Parametric Acoustic Surfaces

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SOFTWARE

ABSTRACT
Acoustics are important performance criteria for architecture; however, architects rarely consider them, except, perhaps, when designing concert halls. Architectural spaces can be said to perform well or poorly in terms of their acoustic qualities. The volumetric geometry of a room as well as its surface characteristics determine the acoustic quality of a space. Acoustic engineering research has proposed several new types of surfaces that can alter the acoustics of architectural spaces in different ways (Cox 2009).

By altering the geometry or material characteristics of the surfaces within a room in specific ways, the acoustics can be controlled. Once the geometric rules governing these acoustic alterations are understood, these rules can be encoded into a CAD system through parametric modeling or the use of computer programming. The architectural designer can then generate acoustically regulating surfaces according to desired performance criteria. In this way, acoustic engineering links to architectural design, and allows architectural design to become acoustically performance-driven.
This paper considers three primary types of acoustic surfaces: absorbers, resonators, and diffusers. Complex surfaces that combine these three performance characteristics in different ways are proposed. The relationship of geometry and material to the physical properties of sound is discussed, as is how parametric systems and computer programming techniques can be used to generate new types of acoustically regulating surfaces.

1 INTRODUCTION
In order to use sound as a driver of design, we must be able to measure and understand the acoustic consequences of our geometric actions. New methods must be developed to create geometry that achieves specific acoustic conditions. Generally, architectural designers are unfamiliar with discussing sound, and they lack the terminology to speak of the experience of sound, or the scientific principles of acoustics. There are limited drawing conventions in place to sketch acoustic concepts, and the physical models that architects develop are used rarely, if ever, for acoustic testing. No CAD software exists that combines both sound and geometry. An architectural designer interested in developing acoustic concepts as part of an architectural design will have difficulty finding tools to aid in this task. This paper demonstrates and proposes new tools and solutions that enable acoustics to become an architectural design problem. Through the investigation of how architectural surfaces such as walls, floors, and ceilings can be designed and detailed to be acoustically regulating, we were able to develop new design tools that include sound as a generating parameter for architectural design. The projects discussed in this paper integrate computer-based acoustic simulation with parametric computer-aided modeling techniques to develop complex surfaces that, through their shape and material, can be part of an acoustically well-balanced space.

As architects, we primarily focus on the visual, and we understand a great deal about designing with light; however, our sonic environment is critically important as well. The "aural environment elevates or depresses our affective responses, it bears directly on our sense of privacy, intimacy, security, warmth, encapsulation, socialization, and territoriality" (Blesser and Salter 2007). As light illuminates our visual environment, sound sources illuminate our sonic environment. The geometry and materiality of the architecture that surrounds us modifies our sonic experience. Human activities produce sound, and our architecture constantly interacts with us through its modification of the sounds we create. Much of the music produced today utilizes electronic filtering to create a desired ambiance or effect; however, music producers also use the acoustic characteristics of physical spaces as a way of altering sound (Reinemar 2009). Architecture is the filter that modifies the sounds that we create.

A critical characteristic of sound is that, unlike light, the speed of sound is perceptible. The sounds of the past exist simultaneously with the sounds of the present. We notice this in the phenomenon of echoes or reverberation time. The science of architectural acoustics began with the work of Wallace Sabine. He determined that the reverberation time, the time it takes sound to decay to inaudibility, was the most important factor determining the acoustic quality of a space. He importantly discovered that reverberation time was the result of a relationship between the area (geometry) and absorptive properties (materiality) of the surfaces of a room and its volume. Sabine acted as the acoustic consultant on the design and construction of the Boston Symphony Hall, which was considered to be a great success.

One of the crucial things Sabine realized through his careful study of other concert halls was that reverberation time was not the only criteria affecting the acoustics of a space: its room geometry and surface geometry were also important. The Musikverrein in Vienna is considered to be one the best concert halls in the world. Its excellent acoustics are thought to be the result of the low angle of its seats and the hard yet geometric complexity of its surfaces. This complexity is expressed at several scales—from the large balconies to the mid-scale windows, doorways, and statues to the small-scale carvings and moldings. Attitudes towards such complex surfaces changed with the architectural styles after World War II. The advent of modernism championed the used of large, planar expanses of hard surfaces. This geometric language and material palette is great for exploring formal compositions and properties. In response to Modernist developments, and due to an increasing amount of noise-making technology, modern acoustic treatments were invented (Thompson 2002). The application of these absorbing materials, such as carpets and ceiling panels, was usually applied post-design, and this is largely the way in which architects design for acoustics today.

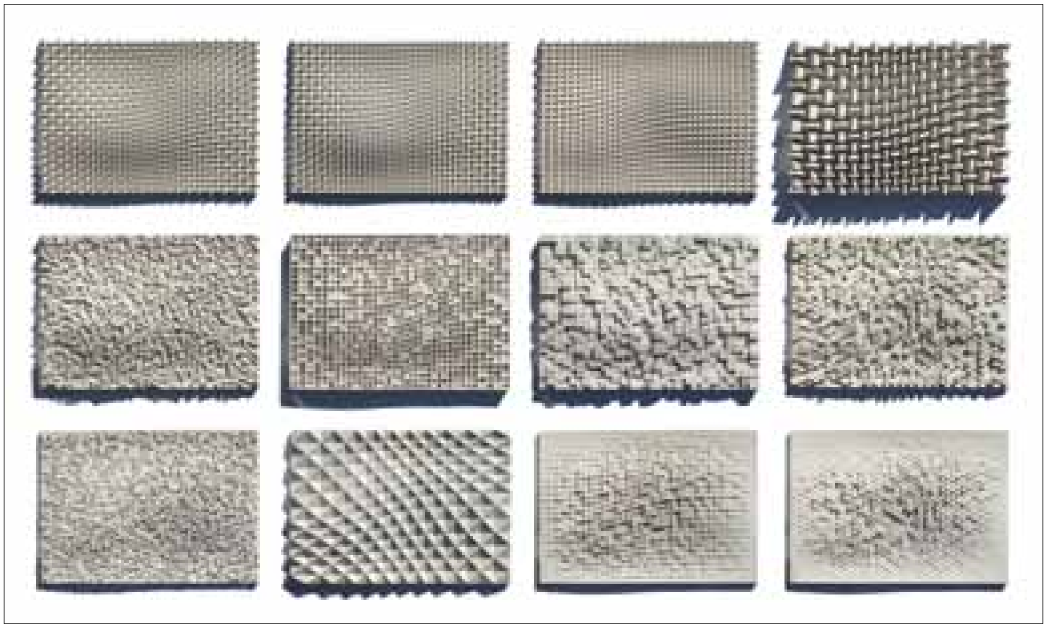

Figure 1 3D prints of parametric acoustic surfaces

This project seeks to connect architectural design with acoustic performance by taking advantage of new parametric and computational design techniques, and by utilizing digital fabrication to produce complex surfaces. Figure 1 illustrates complex surfaces that regulate the acoustic character of a specific space. The use of digital fabrication to produce complex surfaces that are acoustically regulating has been shown (Bonwetsch et al. 2008), and this paper will not specifically address the creation of full-scale built prototypes but, rather, introduce the digital design tools and communication methods necessary to link to these technologies.

2 PARAMETRIC ACOUSTIC TOOLS

Acoustic engineering principles establish relationships between room volume and room shape, surface geometry, material properties, and acoustic performance (Cox 2009, Kuttruff 2000, Long 2006, Egan 2007). This knowledge can be captured in the form of parametric models and computer algorithms. In this project, these acoustic engineering principles were used to create computer programs that generate complex surfaces particularly suited to altering the acoustic performance of a space. These parametric tools were written in Visual Basic and implemented in Microstation. Many different digital design tools were created. These tools generated different geometries to modulate different acoustic effects. The creation of user interfaces allows the tools to be used by other non-specialist designers (fig. 2). This is important as many of these tools are designed for use in an architecture office.

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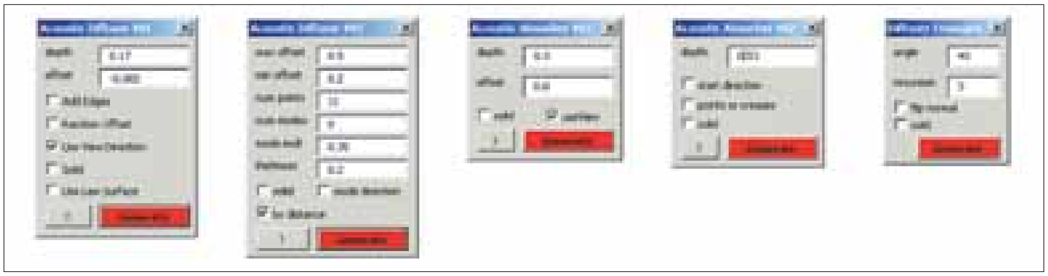


Figure 2 User interfaces for developed for absorbing and diffusing surfaces

These digital tools create new complex forms that have particular acoustic qualities. Because these surfaces are assumed to have known material properties and are generated following specific rules, their acoustic performance can be predicted. However, the individual parametric tools do not currently consider the performance of the overall room in which the surface exists. In order to understand the acoustic properties of the room itself, these surfaces must be studied in acoustic analysis software. In this study, the acoustic analysis software ODEON was used. Data transfer between software packages must be considered. It is important that these digital tools generate triangulated polygons and that this geometry be grouped according to material type. All of the parametric acoustic tools developed here return polygonal geometries that are suitable for analysis, as well as a solid geometry that is suitable for rapid prototyping.

3 PARAMETRIC ACOUSTIC SURFACES

3.1 ACOUSTIC ABSORBERS AND RESONATORS

The amount of absorption that a surface contributes to the overall room absorption is related to its material properties, its absorption coefficients measured in different frequency bands, and its surface area. The acoustic performance of a room can be altered by changing the material properties of its surfaces. However, as acoustic absorption also depends on surface area, by modifying the area of an absorbing surface, the reverberation time of a room can be altered.

The first parametric tool considered in this paper produces a geometry that is based on the foam wedges of the anechoic chamber, an extreme acoustic space with virtually no reverberation time. The tool produces triangular wedges whose geometry can be altered in terms of the number of wedges, the angle of the wedges, and the angle of the side chamfer. The angle of the wedges is important as this affects the number of times a sound strikes the surface before being re-transmitted back into the room. The parametric acoustic tool developed here can either produce a particular percentage increase in surface area or report this data back to the user. The parameters of angle, depth, and chamfer angle can be modified. Many design solutions modify room acoustics through a change in material. Another design solution explored here changes the acoustics of a space through a change in geometry. While the use of acoustic wedges in practice

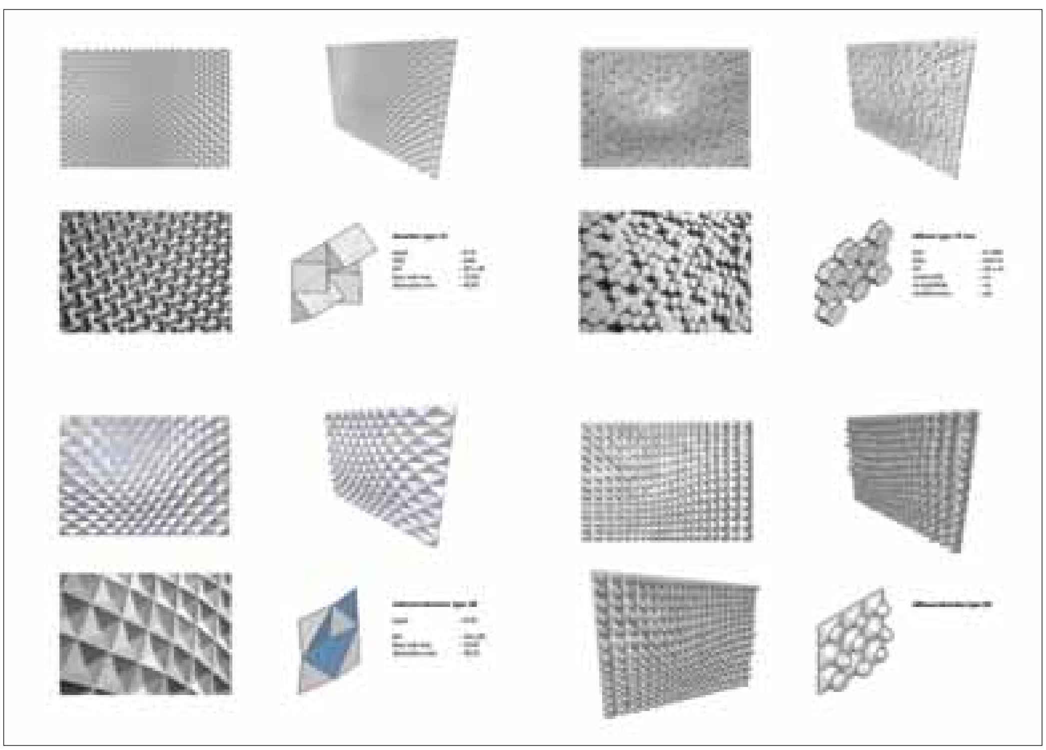


Figure 3 Four acoustically regulating surfaces, clockwise from top left: an absorbing surface, a diffusing surface, a combination diffusing/absorbing surface, and a combination absorbing/reflecting surface

is often limited to extreme cases, this tool suggests a potential for greater control of acoustic absorption through the alteration of surface geometry. A complex surface that was generated using this tool is seen in figure 3.

There are generally thought to be three types of acoustic absorbers: porous absorbers, diaphragm absorbers, and volume absorbers. In room acoustics, it does not make a difference by what method the sound energy is absorbed. The absorbing capabilities of the porous absorber depends on the complex inner structure of the constituent material. The other two absorbers are types of acoustic resonators. Acoustic resonators, either a resonating diaphragm or a resonating volume of air, are primarily used to absorb low frequency sounds. The relationship between the form of the acoustic resonator and its acoustic performance has been well established (Kuttruff 2000). Further parametric tools have been developed that encode these relationships and generate the acoustic resonator geometries. These tools allow for the production of resonator geometries that can absorb sound energy in particular frequency bands. A combination of different types of acoustic absorbers is often necessary to achieve the best sound absorption across all frequency bands.

3.2 ACOUSTIC DIFFUSERS

When sound is reflected from a surface, the reflected sound can be either redirected in a particular direction by large, flat surfaces or scattered in many directions by a complex surface. When a significant amount of the reflected sound is dispersed spatially and temporally, this is considered a diffuse reflection; and the complex surface that is providing the reflection, a diffuser (Cox 2009). It has been noted that adequate diffusion is critical for obtaining an even distribution of sound, and that diffusion can help absorptive materials be more effective by scattering sound so that it is more likely to encounter these surfaces. Acoustical defects such as flutter echo and irregularities in the slope of the reverberant decay can develop in a room without adequate diffusing characteristics (Long 2006).

Recently, there has been some very interesting research into new geometries of acoustic diffusers. However, a diffuser geometry Manfred Schroeder discovered in the 1970s is the basis for many of the diffuser generating tools developed here. The Schroeder diffuser is a one- or two-dimensional array of rectangular forms. The width of these diffusing elements is related to the frequency of sound that is desired to be diffused: the smaller the diffusing elements, the higher the frequency of diffusion that occurs. While the depth of the diffusing element in its well appears to be randomly determined, it actually follows a particular mathematical sequence. The use of these mathematical formulae can add to the predictability of the sound diffusing characteristics of the geometry (Cox 2009). This is not to say that other mathematical sequences or geometric configurations of well depths cannot be used or will not produce better results. While diffusing surfaces are often designed with a rectangular form, it has been proposed that hexagonal forms can be used as well. Very complex forms, such as the more random configuration of rough natural stone, have also been used successfully. Many different geometries will produce diffusion, though the extent to which they do should be verified by testing. The parametric acoustic tool developed here takes an array of polygonal shapes as input and generates a diffusing surface. An example of a hexagonal diffusing surface is shown in figure 3.

Figure 4
Three diffusing surfaces: a fractal triangular pyramid, random well depth diffuser, and a fractal random well depth diffuser

Figure 4 demonstrates how the parametric acoustic diffuser tool can be used. Three types of diffuser panels are shown here: a fractal triangular pyramid, a random well-depth diffuser, and a fractal random well-depth diffuser. Triangles and pyramids can provide good diffusion and are often used in arrays. The scattering performance of the triangle depends on its side angle. An angle of 40 degrees was determined to be appropriate and to provide a good scattering of sound. The size of the triangular pyramids varies, and resultantly, this will scatter both the low and high frequency sounds differently. The layout and number of the triangular pyramids is determined by another parameter, the level of recursion. The second and third types of diffuser panels are based on the geometry of the Schroeder diffuser. They both have constant well width and random well depth. In the third option, the triangular panel is broken up into seven triangles along each side. Each of these triangles is then broken up again into seven triangles. This fractal technique allows the geometry to diffuse multiple frequency ranges.

The parametric acoustic surfaces shown in figure 3 are comprised of geometric components that are populated onto an underlying design surface. This creates a two-dimensional array of acoustically regulating components. This approach has proven its utility and adaptability, and the method of populating components onto a surface is certainly not new (Peters 2007). However, it is not necessary to take this approach. Figure 5 shows a diffusing surface created from geometry generated by a circle-packing algorithm.

3.3 ACOUSTIC REFLECTORS

Figure 5 Random radius, random depth circle diffuser based on circle packing algorithm

An acoustic reflector optimization tool was developed for the design of a triangulated roof for a music pavilion in Copenhagen. This student project was a structure comprised of 230 panels with 358 beams and 129 nodes. One-third of the panels were to be reflectors, one-third absorbers, and the remainder, diffuser panels. The first scheme called for a randomized selection of panels. Because of the large number of panels, this scheme produced a degree of uniformity throughout the space in terms of the absorption, reflection, and the diffusion of sound. To decrease the sound level in the lounge area of the pavilion, an optimization tool was developed that determined panel types that would decrease the sound reflection to particular audience positions. The basic algorithm is illustrated in figure 6. The first step was to define an initial selection of panels, a sound source location, and audience positions. In the second step, the computer program determined which panels could potentially provide good reflections. Hidden panels, or panels with too slight of an angle of incidence were not considered. From this selection of panels, the program found which panels provided either direct reflections to the defined audience positions or almost direct reflections, within a specified tolerance. From this information, one-third of the panels that provided good reflections to the audience were selected to be reflectors. These panels are colored blue in step four. In order to choose the optimal absorbing panels for the lounge area, a similar strategy was used, except panels were defined to be absorbing panels instead of reflector panels. These panels are colored red in step six. This strategy, it was hoped, would provide the different acoustic characters to the audience zone and the lounge zone. After the reflector and absorber panels were defined the rest of the panels became diffuser panels.

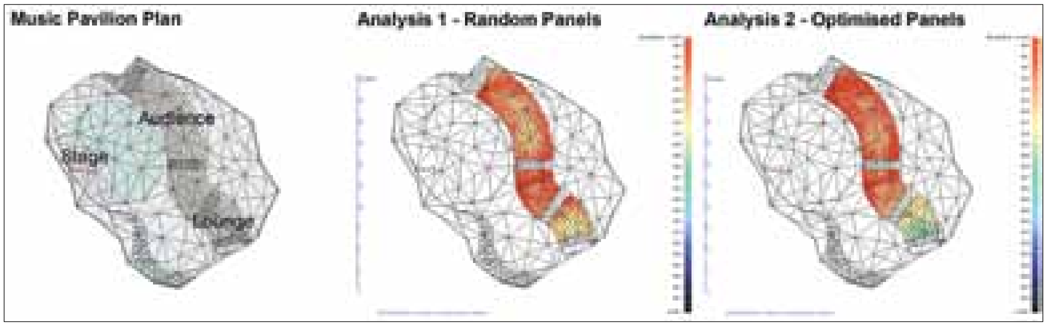
Figure 7 shows the ODEON acoustic analysis of the music pavilion schemes. This analysis shows a grid measurement of the audience and lounge zones. This comparison shows that for the optimized scheme there is 1) increased sound levels and more even sound-level distribution in the audience area, and 2) decreased sound levels in the lounge area. The reduction in sound level was about 3 dB in the lounge area.

Figure 6 Steps taken using the reflector selection optimization algorithm

3.4 VARIABLE ACOUSTIC SURFACES

It may be desirable for the acoustic and material properties of a surface to change or vary along the length of the surface. The acoustic properties of a surface should be able to change their acoustic regulating characteristics as they traverse from room to room, or even within the same room. An acoustic absorbing surface turns into a reflecting surface, which again changes to a diffusing surface. In the example shown in figure 8, this parametric acoustic tool modifies the maximum depth of the well of the diffuser, controlled geometrically by a three-dimensional control surface, so that the diffuser geometry can be seen to emerge from a smooth wall, a reflecting surface becoming a sound-scattering device. There are many possibilities within this family of options for new forms of architectural expression integrated with performance-driven form.

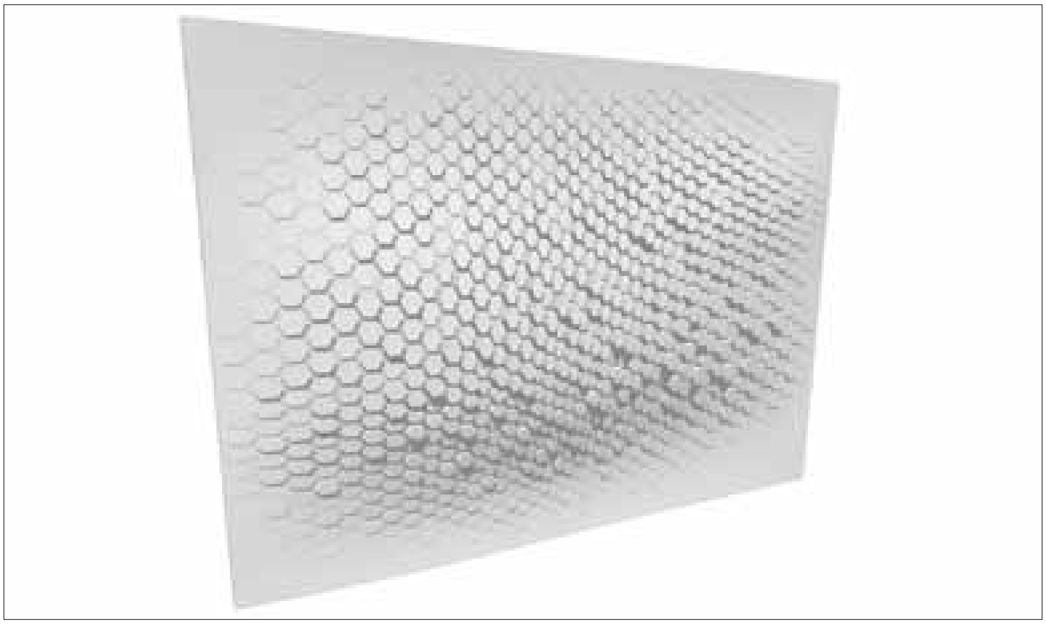
Figure 7 Sound pressure level at 500 Hz for 1) random panel selection and 2) optimized panel selection options



3.5 COMBINATION ACOUSTIC SURFACES

JJW Architects' PBS atrium project was a renovation that sought to cover a formerly open courtyard with a new roof enclosure (fig. 9). This covered space was to be filled with meeting rooms, breakout spaces, and a central presentation area. Similar techniques to those used in the design of the Smithsonian Courtyard Enclosure were used in the design of this project (Peters 2007). A parametric model was developed to create the roof structure and the glazing components. The number and size of glazing modules and the depth of the roof structure can be altered using the parametric tool. The depth of the roof structure is used to carry acoustic-absorbing material. A change in the depth of the roof structure results in a change to the acoustic characteristics. The glazing components are faceted to provide sound scattering. Each glazing module is faceted with both glass and solid panels. The inclusion of the solid panels allows for a greater amount of absorbing material to be placed into the roof structure. Also, the absorption of the roof structure is increased due to the fact that the efficiency of sound-absorbing material is affected by its distribution in a room. The spaced absorbing material absorbs more sound energy than is accounted for by its area (Egan 2007). The geometry responds to other design criteria beyond acoustic performance. The glazing components are oriented towards the north, providing even, indirect light and protecting the atrium from much direct sunlight.

Figure 8 Variable acoustic-diffusing surface.



CONCLUSIONS

Through the use of parametric modeling and computer programming techniques, acoustic performance can be integrated into architectural design. Many of the relationships between acoustic performance and room geometry and material are now understood, and these can be built into our digital design environment. With these new parametric acoustic tools, designers can generate new acoustically regulating surfaces that have a predictable acoustic performance. This can allow complicated acoustic performance criteria to be used creatively in the architectural design process. The actual introduction of these tools and concepts into an architectural office remains to be tested.

The absorption characteristics of a surface can be established using the parametric acoustic tools developed in this project. Using acoustic analysis software, the acoustic performance of a room can be tested in relation to its geometry, absorption,

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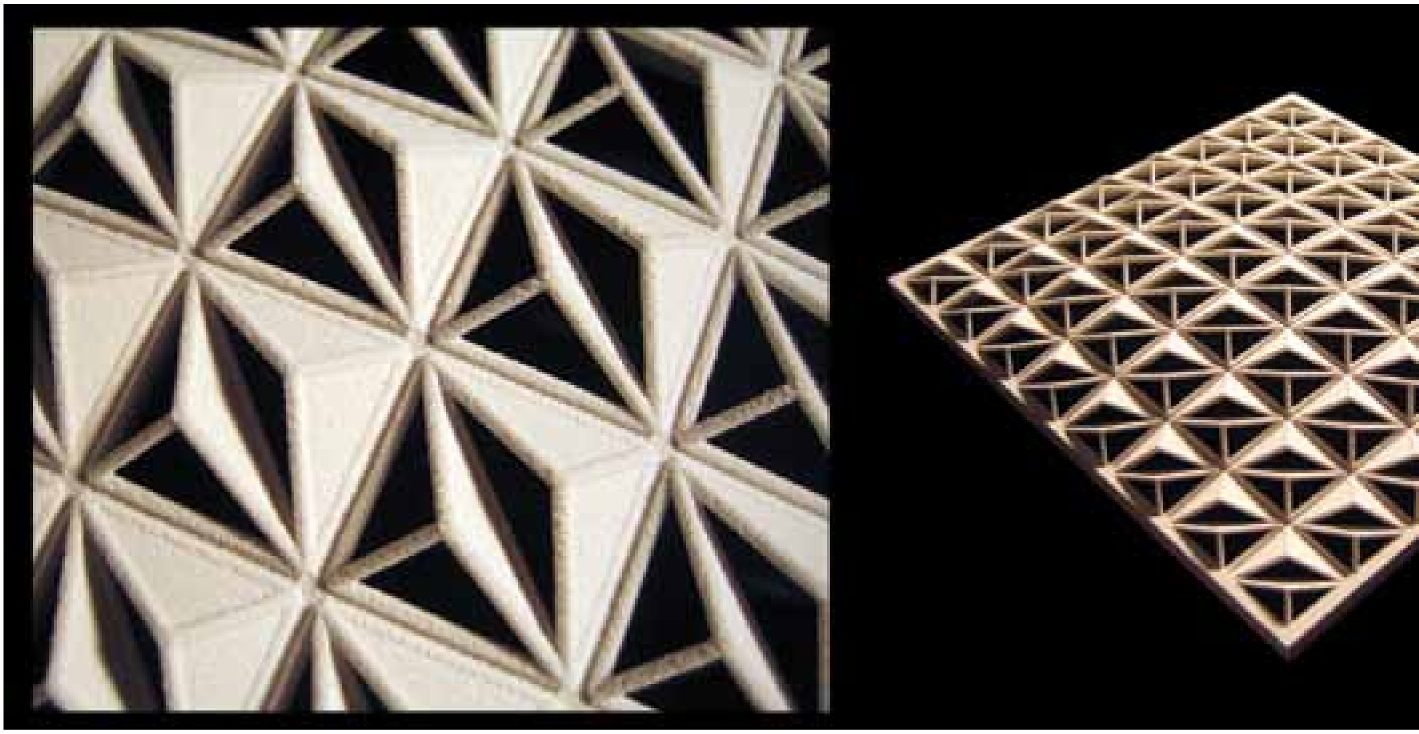

Figure 9
PBS Atrium project by JJW Architects

and diffusion properties. However, it is difficult to predict the diffusing characteristics of the particular geometries created using these parametric tools. While computational methods for the prediction of diffusion characteristics do exist, such as boundary element methods, these have not yet been implemented or tested in relation to the generation of these surfaces.

The calculation of acoustic performance necessitates the need for material absorption properties. This information needs to be attached to geometric entities in the CAD model. This modeling of information should extend beyond the characteristics of single elements. There is a need for geometric elements to be grouped and for adjacent information to be understood. This information would then allow for the prediction of the performance not only of a surface, but of the entire room as well. These acoustically performance-driven surfaces are potentially quite complex structures. While it has been shown that production information for complex surfaces can be accomplished with CAD systems, the manufacture of these surfaces remains to be tested.

It is a relatively simple matter to integrate the CAD design process with ODEON software. The transfer of the 3D model from one system to the other is problem free as long as the data requirements of the analysis software are understood: triangulated geometry, "watertight" geometry, dxf file format, and level separated by material. While the analysis software is easy to use, it is difficult to customize. It would be useful to be able to directly access the calculation routines of the analysis software to be able to integrate this within the designer's CAD package. With this capability, new plug-ins could be created that would allow for the creation of exciting new performance-driven architectures.

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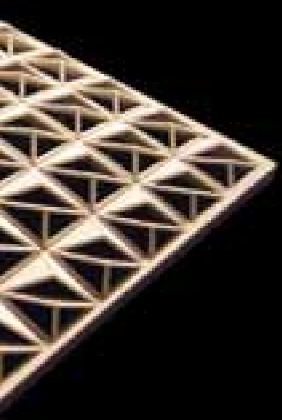

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