Acoustic Performance as a Design Driver: Sound Simulation and Parametric Modeling using SmartGeometry

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Abstract

Acoustic performance is an inevitable part of architectural design. Our sonic experience is modified by the geometry and material choices of the designer. Acoustic performance must be understood both on the level of material performance and also at the level of the entire composition. With new parametric and scripting tools performance driven design is possible. Parametric design and scripting tools can be used to explore not only singular objectives, but gradient conditions. Acoustic performance is often thought of in terms of singular performance criteria. This research suggested acoustic design can be understood in terms of gradients and multiple performance parameters. Simulation and modeling techniques for computational acoustic prediction now allow architects to more fully engage with the phenomenon of sound and digital models can be studied to produce data, visualizations, animations, and auralizations of acoustic performance.

SmartGeometry has promoted design methods and educational potentials of a performance-driven approach to architectural design through parametric modeling and scripting. The SmartGeometry workshops have provided links between engineering and architecture, analysis and design; they have provided parametric and scripting tools that can provide both a common platform, links between platforms, but importantly an intellectual platform where these ideas can mix. These workshops and conferences have inspired two projects that both used acoustic performance as a design driver. The Smithsonian Institution Courtyard Enclosure and the Manufacturing Parametric Acoustic Surfaces (MPAS) installation at SmartGeometry 2010 are presented as examples of projects that used sound simulation parametric modeling to create acoustically performance driven architecture.
1. Introduction

Acoustic performance is an inevitable part of architectural design. We are in a constant dialogue with our surroundings as our sonic experience is continuously modified by the geometry and materiality of the architecture that surrounds us. As Pallasmaa [20] states “buildings do not react to our gaze, but they do return our sounds back to our ears.” Architecture is the filter that modifies the sounds that we create. And as Barry Blesser (2006) has well documented, our aural environment is critical to our emotional well-being. However, in order to use acoustic performance as a design driver we must be able to measure and understand the acoustic consequences of our geometric actions and material specifications.

Raviv Ganchrow notes that architecture, as a design practice, operates primarily within a realm of representation, but there are limited design tools available to explore acoustic concepts. He suggests that the delay of the initiation of sound into the architectural design process might be due to a lack of proper tools for handling sound (see Altena [2]). Surveys of existing design tools show that no architectural software currently exists that combines both sound and geometry (DeBodt [8]). While all architectural design done today is essentially computer-aided, the design environment in which we currently work is, however, noticeably silent.

The use of the computer in architectural design has been used for visualizing already designed concepts, but now is increasingly used as a development platform to create software specifically for a particular design or production tasks (Vrachliotis [26]). Architects are also becoming increasingly aware of, and using engineering performance software as part of their design processes. (Kolarevic and Malkawi [15]) Though simulation once pertained to modes of presentation, there is now a shift in architecture to use simulation and modeling methods as a tool of knowledge as used in the natural sciences. (Gleiniger and Vrachliotis [11]). It is the potential of an integration of evaluative simulation processes with digital ‘form generation’ and ‘form modification’ models that is implied by the term Performative Design (Oxman 2008).

In the last 15 years, engineering acoustic simulation and modeling software has been developed that will compute performance data and produce sonic visualizations, and auralizations. This software can be linked to architectural drawing software through data exchange processes. In addition, there remains the potential, through computational design methods, to incorporate acoustic analysis algorithms directly into the architectural CAD software. The potential exists to develop design tools for architecture that will allow the exploration of acoustic concepts. Round robin tests done at Braunschweig University show good agreement between the six different commercial room simulation programs and that the measurements they produce accurately predict the acoustic performance of rooms. (Bork 2005)

This essay sets out to address the question of how architects can use...
acoustic simulation and modeling techniques and computational design tools, to design for acoustic performance. Two projects are discussed and presented: the Smithsonian Institution Courtyard Enclosure and the Manufacturing Parametric Acoustic Surfaces (MPAS) installation at SmartGeometry 2010. While these projects exist on very different scales and had different approaches to acoustic design, each project used acoustic performance as a key design driver and both projects utilized computational and parametric design approaches. Through studying the design processes of these projects issues relating to design tools, workflow, data, software, fabrication, and acoustic performance are investigated.

2. The Sound of the Smithsonian Courtyard

Hugh Whitehead, of Foster + Partners, is one of the founding directors of SmartGeometry, and his research group, the Specialist Modeling Group (SMG), has been heavily involved with the SmartGeometry workshops and conferences [27]. The work of this group both inspires and is inspired by SmartGeometry. The Foster + Partners SMG has been at the forefront of new developments in parametric design and computational design in architecture. The projects the group has been involved with, such as Swiss Re, London City Hall, and the Smithsonian Courtyard, have driven the development of new approaches and have only been possible through a tremendous amount of research and development, both internally and through events such as SmartGeometry. SmartGeometry events are attended by representatives from both engineering and architecture, and the concepts that are explored investigate and forge connections between analysis and design.

In 2004, Foster + Partners won an invited international competition to design the new courtyard enclosure in Washington, D.C. The design was for a complex roof structure that would perform as a solar shade, a weather protective device, and acoustic absorber. Designed to do ‘the most with the least’, the fluid-form, fully glazed roof canopy develops structural and environmental themes first explored in the design of the roof of the Great Court at the British Museum, bathing the courtyard with natural light. The SMG joined the project team to realize the synthesis of design, performance and geometry. Computer programming was used as one of the primary tools to explore design options. The design constraints were encoded within a system of associated geometries, and this set-out geometry performed as a mechanism to control the parameters of a generative script. While digital design was used extensively, the design evolution still involved the use of many different media and techniques and there was an intense dialog between a large team and many consultants. The computer script was a synthesis of the design ideas and was constantly modified by the architects during the design process (Peters [21]).

Robert Aish [1] identifies geometry, composition and algorithmic
thought as essential themes that need to be understood and used by designers in the creation of computational design tools. To gain control over large data sets, such as the geometric configuration of the Smithsonian roof, it is best to use an algorithmic approach. To control the design, the designer must be able to understand and control the algorithm. This generating algorithm can contain within it many or few rules. These rules can relate to the performance of the structure. Figure 1 shows a parametric model of the project that was created and presented at the SmartGeometry 2006 Workshop in Cambridge, UK. This model was done as a study to investigate the consequences of implementing this design in a dynamically parametric system. Here the roof structure was created as a system of beam components populated in relation to an orthogonal grid and a bspline design surface. Ultimately, the design was generated using a single computer program.

2.1. Acoustic Performance

The speed of sound, unlike that of light, is perceptible. The sounds of the past exist simultaneously with the sounds of the present and we notice this in the phenomenon of reverberation time – or the time it takes for a sound to decay to inaudibility. Reverberation time is recognized as the single most important factor determining the acoustic quality of a space (Egan [9]).

Figure 1. Parametric Model of the Smithsonian Institution Courtyard Enclosure by Foster + Partners from SmartGeometry 2006
Wallace Sabine, a young Harvard physicist, discovered the relationship between sound, space, and material. By knowing the surface area of the constituent materials, their absorption coefficients, and the volume of the space, the reverberation time can be predicted. This notion of “calculation in advance of construction” allows a designer a glimpse of what the space will sound like before it is built (Sabine [24]). This calculation has been the cornerstone of architectural acoustics ever since. An excess of reverberation of sound can make music sound better, and make speech incomprehensible.

Acoustic performance was a key design criteria for the design of the new courtyard. The space was designed to be suitable for large receptions, small gatherings, and a variety of types of performances. The design was inspired by the Foster + Partners Great Court and the British Museum. However, the Great Court does not have much acoustic treatment, and the space exhibits a very long reverberation time. The performance goal for the new courtyard was to reduce the reverberation time to 2 to 3.5 seconds. The heritage facades of the courtyard could not be modified, so the only place for the sound modifying surface was the new glass and steel enclosure.

In comparison to the Great Court, the glazing panels are larger and quadrilateral instead of triangular, the structure is entirely supported on columns instead of edge-supported, and the beams are deeper for both structural and acoustic reasons. The area of acoustic absorbing material was defined as a parameter in the generating algorithm and used as a design driver for this project. Given the absorption coefficient of the absorbing material and by controlling the area of the absorber, the reverberation time of different forms could be predicted. The acoustic performance of the courtyard could then be “tuned” using the generating computer program. The computer was used to develop a project-specific tool designed to explore the many formal potentials that lay within the parameters of the project. Within this algorithm many different objectives could be related to each other and in relation to these, different data sets could then be outputted. This data was then used by different project partners to carry out various analyses of the design options. While acoustic simulation was not internal to this design tool, it linked through the multiple representations of data that could be produced by the computer. A specific geometry and material specification could be generated by the parametric tool that was compatible with the acoustic analysis software.

A theme that is relevant in both SmartGeometry and in the development of the Smithsonian Courtyard Enclosure is the concept of component and carrier. This concept revolves around the design of components, which are sub-assemblies such as beams or panels, which can then be populated or assembled in relation to a larger geometry – the carrier. Components and carrier can be designed separated and, as long as
the rules that connect them are observed, can be brought together later. In this project examples of the components were beams, glazing panels, edge structure which were then populated with reference to a set out grid (the X and Y dimensions) and a bspline surface (the Z dimension). This analogy can extend to the concept of acoustic performance. The material performance of components and the performance of the whole room must be calculated in different ways, and so must be considered both in isolation from each other, but also as a composition. This also corresponds to two types of acoustic analysis: material analysis determining absorption and scattering properties, and room analysis determining acoustic parameters such as reverberation time, speech quality, and clarity. Buildings are not discrete objects, but are compositions of many elements assembled in a variety of ways and these materials act differently. In order to understand the performance of the acoustics of the composition, we must understand the performance of the components.

2.2. Material Testing and Acoustic Performance

The design of beam section was continually developed during the design process. Because there was no place else to put acoustic absorbing material, the beam structure essentially became a giant acoustic absorber. The material composition of the beam therefore included a large area of acoustic absorbing mineral wool mounted to the sides of the steel structure. This absorbing material was partially covered with a layer of thin stainless steel tubes. This layer of tubes created an acoustically transparent screen. If absorptive materials are overlaid by a porous screen it will have little effect on their properties so long as the screen is sufficiently open. If the perforated screen covering the absorbing structure is at least 15 - 20% open area, the material works as if it were un-faced. (Long [18]) The stainless steel tubes visually hid the absorbing mineral wool and also provide some degree of sound scattering at high frequencies. This configuration of materials was tested in a reverberation room to determine its absorption coefficient. The absorption coefficient is obtained for all audible frequency
bands. This information is then used for performance predictions in both statistical acoustic calculations, and also in computer simulation and modeling. This data was then be used in the computational prediction model, linking the form of the architectural digital model to physical performance attributes.

3. Manufacturing Parametric Acoustic Surfaces

The Manufacturing Parametric Acoustic Surfaces (MPAS) project was installed at the SmartGeometry 2010 Workshop and Conference titled “Working Prototypes”. The project was run as one of ten workshop clusters. Each cluster had a different design focus relating to the research interests of the lead tutors, but all cluster groups were charged with the fabrication of a 1:1 working prototype. Similar to previous SmartGeometry workshops, the projects used parametric and computational design software; however, this year the participants additionally used the digital fabrication at the workshop venue to fabricate full-scale working prototypes.

The two primary goals of this workshop cluster were the creation parametric models that adjust their geometry to effect acoustic performance, and the manufacture of acoustically active structures using digital fabrication techniques. Building on previous research, the design process of this project utilized both computational design tools and integrated acoustic simulation. This project attempted to define more sophisticated objectives in terms of acoustic performance. Instead of using reverberation time as the sole measure of acoustic performance, this project developed a more complex understanding of acoustic space through designing for multiple acoustic performance parameters, defining space through differentiated acoustic conditions, and creating sonic perceptual gradients. Different types of acoustically modulating components were assembled together to form a larger structure. The installation had a...
designed acoustic performance at the level of the overall structure, and also at the level of the individual parametric acoustic surfaces. Through the use of acoustic performance as a design driver, the use of digital fabrication techniques, and through a more complex definition of acoustic performance, new forms and material compositions were explored. By linking acoustic theory to the parametric design of material and geometry and the digital fabrication of these structures, a “working prototype” was created.

To design and build a structure as complex as the MPAS project would have been impossible in the four days of the SmartGeometry conference. The cutting time for the structure alone was four days. As a result, the concept design and structural detailing took place in the months before the project. The structure and acoustic design strategy was established before the workshop commenced. During the workshop the structure was assembled, individual parametric acoustic surfaces were designed and fabricated, and the installation was assembled. The installation was exhibited for one week.

3.1. Designing for Sound

It has been said that tools determine the boundaries of art, and that it is the use of the right tools for the thing that one is making, and a deep relationship between the use of the tool and its formal results, that establishes the potentials of what can be made (Berenguer [4]). So what are the tools for designing with sound? Architects have traditionally used the pencil and still think through drawing, but the computer is now increasingly used for creative tasks. But can we draw sound? Do we need a system of notation that lets us explore the sonic potentials of the spaces we design? How can we design and make our sonic environment?

Bjorn Hellstrom has found that acousticians lack the qualitative vocabulary beneficial when communicating with architects and others in the design process. He uses the example of the concept of space, which in the acoustician’s world means volume, resonance, absorption, and in a limited way, geometry; but, from the designers point-of-view the concept of space contains nuances that encompass spatial, aesthetic, perceptual, social, and cultural significations. (Hellstrom [13]) To design the qualitative dimensions of sounds, that is - acoustic design, is to give spaces a sonic character or sonic identity. In order to do this one has to integrate different knowledge fields when decoding the quality of sounds, mainly acoustics and architecture, but also to some extent sociological, psychological, ethnogeographic, musical, and artistic dimensions. (Hellstrom [13], and Augoyard and Torgue [3])
3.2. Acoustic Design and Performance Objectives

Jean-Francois Augoyard and Henry Toque have done much research on “sound effects” for acoustic design of architectural and urban spaces. The MPAS installation is designed to evoke several of these sound effects. The “dullness” effect “which implies total absence of reflected sound signals.” The opposite effect, “reverberation”, is the “effect in which a sound continues after the cessation of its emission.” The “filtration” effect modifies the sound by reinforcing or weakening certain frequencies. Acoustic absorbing materials can do this by absorbing only certain frequency bands. The “cut out” effect refers to a sudden drop in intensity or sudden modification of reverberation time. The “coupling” effect refers to an interaction between two sound phenomena that are distinct yet connected, for example two adjacent spaces that are open to each other but with different reverberation times. (Augoyard and Torgue [3])

The acoustic design of the MPAS project considers multiple acoustic parameters and explores how these parameters can vary within a single space thus creating gradient acoustic conditions. This design strategy is similar to the “morph-ecological” approach, where the creation of dissimilar or distinct systems and the deployment of different material systems create diverse spatial arrangements and climatic intensities (Menges and Hensel [19])

The design concept was to create multiple different types of acoustic spaces. Figure 4 shows a wall dividing a space, on either side of it two different materials, and two different acoustic conditions. When this wall is curved, the number of potential acoustic conditions increases and a quiet, enclosed space is created. This enclosed space has less volume, more absorption, and therefore less reverberation time though it would still be strongly acoustically coupled to the main space. This enclosed space is a “dull” acoustic space. By modifying the geometry of the wall a sound focusing element is created thus creating a zone of amplified sound intensity. The modulation of material properties of the surface from one condition to another creates a gradient of acoustic performance from one space to another.

3.3. Parametric Modeling and Acoustic Performance

A parametric model of the design was developed. Figure 5 shows an image of the parametric model in one of its many configurations. The parametric model allowed for the modification of the structure and the surface. Individual parametric models or computer programs could then be used to generate different panel strategies to populate the surface and structure with acoustically modulating components.

Fabrication data was produced by a custom script. The script flattened the structural elements and calculated the notching necessary for their
Figure 4. Acoustic Design Concepts: A) Sketch with sound-focusing components, B) Sketches exploring acoustic gradients, C) Sketch with sound-diffusing components.
assembly. Unlike the Smithsonian project where a single computer program acted as the synthesis all of the design decisions, the design of the MPAS installation needed to remain quite flexible as many design decisions were not made until the workshop. The parametric model was used to generate options and these were then tested for acoustic performance and fabrication feasibility. Acoustic testing was done using Odeon, and fabrication feasibility was done with 1:20 scale models and 1:1 joint details.

The parametric model was designed to output data that could be easily imported into the acoustic analysis software. Architectural models can be exported from architectural drawing packages and imported easily into this software for acoustic analysis. There are a few considerations that should be made before creating the parametric model in the architectural CAD package. Acoustic performance is material dependent, therefore there must be a coding of geometry by material in the digital model. This can be done by separating information on different layers or levels in the digital model.

3.4. Acoustic Simulation and Modeling for Architecture

Simulation and Modeling Research is related to the question of how reality is constructed and how we can come to know it. It presupposes that knowledge can be obtained by reproducing reality in some substitute medium, in this case within the virtual world of the computer. The goal of simulation and modeling studies are to determine the likely success of the
design according to some criteria. Computer simulations can reveal which aspects of architectural designs can be significant in terms of building performance (Grout and Wang [12]). Commercially available acoustic analysis tools are validated methods by which design options can be compared, engaged with, and contemplated.

Analysis can be a useful design tool as it provides feedback on an aspect of the design that may not be immediately apparent, whether this is structure, sun, or sound. If analysis tools are integrated into the design environment design propositions can be quickly tested. This then allows the designer to engage with the phenomenon under analysis. Visualization tools, and physical models, drawings, allow a designer to contemplate the visual nature of their designs. It is the contention of this author, that given this same opportunity for sound, of course a designer would be interested in controlling, creating, and modifying the acoustic qualities of the design. As previously stated, current architectural design environments do not include sound, but there are several commercially available acoustic analysis packages. The software used for this project is Odeon.

There are different types of knowledge about acoustic performance that can be derived from acoustic simulation and modeling software, see Figure 6. The 3d model can be visually colour-coded according to its material performance in terms of acoustic absorption. This creates a visual impression of a space's performance. All commercially available acoustic analysis software uses computational methods based on geometric acoustics to calculate various acoustic parameters, such as reverberation time. The techniques of geometric acoustics ignore the wave-based nature of sound and assume that the propagation of sound can be defined by straight lines. Ray-tracing and image-source are common geometric acoustic methods (Funkhouser, Jot et al. [10]). While these techniques cannot model interference or diffraction accurately, they have been shown to be highly accurate for mid- and high-frequencies. Through these methods, the analysis software computes the room impulse response, the acoustic fingerprint of the space, and is unique to every sound source and a receiver positions. The room impulse response can be used to calculate many acoustic parameters in addition to reverberation time. These parameters can then be used to evaluate the acoustic performance of a space. These computational methods can also be used to produce sonic visualizations of sound. Images and movies can be produced that show “3d ray investigations” or “3d billiard balls” of sound waves as they are transmitted from a source. These visualizations can be used to find acoustic defects such as scattering, flutter echoes, coupling effects (Christensen [6]). One of the most interesting outputs from the software is the auralization, or the ability to “hear” the virtual space. Auralizations are produced by taking a “dry” sound file (one recorded without room effects) and filtering it with the room impulse response. This produces a sound file of the recording as if it were played...
Figure 6. Acoustic Simulation and Modeling Types of Performance Feedback: A) Material and colour; B) Sound wave animations; C) Acoustic parameter grid values visualized; D) Performance data displayed in frequency bands; E) Room Impulse Response and Auralization of Sounds (not shown)
from that particular position, and listened to at that particular position. The auralization can give an approximation of what this specific geometric and material configuration of a space will sound like (Rindel and Christensen [23]).

The MPAS project uses parametric and computational design tools and five options were developed and tested, see Figure 7. The data was generated as simple triangulated shape geometry and exported as a DXF file. Similar material configurations were applied to each design option for comparison purposes. The side of the surface facing the sound source - the “exterior” side - was a sound reflective material with little absorption, and the other side - the “interior” side - was made a highly sound absorptive material. The geometry was level-separated in the digital file so that it was simple to apply material definitions in Odeon. The computational design tools were used to generate the geometry and so it was possible to directly generate the geometry in the .PAR Odeon file format (Christiansen [6]).

Oxman (2008) identifies three components to digital design systems that support the integration of performance: the geometric model, the evaluative processes, and the ability of the designer to interact with the geometric and various processes. Applying this theory to current acoustic analysis software, the geometric model is done outside of the acoustic analysis system, the evaluative processes is done within the system, and the interactivity of the designer with the geometry and evaluative process is only supported to a limited extent. While many different parameters can be calculated by the acoustic analysis software, new acoustic parameters cannot be defined and explored. Iterative optimizations cannot be carried out by modifying material or geometry. The evaluative processes are not available through a programming interface or scripting language. In order for acoustic performance to become part of the design process, the design environment must support the inclusion of sonic qualities. In order for analysis to become a design tool the mechanisms by which form and material are altered must be understood and these can then be used to drive form.
The five options were tested for different acoustic performance parameters: reverberation time (T30), early decay time (EDT), sound pressure level (SPLA), speech transmission index (STI). The goal was to create different acoustic subspaces through the use of a single, curved architectural surface. The results of the analysis showed that, even though reverberation time remained fairly constant throughout the space, differences in acoustic parameters can be noticed. In particular, the curving geometry produced quiet areas and loud areas. This was apparent as the SPLA level was decreased in interior areas that were shielded from direct sound and higher levels where the form focused sound. The EDT, that is the decay of sound in the first 5 ms of time, also appeared to define the more acoustically dull spaces with EDT being lower in these areas. Acoustic performance is relational to the type material present in a space and therefore, the larger surface area of acoustic material, the greater the effect. Auralizations were produced for five different positions around the structure. These auralizations showed that form was producing different acoustic conditions due to its changing geometry and material.

3.5. Parametric Acoustic Surfaces

Though the design of the form of the MPAS installation was completed prior to the workshop, the design of the individual acoustic panels was done during the workshop. The panel types and their distribution were informed by the acoustic design strategy. Nine different panel types were developed. The most basic type was the acoustic absorber panel. Two types of perforated screens were developed. The gradient perforated screen modulated the absorption of sound from the fully absorbing sound panel to a completely reflecting surface with little to no sound absorbing qualities. A sound scoop investigated a directional strategy where sound was absorbed from one direction and reflected back into the space from the other direction. A sound window component was developed. This component allowed visual connection from one acoustic space to the other. The amount of absorbing material on one side was much greater than the other side, which was totally reflecting, thus creating different acoustic properties. Three types of sound diffusing panels were developed.

While simulation software can be used to predict the acoustic performance of architectural spaces before construction to great accuracy, the acoustic performance of specific materials and detailed geometric components cannot be easily analyzed by currently available simulation software (Peters [21]). To predict sound scattering performance computational techniques must be used or physical models must be tested. (Cox and D’Antonio [7]). Both of these experimental methods are time-consuming and complicated. However, through the use of previously tested geometries (Cox and D’Antonio [7]), or by using certain mathematical formulae (Schroeder [25]), scattering performance for a limited variety of geometries can be predicted.
3.6. Digital Fabrication

Parallel to the development of new digital design tools has been the development of new digital fabrication techniques. Computational and parametric techniques can create a direct link between design and fabrication. It has been shown that through digital fabrication design intent can be realized in a more precise and efficient way (Littlefield [17]; Kolarevic and Klinger [14]). A few project projects have been completed that have digitally designed and fabricated complex surfaces that acoustically modulate sound in different ways (Bonwetsch, Bartschi et al. [5]; Koren [16]).

The MPAS installation made extensive use of digital fabrication methods. No drawings were created for the construction of the installation. Two laser cut models served as assembly diagrams and panel distribution maps. In order to have as much acoustic effect as possible, the installation had to have a large area and be massive. To be as absorbing as possible it had to maximize its surface area, and to limit sound transmission, be as heavy as possible. The structure and panels of the installation were made from laser cut 18 mm medium density fiberboard. A notching algorithm was developed...
in Microstation to produce the data for the fabrication. 50 mm specialist sound absorbing foam was used as the primary acoustic absorbing material. Most of the sound diffusing acoustic panels, the sound windows, and the sound scoops were CNC cut from 4 mm aluminum plastic composite sandwich material. The perforated screens were laser cut from 4 mm plywood.

4. CONCLUSIONS

Unlike artists, architects rarely get the chance to engage with the construction and material we design for. However, this engagement with material and the experience of the phenomenon is critical for an understanding of the potentials of acoustic design. By designing and building with sound-modulating material, a deeper understanding of material and performance is possible. Validation and testing is an important part of performance driven design. By testing the results of our research we are able to determine if the methods we use to produce performance driven designs are working. Perhaps the most important result of this project was that it worked. The material and geometry contributed to creating a
noticeable acoustic subspace. The individual parametric acoustic surfaces were successful to varying degrees. The concept of the gradient absorber/reflector was successful as was the acoustic window.

The Manufacturing Parametric Acoustic Surfaces (MPAS) project finds new potentials in acoustic-driven design. It looks beyond acoustic performance as a single value to acoustic performance as a differentiated field of values. The project considered multiple acoustic parameters such as early decay time and sound level. During the design process the acoustic performance was explored through using acoustic modeling and simulation software, by using form-generating computer scripts based on statistical formula, through listening to auralizations of the installation, and through experiments that acted on the acoustic material itself. Acoustic simulation and modeling proved to be an essential part of the design process. Parametric design and scripting tools were used to explore not only singular objectives, but gradient conditions. This research suggested acoustic design, and sonic experience, can be enriched when it is understood in terms of gradients and multiple performance parameters.

The Smithsonian project demonstrates the potential to successfully include acoustic performance as a design driver, from design through...
construction. The project demonstrates the importance of understanding both the geometric configuration and its material properties. The creation of an algorithmic system that generated design options allowed for performance driven attributes to be seamlessly integrated into the geometric logic of the design. By establishing specific material performance and using the computational model the acoustic performance of the project could become a design driver. Through a consideration of reverberation time, acoustic performance can become a design-driver for architecture. However, this can only make sure that the project is approximately correct in terms of its acoustic performance, and this technique cannot accomplish acoustic design of greater complexity. In order to achieve a design of more elaborate acoustic performance specification, designers need to be able hear their designs, and get performance feedback from their designs.

Whether we choose to recognize it or not, sound is part of our experience of architecture. With parametric and scripting tools performance-driven acoustic design is possible. Acoustic performance must be understood both on the level of material performance and also at the level of the entire composition. The use of acoustic simulation and modeling software allows the designer to calculate multiple acoustic parameters,
produce sonic visualizations, and hear auralizations of the proposed space. However, this process is not fast. The workflow of going from digital model in architectural design software to acoustic simulation and modeling software and analyzing the result takes time. If sound is to become a design driver for architecture, acoustic simulation and auralization must be part of the architectural design environment. This work suggests that further potentials for acoustic performance-driven design and for acoustically form-found structures lie in the further integration of sound into the architectural design environment.

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