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Integrating Acoustic Analysis in the Architectural Design Process using Parametric Modeling

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Summary
This paper discusses how parametric modeling techniques can be used to provide architectural designers with a better understanding of the acoustic performance of their designs and provide acoustic engineers with models that can be analyzed using computational acoustic analysis software. Architects are increasingly using parametric modeling techniques in their design processes to allow the exploration of large numbers of design options using multiple criteria. Parametric modeling software can be performance-driven and sound has the potential to become one of these performance-driven dimensions. This can provide a method by which architects and engineers can work together more efficiently and communicate better. This research is illustrated through the design of an architectural project, a new school in Copenhagen, Denmark by JJW Architects, where parametric modeling techniques have been used in different ways. This paper documents six parametric design strategies and how these concepts can apply to the design of sonic effects and the integration of acoustic analysis. This paper demonstrates that acoustic design concepts can be used to control the parametric model, and that through parametric modeling, acoustic performance can inform the geometry and material logic of the design. In this way, the architectural design and the acoustic analysis model become linked.

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1. Introduction

1.1. Drawing, Modeling, and Prediction

Drawing is fundamental to the practice of architecture [1]. It is a method of exploring ideas about buildings and communicating how buildings are to be built. However, drawing is also a form of prediction; it has been used in architecture extensively by architects to predict how a building will perform in terms of geometry, space, light, and materiality [2]. Drawing is rarely used as a mechanism for the prediction of sonic performance. This paper investigates ways in which the architectural drawing can be used to predict acoustic performance. This investigation requires the integration of knowledge from architecture, acoustic engineering, and computer science.

Almost all architectural drawing is now done with the aid of computers, in this way all architecture is now "digital architecture." The use of parametric tools allows architects to draw in ways that are different than using pen and paper. Parametric modeling, also known as constraint modeling, introduces a fundamental change in the act of design. Designers still add and erase marks on the drawing, but now designers must also consider the relationship between the marks [3]. The drawing becomes an active environment in which designers can test ideas and explore the solution space imposed by the constraints put on the relationships between the parts of the model. Constraints are often considered to be detrimental to the success of a design concept, but there is evidence to suggest that constraints can encourage innovative architectural design solutions [4]. A survey of recent papers at architecture conferences demonstrates the increasing popularity of parametric tools in architectural practice [5].

Many parametric design environments also include the ability to add custom computer programs through scripting languages. Thus evaluative processes can be integrated into the design model and the parametric model can become performance-driven [6]. The parametric model, the new architecture drawing, thus has the potential to predict not only the geometry of the building, but also acoustic performance.

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1.2. South Harbor School, JJW Architecture

In June 2006 JJW won an international architecture competition to design a new school in the Teglholmen district of Copenhagen. The five storey building will have an internal area of about 10,000 m2 and has a budget of 200 million Danish Kroner. Construction begins in 2011 and is due to finish 2012. The structural system is a concrete column and flat slab system. This system has been adopted to avoid beams between the pillars. This leads to a more flexible arrangement of mechanical installations, which in turn allow for a larger ceiling height. The school has the capacity for approximately 840 pupils and staff. The school design includes a science center and a sports center.

Figure 1. South Harbour School, JJW Architecture.

Three major design concepts drive the design of the school: The first is the connection to the city. The design exposes the workshops and science laboratories and demonstrates openness towards the surrounding neighborhood. The ground floor plan allows movement of public through building and engages the public through exposing the activities of the students and staff. Acoustically, this space offers the excitement of the city street with different sounds from various activities and movements throughout the day. The second design concept is to create flexibility through a diversity of spaces. Many different types of spaces are created, from the large atrium space to intimate enclosed classrooms. The ranges of different spaces inspire exploration and many different uses. The third key design concept is the relationship of building to the landscape. The building is located next to the harbor and one face of the building opens right up onto the water. The building also features a continuous landscape that rises from the waterside park up the building and onto its roof.

The research discussed in this paper is being done as a part of a PhD project jointly sponsored by JJW Architecture and CarlBro / Grontmij Engineering. As with much architectural design, some of the work done in design development does not make it into the final project, similarly, not all of the design strategies here were used in the final design of the project.

2. Projects and Experiments

This paper identifies six design strategies for integrating acoustic performance and architectural design: material and geometry mapping, definition of acoustic zones, output of data suitable for acoustic performance simulation, the parametric acoustic surface, the sound design strategy as part of the generating strategy, and direct integration of acoustic performance calculation to allow for bidirectional constraint modeling.

1.3. Material and Geometry Mapping

The classroom is geometrically one of the simplest rooms in the project, but as much of the focused learning takes place here it is critical that these rooms perform well in terms of their acoustic environment. It was the intention of the design team that while these rooms should of course meet the absorption criteria set by the building code, they should not be overly "dead" with too much absorption. Therefore it was critical that the right balance of hard and soft surfaces be used. Wallace Sabine first defined the reverberation time as the relation between space, surface, and material. This straightforward relationship is encoded as part of the parametric model thereby creating a geometry-to-performance link.

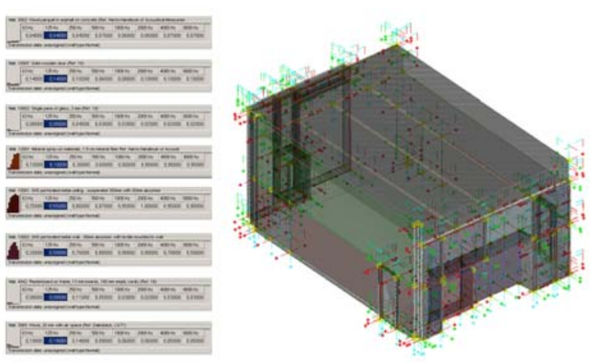


Figure 2. The Classroom

The geometry of the room is constructed using a parametric model which also keeps track of the volume and surface area. The material properties of the surfaces are coded through different materials being placed on different layers. These layers are then associated with different performance criteria through a parametric model. As surface area, volume, and material properties are known, the reverberation time can be instantly calculated. The designer is then able to change the size of the room, of surfaces, add or subtract surfaces, or change surface properties, and get instant feedback on the effect this has on acoustic performance.

1.4. Acoustic Zones

While many architects use parametric modeling techniques and design in three dimensions, most architectural computer drawing systems are used as digital drafting boards and most architects still work in a two-dimensional world of plans and sections. For this project the design team did construct a three dimensional model for visualization purposes, however, the majority of drawings and all of the up-to-date drawings were done in 2D. In general this will not likely change soon as architects contractually must deliver a package of 2D construction drawings and are insured to do so. While most architectural work is in done in 2D, it is the volumetric space of a room that is important for its acoustic performance. Architects models are said to contain too much information, they are not "watertight", the cover areas outside of the acoustic zone being analyzed, and do not layer separate geometric entities by acoustic material, and so those doing acoustic analysis must create a new 3D model [7].

All models are abstractions of reality, as models cannot contain all of the information of reality in them. The degree to which a model is abstracted and what information it contains is determined by what the model is to be used for. A digital 3D model can be used for many different design tasks and can have within it many different types of information [8]. If architects are aware of the data requirements of the acoustic analysis then this can be taken into account when creating the 3d model. Parametric modeling allows for multiple representations to exist within the same model.

Figure 3 shows a visualization of the acoustic zones. The parametric model must be constructed so as to be watertight, constructed from triangulated geometry, be layer separated by material type, not have overlapping geometries, and contain information only for the acoustic zone in question. In this project, the ODEON acoustic analysis software was used. The "glue" algorithm stitched the surfaces together when the DXF file was imported. In this way, the parametric model can generate data suitable for analysis, and the parametric model and the analysis program become linked.

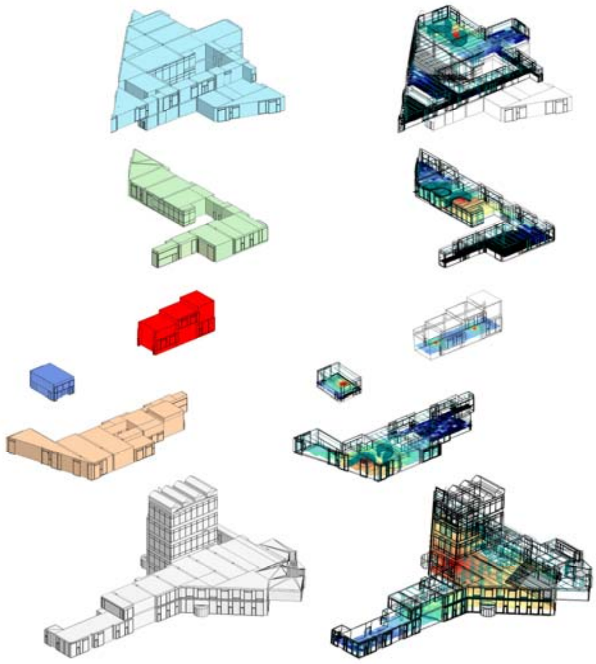


Figure 3. The Acoustic Zones

1.5. Space, Subspace, Surface

An *acoustic space* is defined by the boundary of a room. While in most architectural drawings, or in actual buildings this boundary is not so explicit, in terms of acoustic analysis, this boundary must be clearly defined. The spatial limits of the acoustic zone define the boundaries of the spatial analysis grid. The acoustic space is defined by the parametric model of the acoustic zone.

While in cases such as the classroom, the objective parameters of sound are often constant within a space, in larger more geometrically complex spaces such as the atrium of the school, the acoustic parameters no longer have the same value in all areas. These differences create what I will define here as an *acoustic subspace*. When it is desirable to have the same sound quality through out a space, these differences are considered to be detrimental to the acoustic performance. Building codes dictate that the performance must be a single value for the entire space. However, in architectural terms, the fact that different "spaces" or "subspaces" can be created with sound is a spatial experience that can be exploited to create more meaningful architecture. The acoustic subspace is created through complex spatial arrangements and complex material configurations.

It is the geometric entity of the *acoustic surface* that contains the information of the material performance that is a necessary component to the acoustic performance of the space. This surface performance is often known, or can be predicted in terms of sound absorption. Sound scattering is more difficult to predict and often can only be guessed at [9]. The parametric model can contain information other than the geometry. The material properties of the acoustic surface can be stored within the parametric model.

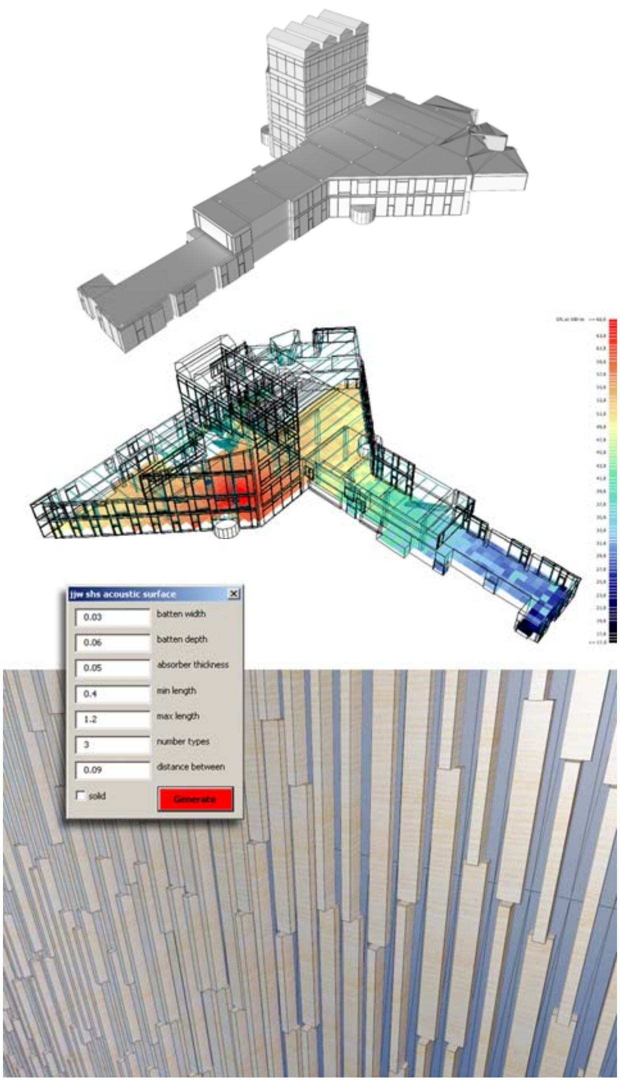


Figure 4. The Atrium

1.6. Parametric Acoustic Surfaces

The surfaces of the gymnasium are hard and reflecting. The only acoustic absorbing surface is the ceiling. While this ceiling does provide enough absorption to meet building code, it was thought that the space may still be too reverberant, and flutter echoes and resonances could build up between the parallel walls. In order to compensate for this, a scattering surface was designed for two of the walls. Acoustically, this surface scatters the sound energy around the room and allows the ceiling absorbers to absorb more sound energy. Architecturally, this surface becomes an ornamental relief pattern that provides a constantly changing pattern of light and shadow throughout the day and activates the wall both acoustically and spatially. Functionally, this surface becomes the climbing wall for the students.

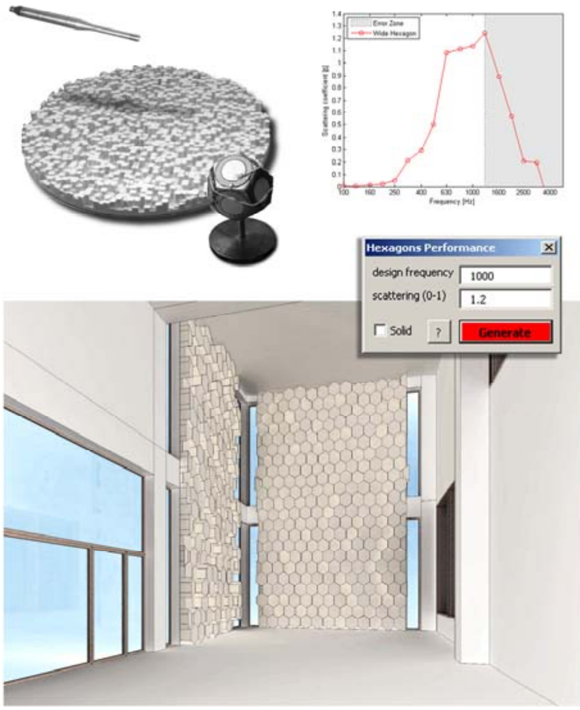


Figure 5. The Gymnasium: Scattering Climbing Wall

In order to accurately predict the acoustic performance of a space both absorption and scattering coefficients must be used [9]. The absorption coefficients for many materials therefore known; however, this is not the case for scattering coefficients. Parametric tools can create many types of novel geometries that will have different sound scattering properties. One method by which to find this value is through scale model testing. Architects are used to building scale models, and testing their ideas through scale models. Architects are increasingly using rapid prototyping technology to build models [10]. For the gymnasium, a parametric system for a wall surface developed in which two different constraints were tested: depth and width. Different rapid prototyped models were created and tested according to the ISO standard [11].

The results of these tests are shown in Figure 5. The analysis of the gymnasium showed that with the scattering wall, there was more than a 10% reduction in reverberation time was achieved when compared to a similar with the same absorbing ceiling except without the scattering wall.

1.7. Sound Design Diagram as Generator

Open-plan learning and working spaces are frequently designed and built in new buildings. These spaces offer functional and spatial flexibility and allow for collaborative working methods. However, there are also documented acoustic problems with these spaces [12]. This school project was originally intended to be a very open-plan design. As the design developed, many of the classroom and laboratory spaces became closed off, acoustically isolated, and therefore have a more controllable acoustic environment.

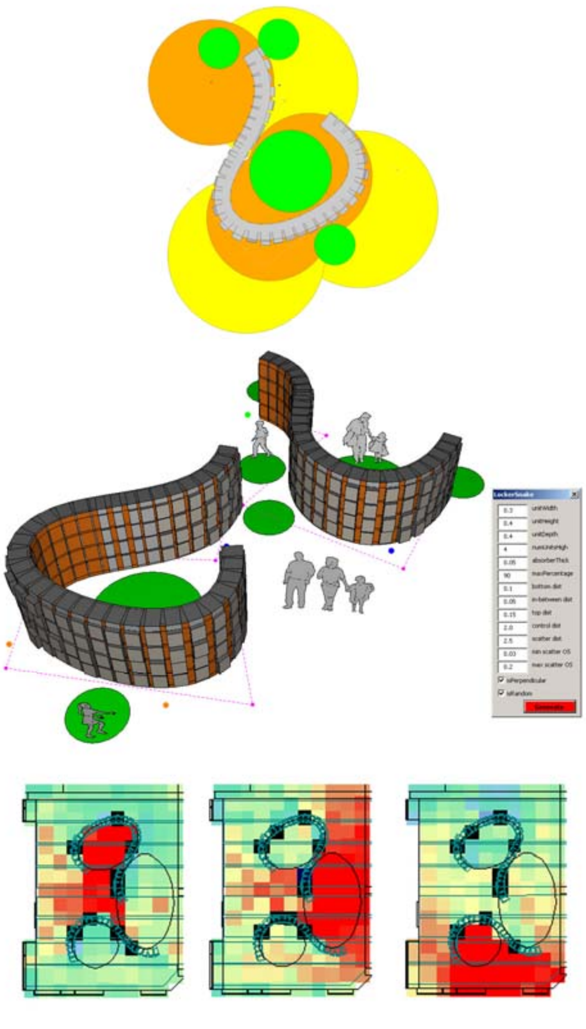
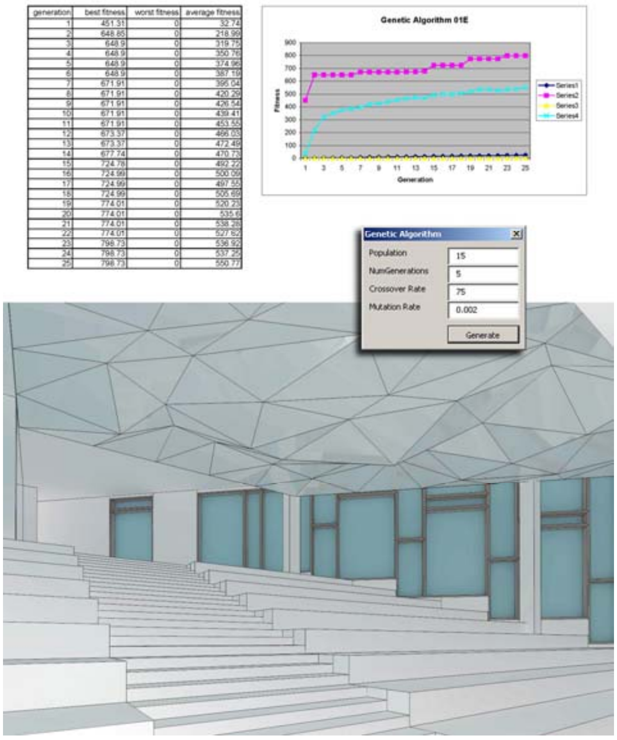


Figure 6. The Locker Snakes: Sound Diagram, Parametric Model, and SPL Analysis

There are, however, still open plan areas associated with each of the four classroom clusters in the school. These open plan areas have a functional requirement that different size groups must be able to meet and do various activities. These groups should be able to meet simultaneously without disturbing each other acoustically. A series of walls in this open landscape spatially define these working spaces, provide the acoustic separation between working spaces, provide the added acoustic absorption needed for the open plan space to meet the building code requirement, and also provide for the functional requirement of locker space for each student. A conceptual diagram was developed. This conceptual "sketch" is comprised of geometric entities that represent acoustic design concepts and does not correspond directly to actual performance. The geometry of this conceptual diagram controlled different numerical parameters in a generative script. Acoustic analysis of the resulting geometry, while different than the sketch does show a relation to it. The generative script produces information that is suitable for acoustic analysis, outputs data for the architectural drawings, and data which can be then sent to fabrication machines.

1.8. Integrating Analysis

The Senate is an informal auditorium space consisting of a stepped room that connects two open-plan learning spaces. The design strategy for ceiling of this space emerged from a desire to focus sound from a single sound source position to the multiple sound receiver positions in the auditorium. The ceiling design is for a triangulated roof structure of a combination of reflecting panels and absorbing panels. If one node of this triangulated structure is moved it affects all of the neighbouring panels. The potential solution space for this geometric and material configuration is therefore quite large. Genetic algorithms are particularly suited to searching large solution spaces for well performing solutions. This evolutionary approach does not "breed" new forms, but finds already existing potentials within the system. What is interesting to designers is that these forms may not have been imagined before. Therefore they are both new and exciting, and acoustically better performing. The design strategy here is both the integration of the optimization script, but also the integration of the evaluative process, the acoustic analysis solver, with the design program generating the geometry. In this way, a *performative* architectural solution is achieved [6]. This process of "form-finding" instead of "form-making" is possible through the integration of the acoustic simulation process within the parametric geometric model.



generation	best fitness	worst fitness	average fitness
1	451.31	0	32.74
2	648.85	0	218.99
3	648.9	0	319.75
4	648.9	0	350.76
5	648.9	0	374.96
6	648.9	0	387.19
7	671.91	0	395.04
8	671.91	0	420.29
9	671.91	0	426.54
10	671.91	0	439.41
11	671.91	0	453.55
12	673.37	0	466.03
13	673.37	0	472.49
14	677.74	0	470.73
15	724.78	0	492.22
16	724.99	0	500.09
17	724.99	0	497.55
18	724.99	0	505.69
19	774.01	0	520.23
20	774.01	0	535.6
21	774.01	0	538.28
22	774.01	0	527.62
23	798.73	0	536.92
24	798.73	0	537.25
25	798.73	0	550.77

Figure 7. The Senate

3. Conclusions

Parametric modeling can be used to integrate acoustic performance concepts into the architectural design process. This paper outlines parametric design strategies used in the design of a new school in Copenhagen, Denmark by JJW Architecture. The first strategy is that through the correct modeling of room geometry and mapping of material properties the parametric model can allow for the real-time calculation of reverberation time. The second strategy is to model a building as a collection of acoustic zones. This allows for the individual calculation of rooms, as well as a distribution of the design problem itself. A third strategy used was to understand the acoustic design in terms of acoustic space, acoustic subspace, and acoustic surface. These concepts each have their own design drivers and while occur together, must be also considered individually. A parametric strategy involving scale model testing was used to understand the scattering properties of acoustic surfaces. A future project would be the implementation of numerical methods for calculating this value. A fifth strategy drives a parametric model of an acoustic surface by controlling the conceptual sound design sketch. This strategy embeds the rationale of the sound design within the generating logic of the architecture. As the acoustic performance is modified, the architectural drawing is updated. A sixth strategy is to integrate the evaluative process into the parametric model. This then allows for form to become driven by acoustic performance. This research has shown that through parametric modeling, acoustic performance can inform the geometry and material logic of the design, and in this way, the architectural design and the acoustic analysis model become linked.

Acknowledgements

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