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Review

Acoustic Performance-Based Design: A Brief Overview of the Opportunities and Limits in Current Practice

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Abstract: Current development in digital design, combined with the growing awareness of the importance of building performance, had drawn attention to performance-based design (PBD) in architecture. PBD benefits both design workflow and outcome, allowing one to control the performance of the design proposal since early design phases. The paper aims to explore its current application in the acoustic field, where its potential is still little exploited in architectural practice. A set of built case studies is collected and briefly analyzed with the aim to shed some light on the state of the art of the application of acoustic performance-based design (APBD) in practice. The analysis suggests that in order to encourage the application of APBD it is needed on one side to enhance the integration and interoperability among modeling and simulation tools, and on the other side to improve the acoustic knowledge and programming skills of the architectural practitioners.

Keywords: performance-based design; acoustic design; digital workflow; architectural design; design optimization; form-finding

1. Introduction

1.1. Performance-Based Design

Architectural problems generally combine a great multitude of objectives, which pertain to different fields, such as cultural, aesthetic, economic, structural and energetic ones. As these objectives often contrast with each other, it is crucial for the design team to find the most favorable solution in overall terms.

According to the classification proposed by Shi [1], architectural objectives can be divided into three categories: structural performance, performance of the physical environment—both of which can be quantified—and aesthetic and cultural performance, which relates to unquantifiable aspects. Digital simulations and measurements on scale-models allow for the evaluation of the quantifiable performances of the design proposals prior to their construction. In common practice, such tools are generally used in late design phases to verify the adherence to the performance requirements prescribed in codes, standards and laws, and evaluate the need for late design adjustments [2–4].

However, in the recent years, another approach has gained popularity, according to which performance simulations are used to drive the design process. This approach is known as performance-based design (PBD): pertinent information on one or more performance aspects is gathered since early design phases, and the proposals are iteratively optimized based on the performance feedbacks. The design process follows the loop of generation–evaluation–modification, until a solution that meets the performance goal is achieved. While not discouraging the inclusion of

unquantifiable goals and aesthetical considerations, pertinent information on quantifiable performances can greatly support decision-making processes in the conceptual design stages.

In early design phases, designers consider a wide range of possible design solutions. Design decisions made at this stage have the greatest impact on the final performances, while late-time design adjustments can rarely compensate poor decisions made in early stages [5–8]. Moreover, design modification taken in early design phases is less costly to implement than those taken in subsequent phases [4,9]. Therefore, PBD approach benefits both design workflow and final outcome, combining a decrease in cost and time, and enhances design quality [10–12]. Indeed, with PBD designers have a greater control over the performances since early design phases and, as a result, the need for late-time design modifications or “a posteriori” measures is prevented, enhancing the overall efficiency of the design process.

The PBD approach emerged in the 1970s and has become increasingly more appealing to architects due to the technological advancement and, in particular, to the development of performance simulation and parametric modeling tools [1,13–16]. Some educational experiences, such as those in [16,17], suggest that architectural students are increasingly being encouraged to use these tools and include performance feedback to support design decisions during the early-stage design exploration.

PBD marks the paradigm shift from the traditional “form-making” to the “form-finding” approach [18]. It allows one to displace traditional know-how, enabling designers to understand the effects of different design features of the proposal on performance, and to identify design scenarios that best fulfill the unique requirements of each project.

The PBD method can be subdivided into two subclasses according to the way the design optimization process is conducted. In “formation models” the modifications are applied manually by the operator, while in “generative models” the design proposals are directly optimized by the computer [19]. The latter subclass is also known as “performance-driven design” [1].

Following the manual procedure, the designers control the form-generation process, allowing for the introduction of unquantifiable criteria and the technical expertise of the operator. For instance, based on performance simulation feedbacks and technical knowledge, the operator generates new design alternatives and tests them until a satisfying solution is achieved. The generation of design proposals can be eased by the use of parametric modeling tools, such as Grasshopper [20] for Rhinoceros [21] and GenerativeComponents [22]. These tools allow one to define complex geometries and to easily modify them by controlling their parameters, thus preventing the need for the operator to manually redraw each design iteration. Adequate technical skills are required in manual processes, since the success of the optimization greatly relies on the correct understanding of the relations between design features and performance [2]. However, the time and manpower required in the processes may limit the number of iterations pursued and the effectiveness of the design optimization [1,23].

On the other hand, generative models allow one to explore a wide number of design options with a limited involvement of the operator, exploiting the functionalities of optimization tools (e.g., Galapagos [24] and Octopus [25]) [1,2,18,26]. These tools, when paired to a parametric model and a performance simulation tool, allow one to automate the search of the most performing solution within the variation space defined by the operator, while also narrowing the space of possible solutions based on the estimated performance [27]. The population of candidate solutions evolves over many generations, until a satisfactory solution is reached. This enables one to explore a wide solution space and to find potentially unconsidered design options to address the specific requirements of the project [3,28]. In automated processes it is also possible to effectively combine different performance goals in multiobjective optimization procedures, which can hardly be implemented manually. In automated procedures, the involvement of the designer is generally limited to the definition of the target performance objectives and of the boundaries of the variation space within which the generative process operates, which may reflect quantifiable and unquantifiable criteria [11]. Despite these advantages, manual procedures may be preferred by

professionals to allow the design exploration to be guided by their intuition and expertise gathered by working in the field.

Manual and automated procedures are often combined in different ways in hybrid methods, allowing one to exploit the advantages of both approaches, based on the requirements of the design process.

The PBD approach enhances the efficiency of the design process by enabling to optimize the architectural proposal with respect to the performance analyzed. However, the application of PBD method is still relatively limited currently. Indeed, current architectural practice often relies on experience-based know-how and performance simulations are mainly introduced in late design phases with the aim to verify the adherence to the performance requirements.

1.2. Performance-Based Design in Acoustics

The implementation of PBD in the architectural acoustics field would allow the designer to better combine acoustic performance objectives with architectural goals. Architectural design and acoustic performances are strictly linked: the emitted sound is altered by the architectural space within which it is deployed, due to sound reflection, absorption and diffusion phenomena occurring over its surfaces. In common practice, however, acoustic concerns are mainly restricted to the design of spaces intended for artistic performances, such as music venues and theatres. In such spaces, the architectural environment is meant to support the sound generated by the artists, and acoustic design is critical for both audience and performers [12].

However, as the benefits of acoustic comfort on the well-being of the population are being acknowledged, acoustics concerns are introduced in a wider variety of design problems [29]. Indeed, acoustic requirements are being increasingly extended to the design of spaces not related to artistic performances, such as classrooms, workplaces and urban environments, where an appropriate acoustic performance would benefit the hosted activities and the well-being of the users [29–32].

The acoustic performances of architectural spaces can be described by a number of parameters (e.g., sound pressure level, sound strength, reverberation time, clarity, etc.), each accounting for different perceptual aspects [33,34]. The acoustic requirements vary in accordance with the function hosted in the space. For instance, in spaces intended for speech, as classrooms and conference rooms, early sound reflections need to be adequately controlled to ensure the speech intelligibility [35]. In music venues, i.e., concert halls, opera houses, theatres and open-theatres, a number of parameters are usually considered to account for different perceptual aspects [36]. The proper management of early and late reflections is crucial, and it is generally obtained by opportunely treating the ambient with reflective and diffusive surfaces. Differently, the acoustic performance of sound reproduction rooms, like home theatres and recording studios, should be neutral, to prevent the space to alter the perception of recorded sounds; in this case a combination of sound diffusing and sound absorbing surfaces is preferred [37].

Currently, different commercial acoustic simulation tools are available (e.g., Odeon [38], CATT-Acoustic [39], Pachyderm Acoustics [40], etc.), allowing professionals to estimate the performance of design proposals using the geometrical acoustic method. The acoustic performance of a given environment is predicted based on its geometrical features and the acoustic properties of the materials applied to the surfaces. Normally, the acoustic analysis is run in an external application from the modeling environment, and a specific virtual model need to be prepared (e.g., geometrical simplification, surfaces divided into layers based on material and specific format) in order to be fed to the acoustic simulation tool. Besides geometrical acoustic simulations, some more sophisticated simulation methods, such as wave-based ones, have been applied to concert halls and other bigger environments [41–43]. However, these methods still require long simulation time and are not currently supported in any commercial acoustic simulation tool.

Although architectural design should pursue aesthetical quality in parallel with acoustic performance objectives, the process of conciliating acoustic requirements and architectural quality is often difficult and time-consuming, given the different design approaches and criteria of the two disciplines [44,45]. In most cases, the architectural and acoustic specialists work rather independently,

with relatively few exchanges between them [28,46]. For instance, the most common approach followed in the design of concert halls relies on well-known typologies (e.g., shoe-box, fan-shaped, vineyard, etc.) and integrates acoustic simulations in late phases of the design process to verify the adherence of the project to performative requirements. In the design of spaces intended for other purposes, acoustic performances are often overlooked, recurring to acoustic treatments to adjust the performances only in late design phases or after the construction. Since the projects at the final stages are already defined, normally, major form-modifications cannot be pursued anymore, and improvements can only be obtained by altering minor design features, resulting often in costly and little effective solutions [5,6,47,48].

In this frame, the implementation of the PBD method in the acoustic field, known as acoustic performance-based design (APBD), would be able to overcome some of the main drawbacks of the traditional method and set-up an effective collaboration between architectural and acoustic specialists. The feedback of the simulations enables one to identify the dependencies between the design features and the acoustic performance, and to optimize the project accordingly. However, despite the mentioned advantages, the application of APBD in current architectural practice appears to be limited.

1.3. Objectives

The aim of this paper is to provide an overview of the state of the art of the application of the acoustic performance-based design method through the gathering of a set of built case studies. The design procedures followed in the development of the case studies are briefly described, to highlight the benefits of the application of APBD and suggest possible improvements to extend its application.

2. Research Methods

This paper presents and investigates a set of 19 built case studies developed with APBD, which were gathered through a literature research. The methodology followed in this work is similar to that applied in review studies pertaining to the architectural field, as in [49]. For this work, unbuilt examples, as well as examples built as scaled prototypes or which lacked adequate documentation, were excluded from the analysis. The research is limited to the publicly available information on the built case studies, which was mainly gathered from journal articles, conference proceedings, books and web articles. Therefore, the presented collection cannot be considered comprehensive, as it excludes the projects, which are not documented in literature, as it is often the case of projects developed by professionals. Moreover, it must be highlighted that, with the exception of case studies developed for research purposes, the publicly released information regarding the design workflow and the performance parameters considered in the optimization process is generally rather limited. Despite these limitations, the presented collection will be hopefully meaningful and will help to delineate the state of the art of the APBD method, by briefly describing the design outcomes, as well as the design processes and the strategies followed to enhance their performances.

2.1. Selection of Case Studies

The research was conducted on the literature available on online databases as Scopus [50] and ResearchGate [51], on Google search, and in the academic libraries of Politecnico di Torino. Although scientific literature has been privileged, the support of Google search engine was exploited to extend the collection of case studies and to find further information. It must be noted that, for certain projects, further details were asked to the professionals involved in the projects via personal communications. Common keywords used in the search enquiries to filter results were: “performance-based design”, “form-finding”, “performative design”, “performance”, “architecture”, “design”, “generative”, “optimization”, “simulation”, “acoustics” and “sound”. Only built examples with adequate documentation were selected for the analysis.

According to these criteria, 19 built examples were collected. In the following section, the case studies were briefly described and information on the design method and the tools used were gathered.

2.2. Case Studies

The 19 case studies, which were briefly described in the following sections, were clustered according to their primary purpose and architectural characteristics. The first section, named “music venues” (Section 2.2.1) collected the projects that were designed to support of music and other artistic performances (i.e., concert halls, acoustic shells, etc.), while the second section, named “other spaces” (Section 2.2.2), gathered projects that were meant to host other functions or were developed as artistic installations.

2.2.1. Music Venues

2.2.1.1. The Philharmonie de Paris

Design: Ateliers Jean Nouvel, Brigitte Métra Associés; Acoustics: Marshall Day Acoustics, Nagata Acoustics, Studio DAP, Kahle Acoustics, Altia Acoustique, Jean-Paul Lamoureux and ASC; Paris, France, 2015

The project is the winning proposal of an international competition for the Philharmonie de Paris, whose main venue is a 2400 seats concert hall primary used for orchestral acoustic music performances (Figure 1). The acoustic brief for the “Grande Salle” explicitly called for an innovative shape for the concert hall with a limited distance between stage and seats, optimization of both early and late acoustic responses and also defined more than 10 acoustic requirements to be met (sound strength, reverberation time, clarity, etc.). The acoustic design started with the study of the sound reflections through laser measurements in scale models and continued with the support of parametric modeling and acoustic simulation tools, using Grasshopper, Maya [52] and Odeon. The solution adopted is made of two nested chambers that balance early and late reflections: the inner provides acoustical clarity and visual intimacy; the outer provides high reverberation, with an overall volume of 37,700 m³. The inner chamber is characterized by the presence of suspended reflectors, called “nuages”, along with the balconies’ fronts and walls, namely “ribbons”, which provide early sound reflections. The design of the “nuages” and “ribbons” was developed through the APBD method, following an iterative form-optimization process guided by the relations between their geometry and the acoustic performance at the audience positions. Initially, the form optimization process was carried out manually, while in subsequent phases it was pursued with the aid of automated processes using Grasshopper and Maya. The “nuages” and “ribbons” have been optimized to provide the desirable amount of early sound reflection over the audience in order to meet the acoustic requirements, such as time delay and level difference between direct and reflected sound, while also considering architectural and theatrical requirements. Odeon simulations were used after the optimization procedure to further verify the design outcome. Such simulations evidenced that the optimization process lead to significant performance improvements without compromising the architectural concept [53–59].



Figure 1. Philharmonie de Paris. Image courtesy © William Beucardet.

2.2.1.2. Elbphilharmonie Concert Hall

Design: Herzog and de Meuron, Acoustics: Nagata Acoustics; Hamburg, Germany, 2017

The design of the main concert hall of the Elbphilharmonie, the “Grosser Saal” (Figure 2), is based on the vineyard configuration and features 2100 seats and a volume of 23,000 m³. The APBD approach informed the design of the 10,000 unique acoustic diffusive panels that line the ceiling, walls and balustrades of the venue, whose engraved pattern has been defined through a generative design process. The development of the project involved the use of an acoustic simulation tool, parametric modeling and optimization systems. Moreover, a 1:10 scale model was also used to test the efficacy of the customized diffusing panels in eliminating long path echoes. Each group of seating of the audience is served by unique gypsum fiberboard panels, to create a balanced reverberation across the entire hall. Their design, which is the result of a close collaboration between acousticians and architectural designers, combines acoustic performance and aesthetics through an irregular pattern of “seashell” cells engraved in their surfaces. The APBD method has been followed in the design of the “seashell” pattern, which is optimized to diffuse sound waves over the seating of the audience and to eliminate detrimental echoes. The cells of the pattern feature a width ranging from 40 to 160 mm, and a depth ranging from 10 to 90 mm. In particular, in locations where it was required to eliminate echoes, the sound scattering performance of the panels were enhanced by the greater depth of the engraved cells, which measures 50–90 mm, while when soft reflections are desired, the cells feature a depth in the range of 10–30 mm. The generation of the pattern of the panels was performed by a custom algorithm, able to define a unique solution for each panel to meet the acoustic requirements. In addition to acoustic simulations, also scale model measurements were used to verify the results of the simulation and ensure the effectiveness of the pattern in echoes suppression [60–64].



Figure 2. The “Grosser Saal” of the Elbphilharmonie. Image courtesy © Maxim Schulz.

2.2.1.3. Anneliese Brost Musikforum Ruhr

Design: Bez + Kock Architekten; Acoustics: Kahle Acoustics, Müller-BBM; Bochum, Germany, 2016

The project is the winning proposal of the design competition for the concert hall for the Bochum Symphony Orchestra, which called for a shoe-box venue with a volume of 14,000 m³, visual intimacy and less than 1000 seats. The concert hall developed by Bez + Kock Architekten conciliates these conflicting goals by locating almost 1/3 of the required volume above the sound-transparent grid-ceiling (Figure 3). The final solution combines elements of the shoe-box and of the vineyard configurations, as the audience surrounds the orchestra. The sense of intimacy is further enhanced by the concave-curved shapes featured by the fronts and undersides of the balconies located at the sides of the venue. The APBD method informed the design of these surfaces as well as that of the acoustic canopy suspended above the stage. The architectural team collaborated with the acoustic consultants in the design process of these elements, which was developed using parametric models created in Grasshopper and a custom acoustic simulation tool integrated in the modeling environment. In plan, the curved profiles of the sides and undersides of the balconies were initially determined on the basis of two center-points, one in the conductor’s position and one in the middle of the parterre. In order to prevent the creation of sound focuses and echoes resulting from the curvature, these surfaces were segmented, and the curvature and vertical tilting of each portion was optimized based on acoustic simulation feedbacks to provide beneficial sound reflections, enhancing clarity and acoustic envelopment. The acoustic canopy located above the stage is made of five double-curved and dynamically shaped panels made of gypsum fiber board. The form of the panels of the canopy was optimized iteratively considering acoustic and architectural goals and their final configuration, which features varying curvatures in cross section, enhances the diffusion of the percussion and brass in the venue. Odeon simulations were performed in late design phases for verification purposes and found good agreement with the results of the simulations employed to support the design optimization [65–67].



Figure 3. Anneliese Brost Musikforum Ruhr. Image courtesy © Mark Wohlrab/architektur-photos.de.

2.2.1.4. Concert Hall of Ureshino Cultural Center

Design: AnS Studio, SUEP Architects; Acoustics: Nagata Acoustics; Ureshino, Japan, 2014

The concert hall (463 seats) is part of the Cultural Center of the city of Ureshino and features a shoe-box configuration with a folding roof (Figure 4). In the design of the roof of the concert hall, origami design and acoustic engineering were combined in order to meet the acoustic performance requirements. APBD informed the design of the folding roof of the venue, whose final shape is the outcome of an interactive design method, which combined a parametric origami software (i.e., a software able to generate different folding patterns based on origami rules), a custom acoustic simulation program and an optimization tool. The acoustic performance requirements for the venue proposed by the acoustic consultants were a uniform distribution of sound over the hall and audience within 30–90 ms, and the absence of echoes and sound focuses. The design method followed three steps. Initially, all the possible design alternatives for the folding roof were generated by the origami program, according to origami rules and the constraints set by the design team, which were related to building regulations, budget, structural aspects and other criteria. Each solution was then analyzed with the custom acoustic simulation program, with respect to the sound propagation and the distribution of sound at the audience positions. Finally, based on the simulation feedbacks, the optimization tool was used to find the solution, which showed the best combination of parameters to balance architectural and acoustic goals. The final solution for the roof, which was selected by the optimization program among a pool of about 200 design alternatives, is based on the Miura-ori folding pattern [68], where the folding depths and angles have been selected based on acoustic simulation feedback [28,69].



Figure 4. Concert Hall of Ureshino Cultural Center. Image courtesy © Kai Nakamura.

2.2.1.5. University of Iowa Concert Hall

Design: LMN Architects, Neumann Monson Architects. Acoustics: Jaffe Holden; Iowa City, IA, USA, 2016

The 700 seats-concert hall represents the main venue of the Voxman Music Building of the University of Iowa. The concert hall is based on the shoe-box configuration and features a sculpted structure suspended from the ceiling, made of 946 unique folded aluminum composite modules, which was generated through performance-based design (Figure 5). The structure integrates and rationalizes in a unique and aesthetically unified solution five technical systems: acoustics, stage lighting, house lighting, audio-visual and fire protection. The form-finding process, which guided the design of the structure was enabled by a collaborative parametric model developed in Grasshopper, which was optimized in light of the objectives defined by the consultants of the different disciplines involved. The project was guided by an iterative design method and was also optimized for fabrication and to be delivered in a low-bid procurement environment. As regards acoustics, the feedbacks from a custom ray-tracing simulation tool, developed in collaboration with the acousticians, were used to drive the design optimization process of the ceiling system. This enabled the architects to autonomously run preliminary acoustic analyses to test the design iterations in early design phases. In particular, the form of the ceiling system was progressively refined to ensure an even distribution of the reflected sound waves towards the audience and toward the upper portion of the side walls. Given the number of disciplines involved, SketchUp [70] and Revit [71] versions of the parametric model had to be used to allow exchanges among the different consultants. Early prototypes of panels and connections of the ceiling system were produced at different scales and tested. Iterations between physical and digital models were used to further refine the project and explore different fabrication strategies. Great commitment was placed in optimizing the fabrication of the system, and direct-to-fabrication data for construction could be generated from the model [72–74].

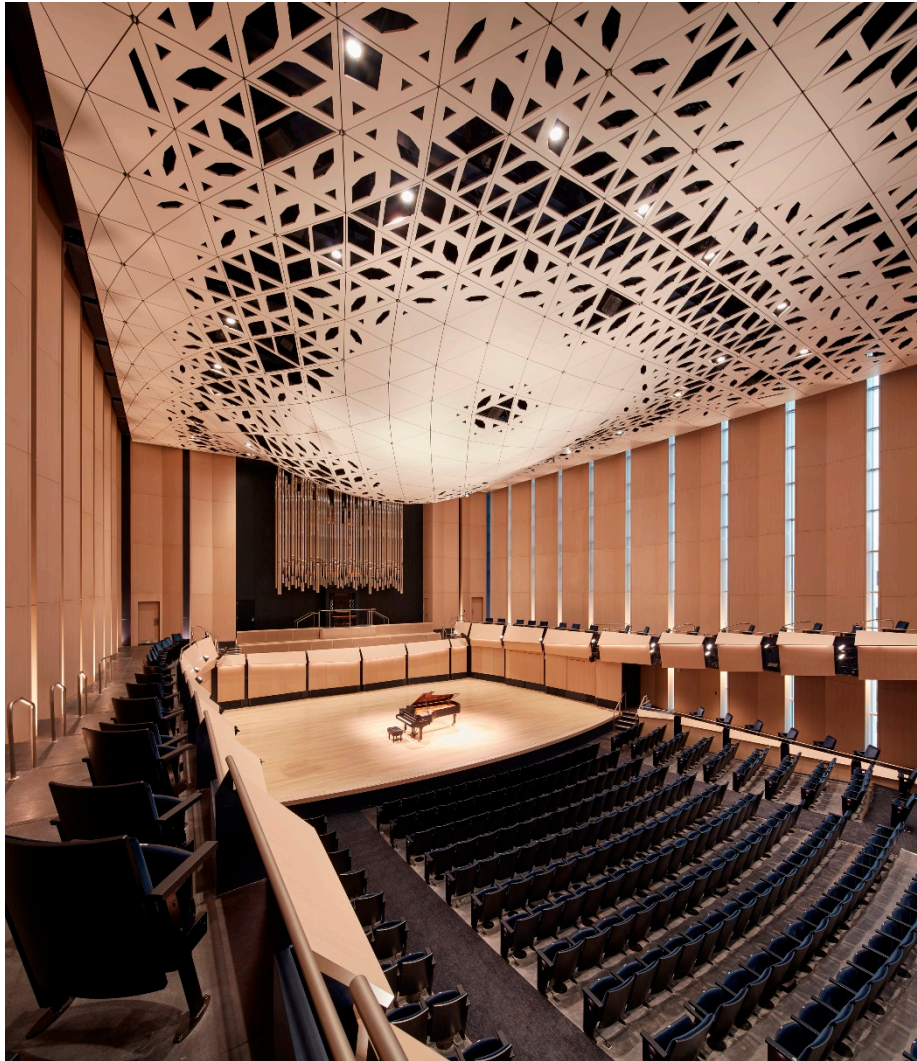


Figure 5. University of Iowa Concert Hall. Image courtesy © Tim Griffith.

2.2.1.6. Symphony Hall of the Fuzhou Strait Culture and Art Centre

Design: PES-Architects, Acoustics: Tongji Architectural Design Group, Kahle Acoustics and Akukon; Mawei New Town, Fuzhou, China, 2018

The Fuzhou Strait Culture and Art Centre includes a 1000 seat symphony hall and a 1600 seat opera hall, both of which were developed with the APBD approach.

The symphony hall of the Strait Culture and Art Centre in Fuzhou features a vineyard configuration and, despite the relatively modest seat capacity, is meant to host a full symphony orchestra of more than 100 musicians (Figure 6). In order to prevent overly loud acoustics, its volume was set at 17,000 m³ and was visually divided in two parts by the suspended reflectors, which overlook the audience. The curvature of the suspended reflectors ensures an even coverage of early reflections, but the major role is played by the walls of the halls, which are shaped as convex sphere portions. The walls that separate the terraces of the audience and those at the periphery of the hall are inclined in a petal-like configuration. The lower portions of these elements generate early reflections, while the upper parts spread the sound energy in the venue. The surface of the petals is coated with ceramic tiles with different textures and patterns, to provide either specular or diffuse reflections. The APBD approach informed the design of the geometrical features and surface patterns of these petals. Grasshopper was used to generate the parametric models, while a custom tool integrated in the modeling environment was used to analyze the acoustic performance according to the early acoustic efficiency approach [75]. As regard the geometrical features, the distribution and

vertical tilting angles of the “petals” were optimized to provide early lateral reflections to all the audience blocks. The surface pattern of specularly reflecting or diffusing ceramic tiles was used to generate useful early reflections and to prevent undesired echoes from the upper portions of the petals. Since it was considered crucial to maintain strong early reflections, the sound diffusing tile pattern was applied only in the portion of the petals creating potentially harmful late reflections, while the remaining part was left with a specularly reflective finish. Such surfaces were identified by using a custom algorithm able to categorize the surface facets based on the delay of the reflections they may generate, considering the combined data from four sound source positions. Although the surfaces were identified by the algorithm, when conflicting feedbacks were found, the final decision was left to the operator. Odeon simulations were used in late design phases for verification purposes [76].



Figure 6. Symphony Hall of the Fuzhou Strait Culture and Art Centre. Image courtesy © Marc Goodwin.

2.2.1.7. Opera Hall of the Fuzhou Strait Culture and Art Centre

Design: PES-Architects, Acoustics: Tongji Architectural Design Group, Kahle Acoustics and Akukon; Mawei New Town, Fuzhou, China, 2018

The 1600-seat opera hall (volume 14,500 m³) is based on the horseshoe configuration and features a continuous skin, with convex and concave curvatures, which defines and unifies walls, balconies and ceiling (Figure 7). The APBD approach was applied to define the form of the skin, which was optimized in order to meet the acoustic requirements of creating a homogenous coverage of strong early lateral reflections over the entire audience and to avoid undesired focusing effects. The acoustic simulations were performed with a custom tool based on a differential ray-tracing technique [77], integrated in the modeling environment. Since the architectural elements are not present as individual entities but are interlinked by the skin, they could not be singularly adjusted, as any form change would impact on the other elements. Therefore, the continuous envelope was modeled parametrically in Grasshopper, and directly optimized based on the acoustic feedbacks, due to the close collaboration between the architectural and acoustic teams. In particular, the skin was subdivided in smaller patches, and each was assigned with an acoustic target, such as creating early reflections or enhancing late reverberation. The orientation of the different skin portions was then iteratively optimized by the operators in order to achieve their target performance requirements and then combined to create the final smooth curved skin. A fine-scale texture of flower-shaped ceramic tiles is applied to the surfaces of the continuous skin; the small irregularities of the pattern provide

sound scattering at high frequencies. The final outcome of the optimization was further tested in Odeon; the verification confirmed the benefits provided by the application of APBD [76,78].

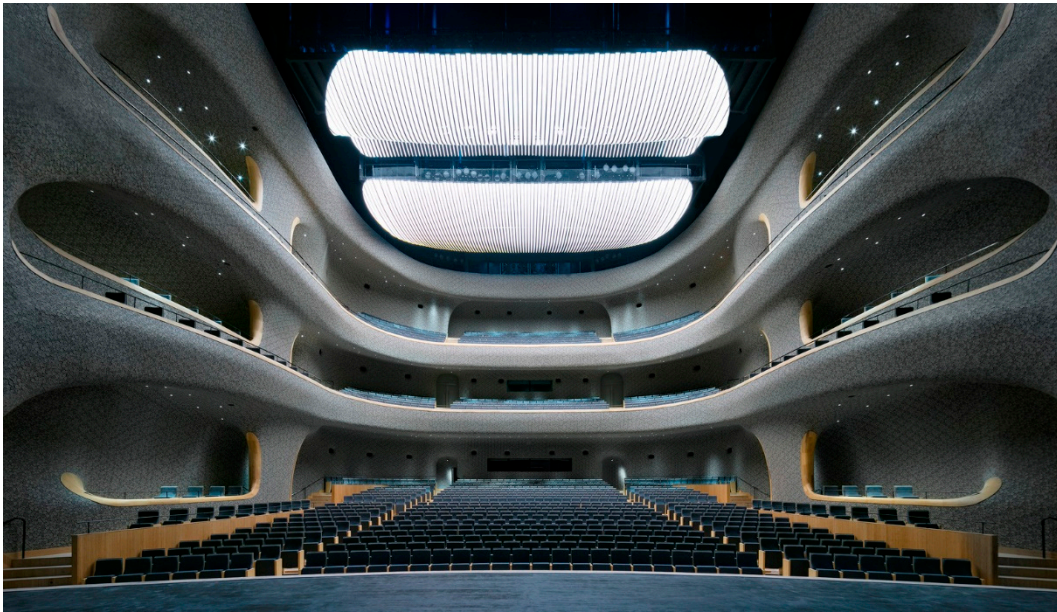


Figure 7. Opera Hall of the Fuzhou Strait Culture and Art Centre. Image courtesy © Marc Goodwin.

2.2.1.8. Conga Room

Design: Belzberg Architects, Acoustics: Newson Brown Acoustics; Los Angeles, CA, USA, 2008

The Conga Room dance club hosts a series of a multitude of programs (dance hall, stage, restaurant, bars and VIP areas) and is located at the second floor of a multipurpose building, mainly occupied by offices. Due to a retrofit intervention, the existing spaces were acoustically insulated and adapted to host the new mixed functions. The bold design of the undulating ceiling system is meant to visually attract clients while also providing acoustic treatment for the dance hall (Figure 8). The ceiling was indeed identified as the most effective location for acoustic treatments to provide sound insulation and amplification. The ceiling system was developed through performance-based design, exploiting the functions offered by CATIA [79] and Rhinoceros for modeling, and Ecotect [80] for the simulations. The ceiling system, made of CNC-milled plywood panels whose pattern and fashion changes differentiate the various environments of the club, was designed to address acoustic issues and to integrate several building infrastructures (house lighting, mechanical, audio-visual, fire protection, etc.). The model of the ceiling structure was iteratively optimized based on the feedback from the various specialists involved and performance simulation. In particular, the ceiling panels over the dance hall are morphed into flower-like structures, which control the acoustic performance of the ceiling. The different arrangements and tilting of the flowers' petals have been optimized based on acoustic simulation feedback to provide the desired amount of sound absorption [81–84].



Figure 8. Conga Room. Image courtesy © Benny Chan/Fotoworks.

2.2.1.9. Stage by the Sea

Design: Flanagan Lawrence Architects; Acoustics: Arup Acoustics; Littlehampton, UK, 2014

The project consists of two double-curved concrete shells located close to the coastline of Littlehampton, United Kingdom. The smaller shell works as a shelter, while the bigger one is an acoustic shell that is used as a stage for outdoor concerts and projects the sounds towards the listeners (Figure 9). During the design process of the acoustic shell, great commitment was placed in combining structural, acoustics and aesthetic goals in a unique solution. The final design of the acoustic shell is the result of an ABPD process, and conjugates the key acoustic performance requirements with architectural and structural objectives to create a durable, effective and inexpensive solution. The design process involved the use of Grasshopper for Rhinoceros for modeling, Dynamo for Revit [71,85] for the acoustic simulations and Galapagos for the design optimization. The design of the structure was developed in a tight collaboration between architects and technical consultants, which enabled us to find the best compromise in overall terms. The digital model of the shell was exchanged among the professionals involved more than twenty times before its final configuration was achieved. The acoustic analysis enabled one to define a shape for the acoustic shell able to effectively support outdoor concerts by reflecting the sounds towards the audience located in the facing sunken garden, allowing the music to be perfectly heard in windy conditions at a distance of 50 m from the stage [86–90].



Figure 9. Stage by the Sea. Image courtesy © Flanagan Lawrence.

2.2.1.10. Resonant String Shell (ReS) 6.0

Design: Sergio Pone, Bianca Parenti, Daniele Lancia, Sofia Colabella; Acoustics: Serafino Di Rosario; Acireale, Italy, 2017

ReS is a temporary outdoor acoustic shell that hosts the classical music concerts of the yearly festival “Villa Pennisi in Musica”. The shell design combines acoustic concerns with structural and technological ones. During each edition of the festival, a prototype of a temporary outdoor acoustic shell is built in the framework of a summer school, and its performances are tested through acoustic measurements. From year to year, the design of the shell is optimized based on the measured acoustic performance and a new design is developed to be built in the following edition. The acoustic shell built in 2017, named ReS 6.0 (Figure 10), was developed exploiting a multiobjective optimization process to define the geometry of the shell. In particular, the inner profile of the shell, which is composed by wooden reflective panels, anchored to an already defined structural system made of arches, was optimized within a magnitude of 50 cm. The process was enabled by Octopus [25], a multiobjective optimization tool, Grasshopper and a custom acoustic simulation tool based on an image-source method. Considering three pairs of sound sources located within the shell (i.e., music performers), the profile of the shell was optimized to maximize the evenness of sound energy in the audience positions. The sound energy was described by the sound pressure level and the standard deviation was calculated to quantify its rate of homogeneity. For each couple of sound sources, the sound pressure level has been estimated using the custom acoustic simulation tool, and Galapagos was used to search for solutions able to minimize the standard deviation. The optimization process identified a set of “equally optimal” solutions, among which the final configuration was selected by considering also aesthetic criteria. CATT-Acoustic was used in late design phases to run more accurate analyses of the optimized shell. The field measurement confirmed that the form optimization leads to a greater and more uniform distribution of sound energy in the audience [46].



Figure 10. ReS 6.0. Image courtesy © Daniele Lancia.

2.2.1.11. Soundforms

Design: Flanagan Lawrence Architects; Acoustics: Arup Acoustics; London, UK, 2012

Soundforms is a movable acoustic shell designed to support outdoor classic music performances, by improving the ability of musicians of the ensemble to hear each other, and by projecting the sound generated towards the audience. A prototype of the shell, developed for small chamber music orchestra, was built and tested in London's Dockland, and was then selected to be installed in the Olympic Park for the 2012 London Olympic Games to host music concerts during the event (Figure 11). The acoustic performances were one of the major drivers of the design process, aside with the development of the structure and its optimization for transport and assembly. The shell form was developed from a portion of torus, and features an upper peak, which was designed to project as much sound as possible towards the listeners, playing a role similar to that of the ceilings of concert halls. The shell has an inflatable skin made of eight PVC coated polyester cushions, fixed to the truss structure. The side walls of the acoustic shell, which performs as reflectors, are integrated in the inner structure of the shell and are visually covered by an acoustically transparent fabric liner, thus enabling one to maintain the visual aspects of the shell without compromising their acoustic performances. Removable reflective panels are installed within the shell, with the objective to balance the amount of sound energy diffused towards the orchestra and projected towards the audience. The APBD method informed the development of the convex profiles of the reflectors, as well as their deployment within the shell, which, in the built prototype, were optimized for a small chamber orchestra. The optimized reflectors were developed by the acoustic consultants in close collaboration with the design team, following a process of subsequent optimization combining architectural and acoustic objectives with fabrication and constructability criteria. The reflectors facets were parameterized in Grasshopper, the acoustic simulations were run using a custom ray-tracing script in Dynamo for Revit, while the optimization process was performed with the support of automated routines using Galapagos. The final solution was then further tested in Odeon to validate the results [27,91–93].



Figure 11. Soundforms. Image courtesy © Nick Guttridge.

2.2.1.12. Tiara Acoustic Shell

Design and acoustics: Alban Bausset, Willem Boning, Arup Acoustics; Fishtail, MT, USA, 2014–2015

The design of the acoustical shell for the Tippet Rise Art Center was commissioned to Arup Acoustics in 2014. The demountable and transportable shell was initially designed to host and support outdoor chamber music concerts for an audience of 50–60 people, by creating an intimate performance space, visually open to the surroundings natural environment (Figure 12). The shell is made of wooden panels, which represent the upper corners of the side and front corners of a fan-shaped room, while the rest of the enclosing surfaces were removed to open the view towards the natural setting.

The goal was to generate a unified acoustic environment for both audience and performers and an enveloping sound impression, despite the lack of reverberation. The virtual model of the shell was parameterized using Grasshopper. The acoustic performances of the structure were investigated using a custom simulation tool based on an image-source method; a source position and 50 receiver positions were used. Based on the performance feedbacks, Galapagos was used to optimize the parametric model by adjusting six parameters controlling the shell form, in order to ensure a broad spread of early energy over the entire audience. The variation space of the model parameters was set based on structural requirements, and in order to prevent the shell from obscuring the view of the mountain in the background. The fitness function counted the second and third order of reflections over the “poorest” receivers of the audience. From the two solution regions found by Galapagos, the design team selected the final one based on structural criteria. In 2015, the initial design solution was further expanded in order to accommodate up to 80 people, by the addition of two kinks to the structure, which were optimized with a procedure similar to that used for the initial solution. The final configuration of the shell provides on average 5.6 s- and third-order reflections to each receiver, with a minimum of one from the front, one from the right side and one from the left side [94].



Figure 12. Tippet Rise Art Center, MT. Photo: Erik Petersen © 2020 Tippet Rise.

2.2.1.13. Aalborg Acoustic Pavilion 2011

Design and acoustics: AREA, Electrotecture Lab; Aalborg, Denmark, 2011

The temporary acoustic pavilion was developed within a research framework. The structure is meant to host electronic music performance and its design was optimized for both acoustic performances and constructive feasibility. The structure is composed by CNC milled plywood plates, which works as sound reflectors (Figure 13). The design process was enabled by the combined use of Grasshopper, a custom acoustic simulation tool and Galapagos solver, which allowed one to combine acoustic goals with production and assembly criteria. The pavilion was also optimized with the aim to open its geometry towards the water while closing it towards the close-by road, to shield it from traffic noise. During the design process, the design problem has been progressively reformulated, in order to reduce the variation space evaluated by the Galapagos solver. With respect to acoustics, the volume of the pavilion and the configuration of the reflectors, which define the envelope of the shell, were optimized in two subsequent steps. In order to prevent the structure from altering the electronic music spread via a loudspeaker, the optimization processes aimed to minimize the reverberation time within the pavilion, calculated with the Sabine equation. This goal was reached by maximizing the number of reflections occurring among reflectors, thus enhancing sound absorption, and by directing the reflected sound away from the pavilion. The optimization was performed considering different sound source positions, which marked the loudspeaker locations in the corners of the pavilion. In particular, the arrangement of the specific set of reflectors serving each loudspeaker was optimized to maximize sound absorption by increasing the number of reciprocal reflections. In the end, the final solution was slightly refined to meet the fabrication requirements [95,96].



Figure 13. Aalborg Acoustic Pavilion 2011. Image courtesy © Isak Worre Foged.

2.2.1.14. Aalborg Acoustic Pavilion 2012

Design and acoustics: AREA, Mads Brath Jensen; Aalborg, Denmark, 2012

The pavilion is composed of an origami folded structure made of triangular wooden panels (Figure 14). The temporary pavilion was developed for research purposes and is intended to host two subspaces with different purposes, which are therefore characterized by dissimilar acoustic performances. A design optimization process was set in the in order to create two areas with opposite acoustic proprieties within the pavilion: a zone intended for classical music performances, featuring a long reverberation time, and an area intended for speech, with a short reverberation time. The tools used in the development of the acoustic pavilion are Grasshopper, a custom acoustic simulation tool and Galapagos solver. The acoustic performances on the listener positions were described by the reverberation time, calculated with the Millington-Sette equation, and by sound pressure level, simulated using a custom ray-tracing tool. The parametric model of the pavilion was composed by two subsystems: the first controls the overall space form, which resemble a tunnel; the second defines the folding structure and presents a higher control point resolution. The panels of the pavilion feature a sandwich structure with foam in the middle layer and plywood on both sides. Three panel variants were developed in order to provide three different rates of sound absorption, by opportunely perforating the interior plywood side of the panel, and therefore exposing the sound absorptive foam layer to the impinging sound waves. The optimization process was able to control the orientations of the control point of the primary and secondary subsystems, as well as the acoustic variants of the wooden panels, which compose of the structure. After 700 iterations, the reverberation times in the two subzones of the design solutions generated by the optimization process stabilize at values of 0.2 s and 1.4 s [97].



Figure 14. Aalborg Acoustic Pavilion 2012. Image courtesy © Isak Worre Foged.

2.2.1.15. Resonant Chamber

Design: RVTR; Acoustics: Arup Acoustics; Ann Arbor, MI, USA, 2012

Resonant Chamber is a responsive acoustic envelope system, based on rigid origami principles, that is able to dynamically alter the sound environment in which it is installed based on a set of inputs collected in real time by sensors or using preprogrammed configurations (Figure 15). The flexible structure can be deployed in a music venue to alter the sound during the performance, playing the role of an instrument at the architectural scale itself, or can be installed in more ordinary spaces, to calibrate their acoustic performances to given requirements. The faceted “sound cloud” is able to dynamically transform its configuration in response to acoustic changing conditions and to variations in the listeners’ positions. The tools used to develop the project were Grasshopper, a ray-tracing tool for acoustic simulations and Kangaroo [98], to model the dynamic deformation of the system. The structure is made of a combination of different plywood panels, featuring either sound reflective, sound absorbing or electroacoustic properties, arranged around an electronic panel that contains circuit controls and sensing inputs. In response to the inputs, such as ideal reverberation time, absorption coefficient, directional amplification and early/late acoustic response, the system adjusts its acoustic properties. In particular, resonant chamber modifies the acoustic performances of the space within which it is installed by gross deformations of its shape, able to alter the aural volume, and by locally adjusting the folding configuration, to change the panels exposed to the sound waves. The optimal geometry and the characteristics of the materials were determined by acoustic simulations and measurements on physical prototypes [99–103].



Figure 15. Resonant Chamber. Image courtesy RVTR © Adam Smith.

2.2.1.16. Courtyard Enclosure of Smithsonian Institute

Design and acoustics: Foster + Partners; Washington, DC, USA, 2007

The design of the courtyard enclosure for the Smithsonian Institute's Patent Office, an historic building in Washington, was developed in the framework of an invited international competition, won by Foster + Partners. APBD informed the design of the courtyard enclosure, which is a complex roof structure meant to perform at the same time as a solar shade, an acoustic absorber and a weather protection device. The proposal consists of a glazed undulated canopy, which features a diagonal grid of structural beams and is supported by eight columns arranged in three domes (Figure 16). Since the space underneath was meant to be flexible and hosts a variety of events, such as receptions, seated dinners and music and theatrical performances, the acoustic treatment was integrated in the bearing structure of the canopy. The Specialist Modeling Group, a research team within Foster + Partners, developed a custom generative script able to control the entire roof system based on a set of parameters, allowing for exploration of a wide range of design alternatives. During the design process, the different design goals were mutually related and synthesized by the generative tool, which was constantly adapted as the design requirements became more specific. The acoustic performance goal was to reduce the reverberation time between 2 and 3.5 s. To this aim, the structural beams of the canopy were designed to work as sound absorbing devices. The sound absorbing layers of mineral wool were mounted at the sides of the core steel structure of the beam and were covered by layer of thin steel tubes. The latter layer, while visually hiding the sound absorbing material, is

“transparent” to sound, exposing the sound absorbing filling to the impinging sound waves. To provide the desired reduction of reverberation time, the area of the sound absorbing material was a key parameter in the generating algorithm. Although acoustic simulations were not integrated in the modeling tool, the digital models of the enclosure could be easily exported to be analyzed in the external software. Ultimately, the final solution for the roof was the result of more 400 design iterations explored during a period of 6 months [104–107].



Figure 16. Courtyard Enclosure of Smithsonian Institute. Image courtesy © Brady Peters.

2.2.2. Other Spaces

2.2.2.1. FabPod

Design and acoustics: Nick Williams, Brady Peters, John Cherrey, Jane Burry, Mark Burry, Alexander Peña De León, Daniel Davis; Melbourne, Australia, 2013

The project is an acoustic enclosure for meetings, able to host eight people, housed in an open-plan office at RMIT University (Figure 17). The FabPod project is part of a research investigating the sound diffusing properties of hyperboloid surfaces, which was previously explored on a prototype wall in 2011. The acoustic design imperatives were to reduce the sound transmission through the enclosure and to provide a homogeneous internal acoustics that was conducive to small meetings, without creating an acoustically “dead” space. In order to meet these objectives, the FabPod combines sound absorption and sound diffusion within the cell, creating a diffuse sound field by exploiting the sound scattering properties of hyperboloid surfaces. A similar strategy was applied also to the outer side of the installation, with the aim to improve the auditory experience in its surroundings. The project is intended as a flexible structure, able to be applied to a range of scenarios, and therefore great consideration was dedicated to fabrication quality and mass-customization. APBD was applied to the definition of the overall enclosure form and to the geometrical and material properties of the

surface pattern. Three material options were developed for the facets of the interior surface (plexiglass, metal and felt), featuring different rates of absorption. The parametric model of the structure was defined in Grasshopper and four different workflows were developed, each one using a different acoustic simulation tool, to design either the enclosure form or the pattern of hyperboloid blocks. Pachyderm Acoustics and Odeon, which are based on geometrical acoustics, were used to analyze the form of the enclosure, and two custom wave-based acoustic simulation tools were used to simulate the acoustic performance of the hyperboloid surfaces. Different acoustic parameters were taken into account, including reverberation time, sound pressure level, speech transmission index (STI) and the scattering coefficient. The final design consists in a semi-enclosed envelope, which wraps around the meeting area and is composed by an irregular pattern of 180 unique hyperboloid blocks, featuring different acoustic properties [108–113].

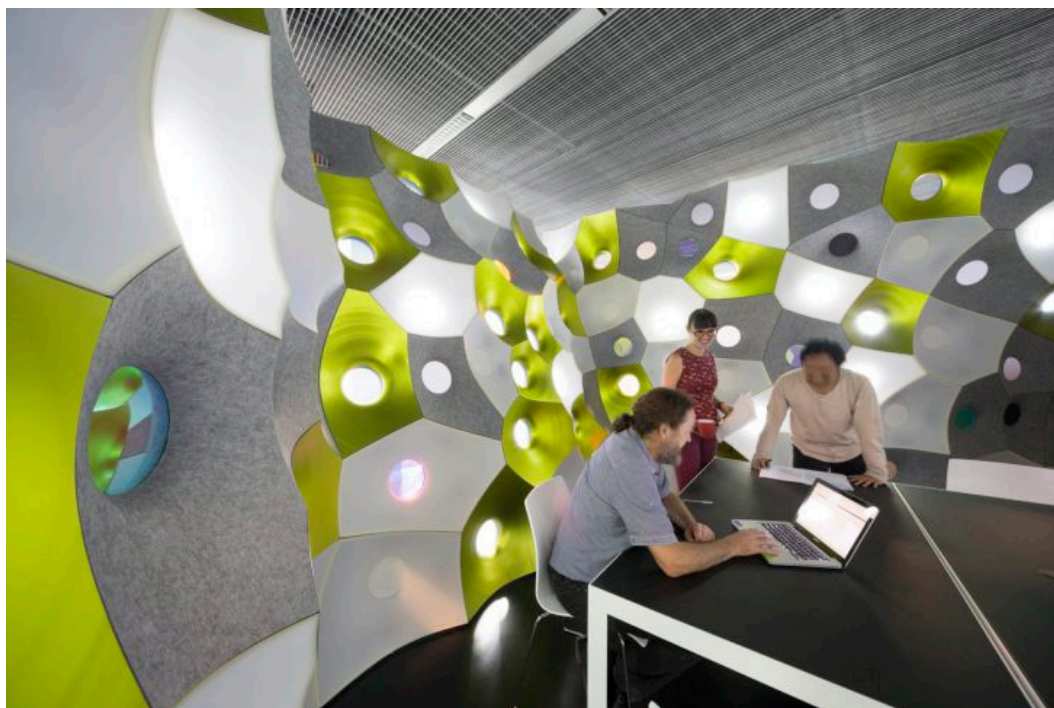


Figure 17. FabPod. Image courtesy © John Gollings.

2.2.2.2. Manufacturing Parametric Acoustic Surfaces (MPAS) project

Design and acoustics: Brady Peters, Martin Tamke (CITA); Barcelona, Spain, 2010

The temporary project was installed at the Smart Geometry 2010 Workshop and Conference and consists of a curved wall composed of different panel types, which generates different types of acoustic subspaces (Figure 18). The project explores new forms and material compositions and digital fabrication techniques. The APBD approach was applied to the design of the undulating form of the wall and to the panel composition. The design of the installation was developed in GenerativeComponents with the support of generative computer scripts, while acoustic simulations were run in Odeon. The acoustic goal was to create different acoustic subspaces in the surroundings of the installation: from a quiet, enclosed area, characterized by a high rate of sound absorption, to an amplified sound area, generated by sound reflective surfaces, with a gradient of acoustic performance between the two conditions. Such different acoustic performances could not be effectively described by the reverberation time alone; therefore, a number of other acoustic parameters were introduced in the analyses, such as early decay time, speech transmission index and sound pressure level. Moreover, auralizations were used to listen to the sonic environments generated by the installation prior to its construction. The acoustic performances drove the design of both the overall shape of the installation and its panel composition. Nine panel types with different

acoustic performances were designed and opportunely integrated in manufacturing parametric acoustic surfaces (MPAS) in order to produce the desired acoustic effects. The collection of panel typologies includes a sound absorbing panel, different types of sound diffusing panels, variously perforated screens, a panel with different properties depending on the direction of the impinging sound and a “sound window”, which provided visual connection from one acoustic space to the other. Based on acoustic performance feedbacks, the geometrical form of the wall and its panel composition were controlled to generate the different acoustic subspaces in the surroundings of the installation [104,114–116].

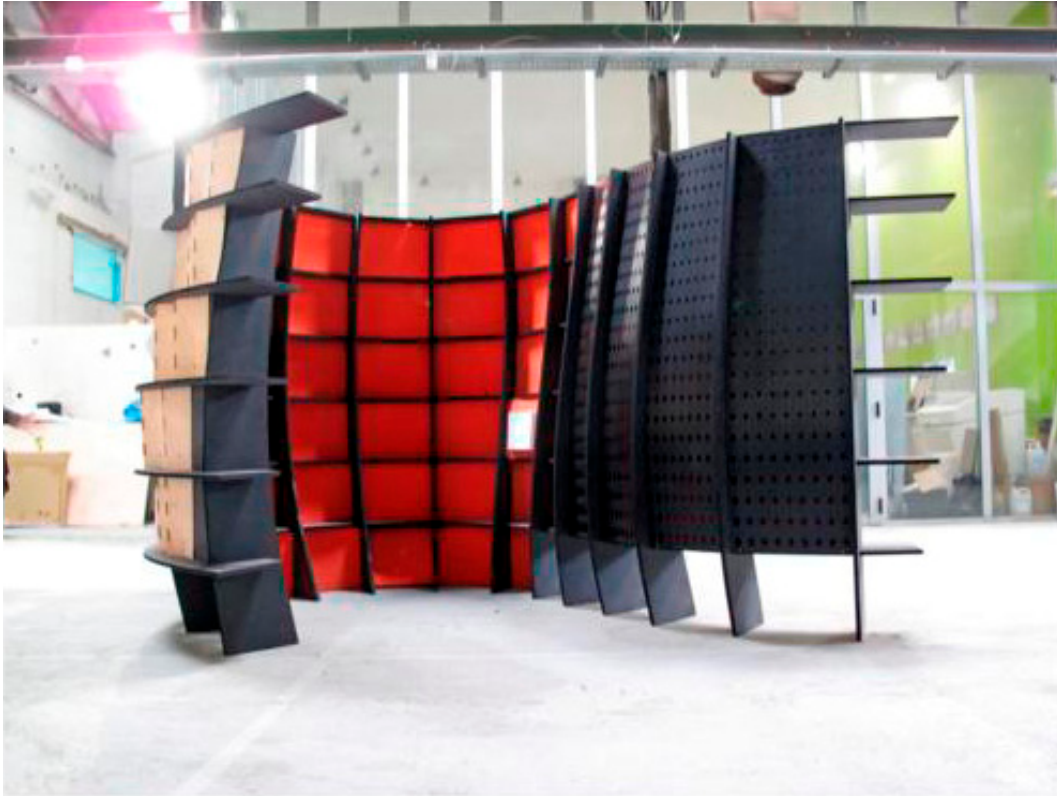


Figure 18. MPAS project. Image courtesy © Brady Peters.

2.2.2.3. Distortion II

Design and acoustics: Brady Peters, Martin Tamke, Stig Nielsen (CITA); Niels Jacubiak Andersen (Krydsrum); Magnus Gustafson and Patric Gustafson (Akustikmiljø); Copenhagen, Denmark, 2011

Distortion II is an experimental research project developed to create a bending acoustic surface able to create visual and acoustic effects within an open-plan space (Figure 19). The temporary structure is composed by a folded surface, made of composite plates arranged in a series of trihedral corners with different dimensions and orientations. Four different digital production techniques were used in the installation, i.e., laser cutting, knife cutting, CNC routing and metal bending, and fabrication files were generated by a custom tool. The installation explores the potentials of acoustic subspaces (see also MPAS project) and creates a sound-amplified area and a sound-dampened zone. To this aim, the APBD approach was applied to define the materials, the level of enclosure of the structure and the geometry of the panels to control sound reflections. The acoustic parameters used to define and measure the inhomogeneous acoustic space surrounding the installation were reverberation time, early decay time, sound strength and an experimental parameter (STV IA-diff) [117,118]. Two design workflows were used in the development of the project: in the first Odeon was used to run the acoustic simulation, while in the second the acoustic analyses were directly run within the modeling environment using a custom ray-tracing tool, to provide instantaneous performance feedback for the optimization process. The latter workflow was only used in conceptual phases, while

Odeon was extensively used in subsequent ones to accurately calculate the different acoustic parameters considered. The plates that compose the installation feature opposite acoustic properties on their sides, being composed by a layer of sound absorbing material, a structural MDF panel and a layer with a sound-reflective aluminum face. The arrangement and materials of the plates of the trihedral corners were optimized through an iterative routine to generate the two acoustic subzones. In the sound-amplified zone, the plates sides feature sound reflective properties and are arranged in order to create focusing, while on the sound-dampened area, the faces of the plates feature sound absorptive properties and their configuration promotes sound diffusion [117,119].



Figure 19. Distortion II. Image courtesy © Anders Ingvarsten.

3. Discussion

The information regarding the design processes of the case studies is summarized in Figure 20, where the case studies within the categories “music venues” and “other spaces” have been further classified in accordance to their architectural typologies. The table gathers information regarding the primary functions, the design features developed with APBD, as well as regarding the procedures and tools used in the development of the projects.

	NAME	PRIMARY FUNCTION	FEATURES TO WHICH APBD WAS APPLIED	AUTOMATED/MANUAL	DIGITAL TOOLS EMPLOYED	
MUSIC VENUES	concert halls	PHILHARMONIE DE PARIS	music performance	geometry of nuages, fronts and walls of balconies	with automated processes	Rhinoceros, Grasshopper, Maya, Odeon
		ELBPILHARMONIE	music performance	surface pattern of the diffusing surfaces	with automated processes	Rhinoceros, parametric modeling software, custom acoustic simulation tool, optimization program
		ANNELIESE BROST MUSIKFORUM RUHR	music performance	overall geometry of the canopy, balcony front and undersides	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Odeon*
		CONCERT HALL OF URESHINO CULTURAL CENTER	music performance	overall geometry and folding pattern of roof	with automated processes	parametric origami generator, custom acoustic simulation tool, optimization program
		UNIVERSITY OF IOWA CONCERT HALL	music performance	overall geometry and surface pattern of the ceiling system	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool
		FUZHOU SYMPHONY HALL	music performance	geometry and surface pattern of the "petals"	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Odeon
	opera hall	FUZHOU OPERA HALL	music performance	geometry of the continuous skin	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Odeon
	dance club	CONGA ROOM	music performance	panel configuration of the ceiling system	manual processes	CATIA, Rhinoceros, Ecotect*
	outdoor acoustic shells	STAGE BY THE SEA	music performance	overall shape of the acoustic shell	with automated processes	Rhinoceros, Grasshopper, Dynamo for Revit, custom acoustic simulation tool, Galapagos*
		RESONANT STRING SHELL (ReS) 6.0	music performance	overall shape of the acoustic shell, components	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Octopus, CATT-Acoustic
		SOUNDFORMS	music performance	overall shape of the acoustic shell and reflectors	with automated processes	Rhinoceros, Grasshopper, Dynamo for Revit, custom acoustic simulation tool, Galapagos, Odeon*
		TIARA ACOUSTI SHELL	music performance	overall shape of the acoustic shell	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Galapagos
	pavilions	AALBORG ACOUSTIC PAVILION 2011	music performance	overall geometry of the pavilion and surface pattern	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Galapagos
		AALBORG ACOUSTIC PAVILION 2012	speech / music performance	overall geometry of the pavilion and surface pattern	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Galapagos
	indoor inst.	RESONANT CHAMBER	various performances (including music)	overall shape and configurations of the responsive system	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Kangaroo
enclosure	ENCLOSURE OF SMITHSONIAN INSTITUTION	various performances (including music)	overall shape of the courtyard enclosure	with automated processes	custom generative script, acoustic simulation tool	
OTHER SPACES	meeting room	FABPOD	speech	overall geometry and surface pattern	manual processes	Rhinoceros, Grasshopper, Pachyderm Acoustics, Odeon, custom acoustic simulation tool
	indoor installations	MANUFACTURING PARAMETRIC ACOUSTIC SURFACES PROJECT	other	overall shape of the wall and panel configuration	with automated process	GenerativeComponent, Odeon, custom generative script
		DISTORTION II	other	overall shape of the wall and panel configuration	manual processes	parametric modeling tool, Odeon, custom acoustic simulation tool

* E. Badino, personal communication

Figure 20. The table offers an overview of the projects, gathering relevant data on their architectural features and on the design development.

3.1. Architecture and APBD

The collection of case studies shows a great degree of variation with respect to their functions and profiles: from world-renowned concert halls to more ordinary architectures, research projects and artistic installations.

Most of case studies are major projects, such as concert halls venues, developed by renowned architectural firms and acoustic consulting groups, or were developed as research projects. In the first case, the resources and specialized expertise that are often available to major architectural firms, along with the reliance on external consultants, enable an innovative approach such as APBD to be effectively applied. However, such resources are generally not available in more ordinary projects, especially when the architectural firms involved have no technical expertise on parametric modeling, acoustics and programming, as it is often the case. This result suggests that this procedure requires specialized expertise and resources, which are not commonly available for ordinary architectural projects.

Most projects are spaces meant to host music performance (16 projects out of 19), while only a small fraction of the projects is developed for other purposes (e.g., artistic installation, meeting room and multipurpose space). This suggests that the application of APBD is in line with the general trend of including acoustic concerns mainly in the development of spaces intended for music performances. However, certain projects, such as FabPod, Resonant Chamber and the Courtyard Enclosure of the Smithsonian Institution, shows the application of APBD for spaces intended for a wider variety of purposes.

Across the collection, APBD has been applied to either major or minor architectural features of the design, ranging from reflectors and pattern textures in concert halls, to the overall shape of smaller architectures, such as acoustic shells or artistic installations. In the design of concert halls, the main structure of the venue is generally based on well-known typologies (e.g., shoe-box, vineyard, etc.), while APBD is applied to reflective surfaces or diffusive pattern. In smaller intervention, such as pavilion and acoustic shells, APBD has been applied also to entirely shape the structures, often combining other goals, such as fabrication criteria. This highlights that PBD approach is often paired with a more conventional approach in large projects to better combine the large number of requirements, which need to be considered.

3.2. Digital Workflows in APBD

APBD is normally applied due to the combined use of parametric modeling and acoustic performance simulation tools. Moreover, optimization tools can be exploited to automate the search of the most favorable solutions with respect to the target performance goals.

The parametric modeling tool that was used in the great majority of the considered projects is Grasshopper [20] for Rhinoceros [21]. Acoustic analyses were mainly run using custom tools based on geometrical acoustics, while the commercial package that was used the most is Odeon [38]. In many cases, optimization tools based on evolutionary algorithms, such as Galapagos [24] and Octopus [25], have been utilized to support the design process.

Parametric modeling eases the design optimization process, by allowing one to easily modify the design by controlling the model parameters. Grasshopper is one of the most commonly used parametric modeling tools. It is a graphical algorithm editor integrated in Rhinoceros, which is a commercial modeling tool widely employed in architectural practice. Grasshopper enables one to generate parametric models of complex geometries on the basis of algorithms set by the designer. Grasshopper does not require any programming knowledge and is therefore employed by designers with relative ease.

Currently, a wide number of acoustic simulation tools, such as Odeon, CATT-Acoustic, etc., are available, allowing professionals to quickly perform simulations based on geometrical acoustic methods. Odeon is the commercial package that was more widely employed in the collected case studies. Acoustic simulation tools require a solid acoustic knowledge base to correctly set up the simulation and interpret its results. In most cases, the acoustic knowledge of architectural professionals is not adequate to correctly employ these systems, making the reliance on external acoustic consultants unavoidable.

Another limitation is due to the lack of integration among simulation and modeling tools, which are generally stand-alone applications, and the limited interoperability resulting from the specific formats or geometrical models required to run the acoustic simulation. Some tools, such as the SketchUp plugin of Odeon [120], ease the file exchange between the modeling and simulation environments. However, the generation of specific model for acoustic analyses is often mandatory to meet the requirements of the simulation tools (e.g., geometrical simplification, watertight model and layer division by materials). Therefore, architectural design and acoustic performance analyses need to be run into two separated environments on specific virtual models, resulting in a time-consuming process, which often limits the number of model exchanges among professionals. As a result, design optimization in early design phases can be difficult to achieve from the feedback provided by these tools, which are more commonly used in late design phases for verification purposes, as shown in many case studies. A noteworthy exception in this frame is Pachyderm Acoustics [40], an open-source

acoustic simulation tool integrated in Rhinoceros/Grasshopper, which was used in the development of FabPod.

In many case studies custom tools were employed to avoid the issues resulting from the poor level of interoperability and to perform specific analyses. For instance, the use of custom tool has been reported in 16 out of 19 case studies. Such tools are generally used in early design phases to provide quick estimations of the acoustic performances directly in the modeling environment.

Currently, different modeling platforms offer the possibility to the users to create custom programs (e.g., Rhinoscript, Grasshopper, Python, etc.) within their environment, widening the possibilities offered by the regular preset functionalities. In most cases, custom tools have been used in early design phases to run simplified performance analyses, easily visualize the results and optimize the design proposal accordingly. By clarifying the relation between acoustic and architectural design, these tools support an effective collaboration between architect and acousticians, and possibly the other technicians involved, enabling one to integrate different goals in the design proposal. Custom acoustic simulation tools are generally based on geometrical acoustic technique and apply ray-tracing or image-source methods. The performance feedback obtained, although simplified, is considered accurate enough to orient the design decision in early design phases. In many cases, more accurate analyses were run in late design phases with commercial acoustic simulation tools to further validate the results. Following a different approach, custom tools can be used to run sophisticated acoustic analyses, such as wave-based ones, which at the time of writing are not included in any commercial acoustic simulation package. In wave-based simulations, the wave behavior of sound phenomena, which are normally neglected in geometrical acoustic simulations, can be accurately simulated in 2D environments. For instance, in the development of FabPod, wave-based acoustic simulations were used to assess the scattering performance of the surfaces, which could not be accounted with geometrical acoustic techniques. Despite the wide range of possibilities offered by custom tools, the programming skills and acoustic knowledge required in their development and application are normally not available to architectural firms. However, currently the availability of several online coding courses and of platforms such as ACOUCOU [121], which offers free education materials on acoustics, may help to fill the gap. Furthermore, the introduction of PBD approach in architectural education would help students to become more familiar with building performance and simulation tools. Some of the case studies analyzed (e.g., ReS 6.0, Aalborg Acoustic Pavilions, MPAS project and Distortion II) were developed in an educational framework, and students were actively involved through summer schools and workshop; previous educational experiences with the PBD approach have been also documented in [16,17].

The design optimization can be performed either manually, for subsequent iterations by the operator, or in an automated matter. In the latter case, the parametric model is automatically optimized on the basis of performance feedback until one or more satisfying solutions are achieved, resulting in a quick and efficient process. The support of automated processes has been reported in the development of most case studies (11 out of 19). The optimization tools that were used in the case studies analyzed are Galapagos and Octopus, which are based on evolutionary algorithms, and are directly integrated in Grasshopper for Rhinoceros. Such tools enable one to run either single objective or multiobjective optimization of parametric models defined in Grasshopper, based on target requirements and variation space set by the user. The performance feedbacks needed to set up the optimization process are generally obtained from the custom acoustic simulation tool integrated in the modeling environment.

The design proposal can be optimized since early design phases based on the simplified performance feedbacks from the custom acoustic simulation tools, while more sophisticated simulation systems, such as Odeon, can be employed in late design phases when most design features have been already defined. These tools can be used to verify the performance of the preselected design proposals and provide the designers with detailed suggestions for further design improvements. For instance, commercial packages were used in late design phases to validation purposes in the Philharmonie de Paris, in the music venues in Fuzhou and in ReS 6.0.

4. Conclusions

As the impact of acoustic performances on human well-being are being acknowledged, acoustic concerns are expected to be increasingly integrated in the design of spaces with a variety of functions. In common practice, acoustic consultants are rarely involved since early design phases, and acoustic optimization and architectural design tend to be rather independent processes. In this frame, the application of performance-based design in acoustics seems very promising to optimize design proposals in light of performance feedbacks obtained from acoustic simulation tools. However, the method finds little application in current architectural practice, and is mainly restricted to notable architectures and research projects. A set of case studies developed with APBD has been collected in the attempt to shed some light on the state of the art of the application of the method in current architectural practice, evidence the design strategies followed and suggest some possible fields of improvement to further encourage its application.

The development of integrated platforms that combine acoustic analyses and architectural modeling, the increased interoperability among modeling and simulation tools, would ease performance analyses in early design phases, and will allow for an effective collaboration among architectural and acoustic specialists.

The enhancement of acoustic and coding skills of designers, which can be promoted by the provision of specialized teaching platforms, would support the development and application of custom tools to run simplified analyses in the modeling environment during early design phases, hopefully encouraging the application of APBD in practice.

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