# Acoustic Consequences of Performative Structures

## *Modelling Dependencies between Spatial Formation and Acoustic Behaviour*

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**Abstract.** *The paper discusses an interdisciplinary exchange between parametric design and acoustic simulation. It reviews a strategic development of temporary dynamic structures that can be manipulated by intersecting variations of formation in generative architecture with acoustic simulation. The research investigates drivers that interface knowledge between parametric design, structural engineering and fabrication, interaction design and acoustics, and theatre and performance. It reviews the simulation of a temporary theatre installation into an existent industrial hall, whereby different formation of a modular structure are explored, and the acoustic effects of this installation are evaluated in relation to an enhancement of the audiences spatial and acoustic experience. The research goes beyond the morphological, aesthetic or structural values that have become key aspects of contemporary digital architecture, and relates them to the field of auralisation (forecasting acoustic behaviour). In that manner, the simulation and analysis of a future (material, spatial) objects is developed through the communication of an interdisciplinary team, thus exploring synergetic qualities of the physical and the digital.*
**Keywords.** *Computational design; generative geometries; acoustic simulation.*

### INTRODUCTION: DESIGNING SPACES FOR PERFORMANCES

The design of spaces for the temporal arts, such as theatre, musical concerts, or dance performances, responds to performance criteria in a manner that is strongly affected by an understanding of space as a responsive, adaptive, immersive environment. Consequently, their programmatic, aesthetic, structural and acoustic requirements differ from spaces that are less responsive, or more anchored in 'static' organizations, such as residential or commercial architectures. Integrating acoustic performance at an early design stage is critical for the design of temporal art spaces. Yet more often then not, such design is developed in consecutive order; from initial design objectives, to structural engineering, to an acoustic evaluation; with feedback on acoustic performance usually given after completetion of design; and limited interdisciplinary exchange informing design iterations that would become a parameter to other disciplines. In contrast, this paper reviews a design process in which design relationships are established in conversation by architect, structural engineer and acoustic engineer – and in intersecting areas of computational design: generative design and design visualisation, acoustic analysis, structural analysis, and spatial acoustical forecasting (auralization). Such an interdisciplinary approach can help to bridge gaps between areas of expertise, and to investigate the potential for novel architectural solutions of performative, responsive, immersive environments.

In the temporal arts, specifically the strategic development of dynamic structures challenges the exploration of design relationships, due to varying aspects of performance relative to context. While the theatrical performance refers to actor and narrative, performativity in responsive environments refers to space itself reacting to context impact. Yet performance can also be understood as the continued incorporation of diverse parameter contingencies (material, technical, geometric, programmatic, social and economic) that can potentially inform an interdisciplinary exchange and collaboration. The present paper discusses the proposal for a temporal arts space where different formations of a responsive surface are deployed in a 'staging' of architectural space; a theatrical space that continues to emerge under aspects of spatial and sonic experience. Here, performance is two-fold; a performed theatrical sequence in a spatial installation that equally 'performs' in correspondence with the performance of an actor within space. This understanding of spatial and acoustic performance reviews architecture as a cultural expression that derives its lifespan from the reflective ability to address a change (Grosz 2001). Specifically in the context of performative cultures, the acoustic consequences of generative and structural form variations open architectural space to material interaction, human perception and affect.

This paper outlines an initiative for research on acoustic consequences of performative structures with the key aims: to design, deploy and evaluate simulations of and prototypes for real locations; and to interface digital technologies in a theatre/performance environment. In an interdisciplinary communication, different research expertise, interests and agendas are brought to the project and inform the design. The research address thus synergetic qualities of the physical and the digital, for a culturally end experientially rich environment.

## BETWEEN PARAMETERS AND ANALYSIS: GENERATIVE DESIGN

The advancement of digital technology has impacted a wide span of areas that intersect in the field of architecture, leading to a specialisation in software programs that address design, analysis or simulation of existing or future spaces. Hence, design processes are computational, interdisciplinary and iterative. By this we mean that: it is computational because it applies computer software to develop design variations; it is interdisciplinary in the analytical tests and simluations that are used to verify criteria and parameter sets in design; and it is iterative in the continued optimisation of formal solutions informed by interdisciplinary input. Through computational design, a parallel investigation through different digital data sets is enabled. More importantly though, this provides a language that is apt to approximate formations and variations through parametric and algorithmic descriptions. These descriptions follow a system logic; the logic of a mathematical framework whereby the end result is undefined but its rules are explicit, and diverse, a complex assembly of parts that are associative in their formal dimensional and material definition. Performativity (Kolarevic, 2005) and new performative space (Liu, 2009) have increasingly become of interest to architectural design.

During the last decade, the system logic of computational design has fostered a number of interdisciplinary approaches that inverstigate perrformative strategies, such as of emergence in architecture and biology (Hensel, Weinstock, Menges, 2004), or of (self) formations shared between architecture and structural engineering (Otto, 1960). Yet computational design also allows a strategic development of acoustic performance by way of interaction; through generative design and acoustic analysis in digital models, it enables a ‚reverse engineering' process that drives generations of design solutions under a continuous information flow between the design of a space and the effects that space causes: that is, a modelling of dependencies between spatial formation and acoustic behaviour becomes possible.

While such reverse engineering applied between computational generative design and acoustic simulation can lead to a different understanding of spaces for the temporal arts, this field has not yet been widely explored. An interdisciplinary exchange usually connects computational design to either structural engineering (Tessmann, 2008), or acoustic theories (De Bodt, 2006), however, no expansive research combines a multidisciplinary approach in which 3D modelling software is deployed to review the acoustic effects of generative design. We can design and generate exchange files engineering, analysis, and simulation software. A spatial-acoustic paradigm can be addressed through iterative analysis interfacing: the generative digital design as realm of strategic design; the structural analysis realm as area of construction; and the acoustic analysis as an arena of the immersive experience. This research explores transfers between the virtual/digital into the real/constructed by introducing 3D modelling and scripting software (MCNeel Rhino and Grasshopper), 3D structural analysis and simulation (Grasshopper/ Kangaroo, SpaceGass or R-Stab), and acoustic analysis (B&K Odeon or AFMG EASE), in order to provide a platform upon which different partners of collaborative design team can exchange, and design together.

## PROJECT DESCRIPTION: CONFIGURATIONS

The project ('Musical Chair', Rosengren-Fowler/ Blyth) is designed as a canopy, inserted as a secondary smaller volume within the expansive volume of the existing industrial hall, providing a sense of an enclosed space (Figure 1).

The potential of theatre and performance in a temporary setting (as opposed to more static, or fixed theatre and concert environments) is subject to simulation between a real and projected environment. How can generative design reflect acoustic criteria? Interdisciplinary design collaborations can support the forecasting of dependencies between spatial formations and acoustic performance, as discussed via the following case study. The context of the research is an invited design project for Sydney Festival 2012, undertaken with students of the Master of Digital Architecture Research, Faculty of Architecture, The University of Sydney. The project investigates a temporary theatre installation for a former machine workshop (Turbine Hall) of Sydney Harbours shipping dockyard, Cockatoo Island.

The ability of an audience to understand lines delivered by actors is essential to any performative space. Performers equally rely on the acoustics of such space to listen to each other, and to listen to their own voice reflected back from stage surfaces and surfaces enclosing the audience. In a condition of non-amplified performance (as is the case in theatre settings, or in common public and semi-public spaces such as museums, community halls, hotel lobbies, etc), speakers will adapt their voice projecting into space. A successful acoustic performance is a base condition for good performative arts spaces.

Due to the hall's materiality (hard surfaces: concrete floors, spatial trusses, and large volume), the present space poses a real problem for vocal performance that arises due to the lack of early sound reflections supporting the direct sound for the audience, and with no acoustical stage support for the performers. For that reason, the formation of a serial module that can act as sound reflectors in the areas of performance is used as a strategy for design. The proposed performance space would be suitable for between 400-600 attendants, seated in an ally thea-

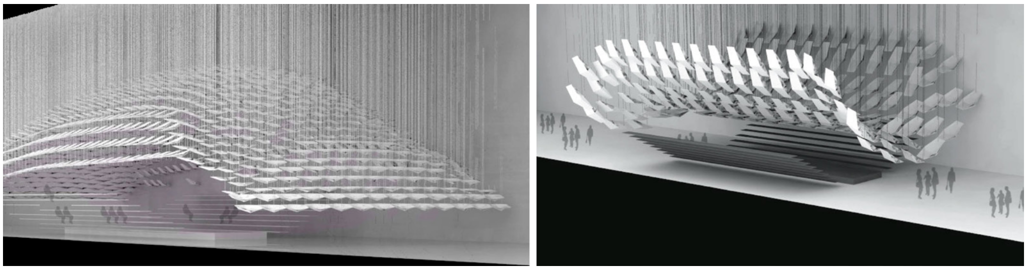


*Figure 1*
*Theatre Space with Acoustic Performance: 'Musical Chairs' .*

tre configuration. The structure is suspended over stage and audience area, and formed by a multitude of elements that can be manipulated to individually respond in movement to different formations. The design is latent in the sense that it can express different spatial settings, and induce different acoustic spaces of varying qualities. The resulting surface resembles aesthetically a swarm that rises from the ground plane to hover above, enveloping the audience within a volume of elements and strings.

## ANALOG/DIGITAL MODELS: PARAMETRIC VARIATIONS, MECHANICAL ENGINEERING

The canopy's different modes of movement were simulated by deploying the system logic of swarm behaviour. The design follows standard swarm criteria that prevents 'flocking', or in this case accumulation, by implementing rules of separation (avoid crowding neighbours, short range repulsion); of alignment (by strings, steering towards neighbours); and of cohesion (steering towards average levelled position of neighbours, long range attraction). While these rules administer the relative positioning of individuals in a field to each other, they are used here to produce theatrical shapes.

Transferred to a 'neutral' surface, these rules inform a 3D modelled through module repetition (McNeel Rhino) and scripted (Grasshopper) through actuator points, in order to manipulate the individual movement of elements, and to equalize an overall deflection of the surface itself. Depending on the position of each actuator that release or pull the surface relative to the overall hanging system, a total number of 9 acuators is sufficient for producing 9 different formations for the canopy structure (Figure 2).

The revision of the system through analogue mechanical engineering translates the digital form studies into analogue formations: through a complex system of lacing and kinetic mechanisms responsive to levers. Similiar to the digital model, the

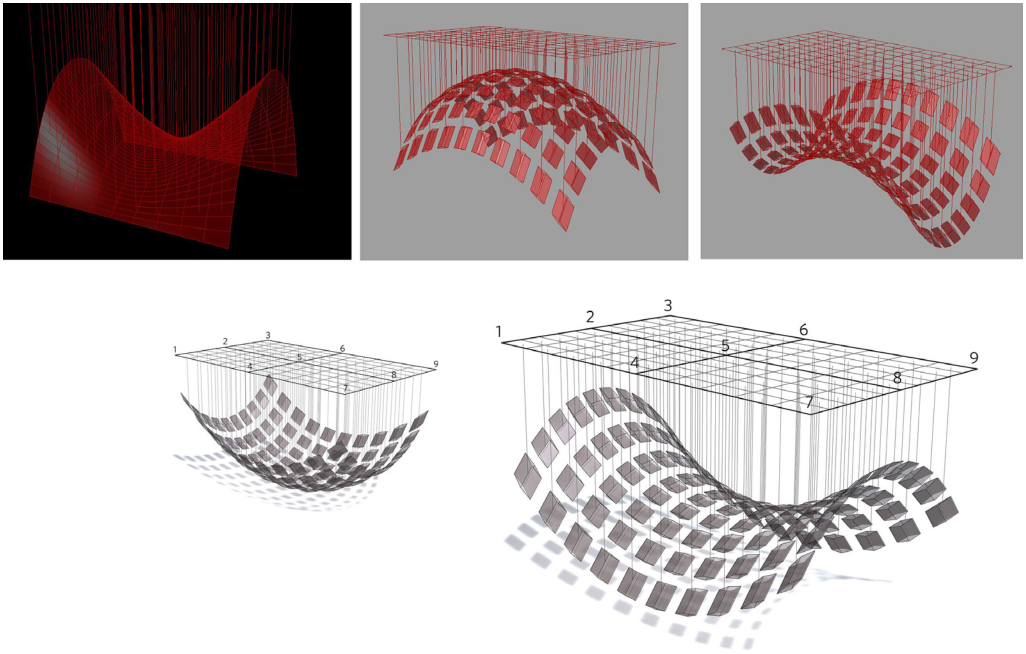
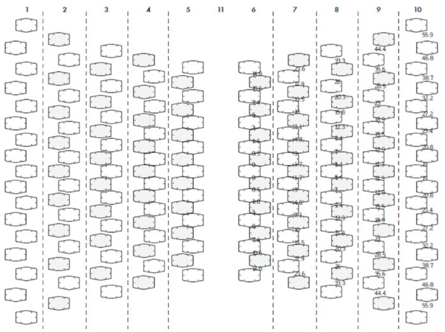



*Figure 2*
*Surface formations by leveling 9 actuator points (GH variations) .*



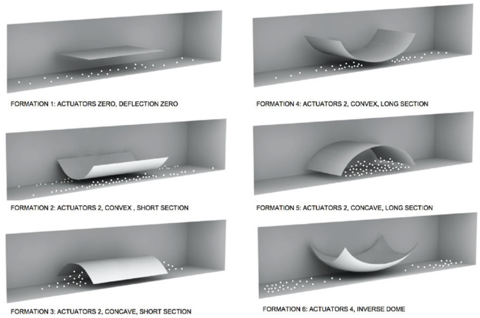



*Figure 3 (left)*
*Structural engineering: surface and kinetic mechanisms (i, ii) .*

*Figure 5 (right)*
*Overview of performative manual for Temporal Arts Space.*

mechanical model uses a system of pivoting members that each control the curve of a particular direction. In contrast to te digital model though, the computational prompt that combines different elements needed to be replaced here with a complex series of stringing, and two mechanism that draw together the former digital actuator points. For the analog prototype, the Turbine Hall is devided by rows of elements run across its width. Vertical cable lines (x 2) per element are positioned at each element's end point. In order to calculate varying distances between elements, a grid is projected to a double curved surface, and the centrepoints of elements are then measured to determine intermediary spaces between individual elements when strung together.

The diagram (Figure 3) shows three different strings connected through mechanism (i) and (ii). All connection points on the mechanisms are situated as to enable curve, inverse of curve, and all transient stages in between. Again, 9 main shapes can be created with the two mechanisms, which both have three basic positions: positive, 0 and negative. By combining these three positions of the two mechanisms, all shapes can be produced in a real, physical environment. Initially explored as analogue scale models with PVC heat-bended panels hung from strings (prototype 1:20), the final design uses standard industrial plastic chairs hung from suspension wires supported by a light steel-frame structure disclosed in the steel-frame trusses of the existent hall (confirmed in prototype 1:1).

The resulting nine main formations orchestrate a synchronized movement of performing bodies and performing chair canopy that is used to create dramatic emphasis; levels of acoustic and theatrical intimacy can be formed through movement; altering compression and expansion of space to enhance the dramatic language of the performance. Most importantly, these spatial formations result in considerably different acoustic performances (Figure 5).

## ACOUSTIC ANALYSIS: THE SOUND OF STRUCTURE AND SPACE

The acoustic characteristics of a space play a significant role in its users' experience. This is particularly important where the acoustics of the space are intrinsically tied to the activities intended for it. Specifically in the environment of performance, the spatial temporal characteristics (stage setting), the population of the space (by audience and actors) and the basic spatial settings (the theatre box) act as varying, interchangeable criteria that influence a user experience visually, acoustically and experientially. Physical models to understand acoustics have been used since the 1930s (Barron 1983). In the late 1960s computer simulation was introduced as a viable simulation technique for architectural acoustics (Krokstad, Strom, and Sorsdal 1968), and early simu-

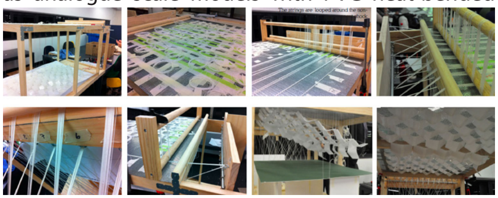


*Figure 4*
*Analog model studies intersecting scripted behaviour and kinetic mechanism.*

lation software rendered indirect sound using mirror images or ray tracing. Today, it is more common to use a hybrid of both techniques (Vorländer 1989).

Computer acoustic simulation of spaces allows a communication between architectural and acoustic designers, whereby different configurations can be explored, and beneficial and unfavourable features identified in a proposed design at early stages. In a typical acoustic simulation process, an acoustic designer will receive a three-dimensional computer model prepared by an architect, which can be simplified and run through to an acoustic simulation package. The most common techniques for acoustic computer simulation are mirror image and ray tracing, or a hybrid of both techniques, whereby several acoustic parameters can be obtained from the simulation including reverberation time and measures of the speech intelligibility within the room.

Several acoustic parameters can be obtained from the simulation including reverberation time and measures of the speech intelligibility within the room with results matching those of real spaces (Bork 2005). Additionally, the simulation allows to create first-hand experiences for auditioning a range of possible spaces, using a technique that has been termed "auralization." These auralizations allow us to listen to a room with a great deal of accuracy before the room is built, and has been more precisely defined as follows: "Auralization is the process of rendering audible, by physical or mathematical modeling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modeled space." (Kleiner, Dalenback, and Svenson 1993). The application of advanced digital technology allows in this manner not only a simulation and thus forecasting of spatial or structural requirements, but also a control over the interdependencies between form and structure as a result in spatial effect: acoustic simulations can be deployed to create auralisations, whereby the design team can listen to a room prior to its construction, thus provides offering an accessible way to present acoustic parameters. Furthermore, in the subsequent iteration process reverberation times can paralleled with structural and spatial formations, thus allowing a shared design result informed by structural engineer, acoustic designer and architect in conjunction.

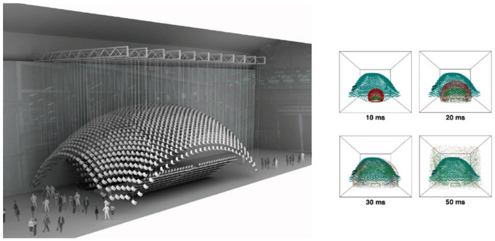
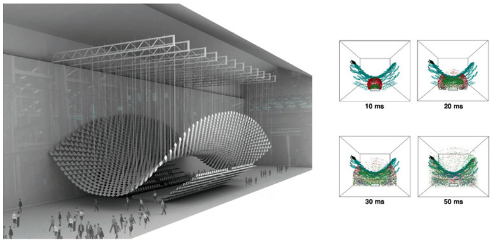



*Figure 6*
*'Dome', 3d modelling and acoustic analysis.*

## ACOUSTIC SIMULATION (DOME VS SADDLE)

Paralleling the generative design and mechanical engineering, acoustic simulation was undertaken to add acoustic parameter to the previous aesthetic and structural values; in order to identify the formation able to provide the most effective acoustic environment. One of the most common parameters used to describe spaces acoustically is *reverberation time* (defined as the time in seconds required for a sound to drop in level 60 decibels from its initial value, with 60 decibel considered as the level that sound heard at a medium sound pressure level must fade to become inaudible). Reverberation is highly dependant on space configurations, partition positioning, material finishes, audience area size and position. In spaces with higher absorption (typically softer finishes), sound will decay rapidly; in those with lower absorption (typically harder fin-

*Figure 7*
*'Saddle', 3d modelling and acoustic analysis.*



ishes), sound will decay slowly. As is the case with the Turbine Hall, its hard surfaces result in high reverberation times, ie inappropriate acoustic performance for speech performances. As a departure point, an increase of density of early reflections will also increase the *speech intelligibility* in the Turbine Hall (the ability of a listener to understand the words being transmitted either directly by a human source or over a sound reinforcement system). The nine configurations all share the characteristic of not completely enclosing and isolating the stage and audience areas, but differ in acoustic characteristics that influence the acoustics within the performance space. The proposed spatial configuration are thus directly analysed for their potential improvement of the existent acoustics of underlying space.

Two configurations were compared in advance of construction via a computer simulation of sound propagation, whereby a direct interdisciplinary exchange was enabled by transferring the original 3D modelling data (McNeelRhino/Grasshopper: .3dm files exported as .3ds) to acoustic analysis (Odeon). Their acoustic performance was measured by digitally referencing both the canopy fomation, and the greater hall in relation to each other. Two envisioned configurations, termed ‚Dome' and ‚Saddle', were compared in advance of construction via a computer simulation of sound propagation, and will be discussed in the following. Acoustic performance was measured by digital modelling- the strategy references both the immediate chair canopy and the greater hall. Given a three-dimensional model of the space, an acoustical model can be constructed for examining what will happen to a virtual sound source located on the stage. To simulate sound propagation, the source is made to emit a number of sound particles that support the desig by a visual forecasting of the acoustic behaviour. Each sound particle behaves as a ray, reflecting specularly from surfaces, in the same manner as light rays reflect from mirrors. The number of sound particles is specified by the user and distributed randomly within a spherical radiation pattern. With enough particles (usually in the thousands), an approximation to a spherical radiation pattern is achieved. In addition, an auralisation, the sonic forecast of these two specific formations, was undertaken.

In the 'Dome' formation (Figure 6), sound rays expand in time. Its panels are spaced apart, so that large amounts of sound rays escape to the hall. This configuration thus does not provide much benefit for the audience or performer because the introduction of early reflections by the panels is minimal. The auralisation revealed that sound was lost by the relative distance between panels.

In the 'Saddle' formation (Figure 7), sound rays reflecting from the panels reach the audience earlier, because modules are closer to each other, allowing less sound to escape and dissipate uselessly with the larger hall enclosure. The auralisation revealed that sound was enhanced by the relative adjacency between panels, and enhanced reverberation (which could be further enhanced by a change from the reflective plastic material, to a padded or textile surface).

In order to evaluate the influence of the suspended surface on speech intelligibility in the audience area, the acoustic Early Energy Fraction or $D_{50}$ was chosen as an appropriate metric. $D_{50}$ is a measure of the ratio of energy arriving within the first 50 milliseconds divided by the total reverberant energy. $D_{50}$ is a good indicator of the proportion of early reflections that aid in making a speech sound clear and louder and late reflections that would commonly muddle the speech sound. The minimum $D_{50}$ value for acceptable speech intelligibility is 0.5 in the frequency bands between 500 and 2000 Hz. Results obtained from the modelling of the empty hall and the two configurations, and compared to values for existing theatres demonstrate improvement and general performance of space, see table. It should be noted that for this initial investigation only the structure configuration was taken into account. The performance

*Table 1*
*Acoustic analysis and comparison of performance.*

| **Theatre** | **$D_{50}$ 500-2000 Hz** |
|---|---|
| Turbine Hall Empty | 0.48 |
| *Dome Configuration* | 0.59 |
| *Saddle Configuration* | 0.66 |
| *Festival Theatre, Chichester* | 0.65 |
| *Crucible Theatre, Sheffield* | 0.72 |
| *Barbican Theatre, London* | 0.71 |

*Figure 8*
*Sensual experience of the performative surface (prototype 1: 2, based on children's chair).*

of the space could be further enhanced with changes in materials to specific surfaces within the hall.

On a more general level, the acoustic simulation showed that a change from the empty hall to the 'Dome' configuration, and finally the 'Saddle' configuration will give progressively better acoustical support for performers. In extend of a performative benefit, the research could thus outline that the proposed structure serves several advantages; it provides an enhanced performative backdrop by an actual responsive installatio; and it offers different theatrical settings that - in specific formation - improve the acoustic qualities of the space.

## CONCLUSION

The interdisciplinary exchange of expertise and data transfer via digital software allowed the team of structural engineers, acoustic designers and architects to sync their knowledge, and to shortcut design in iterative progression. This allowed the review, design and testing of a wide range of criteria for the spatial and acoustic qualities of a performance space, resulting in better performances, spatial enhancement and sensual experience through the interfacing of computational design and acoustic simulation. The research agenda developed around the project conversations provided us with a research platform that has started to integrate relevant design questions arising between generative design, acoustical simulation, and in further projects also structural analysis. The research proceeded through the various, yet combined software of computational design, meachnical engineering, and acoustic analysis that allowed an improved spatial management and a better spectator experience in performance environments.

Design process, acoustic analysis and auralisation were used to improve the sound of space in relation to the audience, and in identifying the formation able to provide this improvement. In paralleling digitally derived variations and analogue mechanical prototypes, the project employed a 'reverse engineering' process in which the acoustic forecast provided the main parameter of operation and form definition. The immediate benefits of such methodology can be framed as advanced design and enhanced process between knowledge realms, but more importantly a deeper understanding of the acoustic consequences of performative structures; the sound of a future architecture.

Through direct investigations of forms responsive to contextual changes, fluid situations and spatial experiences, the research connects the requirements of architecture as that which enables theatrical performances, but it also opens on the possibilities of intuitive design, spatial perception, and social interactions (Figure 8). By reviewing the interfacing of prior disconnected disciplines of digital architecture, structural engineering and acoustical science, the paper has reviewed an interdisciplinary approach that spans between generative design, structural engineering analysis and acoustic analysis to investigate temporary architecture solutions. The research hereby also forecasted future communications and transfers; team design and collaborative approach that will continue to increase through shared software communication in diverse team situations of today.

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