutionary optimization solver, Octopus, was used to produce options that optimized acoustic performance keeping the center point of panels in the Z-axis to 1 meter and limiting the number of tessellations to four per surface. In Echenagucia et-al., [28] a multi-objective solver was used to inform the shape of a concert hall. The authors discovered that due to the curved surfaces losing their accuracy when being converted to meshes, the use of NURBS surfaces is better suited for RT studies in Rhino.

4.6 Digital Fabrication

Digital fabrication enables a file-to-factory process that enables the creation of highly precise and complex-shaped geometry which could have benefit to acoustic performance as seen in Turco et al. [31] origami project. Belanger et-al., [23] describe their project where parametrically-driven auxetic patterns were created, then discretized and exported as a text file into a custom Matlab script for a wave-based finite different time domain (FDTD) acoustic simulation. Well-performing auxetic patterns were chosen to be cut using a CNC waterjet onto stretched pane of glass, which was then formed over a slumped mould. In Koren's [29] paper about the Elbphilharmonie Hamburg (EH), he described how Cox and D'Antonio [41] developed plug-in for Rhino, consisting of 18,000 lines of Visual Basic code to create the NURBS surfaces of the EH's interior acoustic panels. Each of these 10,000 uniquely shaped panels had to be CNC-milled from gypsum fireboards, requiring an additional 20,000 lines of code to automate the digital production process. [29]

4.7 Drawing and Visualization of Sound

The visualization of simulation is essential to translate numerical results to meaningful information. Commercially available acoustic simulation software has built-in capabilities to visualize results as tables, charts, or coloured 2D and 3D drawings. However, with current parametric acoustics techniques, there are less standard built-in capabilities, but there exists the potential to customize the output of simulation data. As seen in the works of Lim, [32] Scelo, [30] Wulfrank et al., [27] and Gómez et al., [39] the drawing of sound as rays is very effective at visually conveying the acoustical performance of a space in a still image, while FDTD approaches can be utilized to create convincing animations of sound waves as seen in Peters et al. [12] and Belanger et al. [23]

4.8 Exploring Design Space

One of the key benefits of parametric modelling is that it enables designers to explore many different design options as seen in the works of Bassuet et al., [26] Peters [25] and Vomhof et al. [22] Once the parametric model is constructed, design options can be quickly generated by changing parameters and studying the resulting generated model. What parametric acoustics brings to this process is the inclusion of acoustic performance metrics as part of this generated model, as seen in Lu et al. [33] auditorium work where a balance of acoustic performance and design aesthetics is sought out through parametric modelling iterations. This integrated analysis enables acoustic properties to be considered alongside other parameters during early design stage explorations. This technique does require the selection of appropriate measures of acoustic performance and clear and meaningful ways of communicating this performance.

4.9 Spatial Performance

A parametric acoustics design approach is inherently computational, and the calculation of a series of results is trivial to set-up and it's solving is simply a matter of computing time; therefore, parametric acoustics encourages the calculation of multiple results as much as single results. Why calculate for a single position when one can see the spatial distribution at all points in a room? This technique considers spatial differentiation of acoustic qualities and makes it easier to identify problems and opportunities that this differentiation in acoustic performance brings about. O'Keefe et al. [40] developed a custom ray tracer plug-in for Rhino that could calculate reflections off NURBS surfaces as they realized the power of receiving immediate visual feedback in contrast to computing for numeric parameters, which take much longer to calculate. They tested their plugin on a case study for the orientation of acoustical panels in the Queen Elizabeth Theatre in Vancouver and concluded that this new approach helped them overcome the challenges of dealing with a wide room.

5 Conclusion

With the introduction of parametric modelling software and integrated simulation to architectural education and practice, we propose that there is an opportunity to include acoustic performance as a key design consideration within the building design process, even from an early stage. We call this design workflow "parametric acoustics." A literature review was carried out that studied recent papers that utilize parametric modelling and acoustic simulation. In this review we identify the most popular modelling and simulation software. Additionally, we have identified nine techniques of parametric acoustics. This is not meant to be an exhaustive list, but a step towards developing a dialog about the use of parametric modelling and about integrating simulation with the digital architectural design environment. We hope that this knowledge will used to help initiate the development of a toolkit that can used by architects to bring acoustic performance into their designs and result in better sounding buildings.

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