

archi|DOCT

*The e-journal for the
dissemination of doctoral
research in architecture.*

Supported by the ENHSA Network | *Fueled by the* ENHSA Observatory

February **2019**

www.enhsa.net/archidoct

ISSN 2309-0103

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GEOMETRY

Robotic Fabrication of Acoustic Geometries - an explorative and creative design process within an educational context

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Abstract

The aim of this paper is to describe and exemplify a design method for exploring acoustic performance and robotic fabrication of wood panels. Cognitive and creative impact of the design method will be investigated through qualitative observations, complemented with a qualitative PCA analysis, of a 3-week design studio with architectural students on master level. The paper describes a computational system that supports non-experts in generating curve-based geometries informed by acoustic analysis and simulation of robotic milling. The results of implementing the design method into the early design process of a mobile library structure will be presented followed by a discussion of the implications that this design method could have for the explorative and creative design process as well as the competencies required of potential users.

Keywords

Robotic fabrication; Acoustic performance; Computational design; Creative design processes; Design methodology

Note

The design method and the 3-week design studio was created and conducted in collaboration with the author's supervisor Isak Worre Foged. The author would like to thank both Isak and the author's main supervisor Hans Jørgen Andersen for valuable input to this paper.

I. Introduction

When perceiving a building and the individual architectural geometries of which it is constructed one often relies on the visual sense - sizing the structure, detecting its patterns, its colours, its textures, the light that hits its surfaces. The process of architectural design is equally based on a visual exploration of sketches, drawings, physical- and digital models.

When perceiving the acoustic properties of an architectural building the visual sense is of no use and one must rely on one's sense of hearing. For the design process the same shift from visual to hearing has not been possible and during the design process the acoustic aspects has been based on practical knowledge and experience as well as theoretical knowledge about the properties of sound waves. Recently, new computational simulation methods have made it possible for architects to calculate and digitally visualize acoustic properties and how geometric variations affect its performance (Foged, 2018b). These computational tools thereby open for new opportunities for creative design of acoustically-driven geometries.

In the last decade, the development of new computational tools and corresponding methods has had a huge impact on the field of architecture. Utilising the power of computation architects have explored new ways of generating, analysing and simulating complex geometric structures. One of the many benefits of these new computational tools is the ability to communicate with CNC production machinery – including industrial robotic arms. New interfaces for popular CAD-software has enabled both simulation and toolpath-generation for industrial robotic arms (Brell-Çokcan and Braumann, 2010) allowing architects to explore aspects of design and fabrication in a parallel process – thereby internalising material properties and manufacturing aspects in the process of design exploration. The integration of both geometrically based design generation conducted in parametric software, acoustic simulation of design options, and robotic simulation of the fabrication process calls for an integrated and explorative design process (Foged, 2018a).

The creation and application of integrated computational-based design processes has the potential of revealing new solution spaces and new ways of searching these spaces for viable or optimal solutions. Exploring this type of computational design process sets new requirements to the technical and software-based skills of the architect, but the cognitive load of simultaneously handling many design parameters and constraints can also pose a challenge and have an impact on the creative flow and thereby the ability to construct and explore a given design space.

During the last decade, several commercial and research-based projects has investigated the use of computational design in architecture and explored the potentials of using computer simulations to inform and guide geometric variations of architectural objects. Although most attention has been on simulating structural properties (ex. FEA) other performance criteria such as solar radiation, view analysis and acoustics, has also been explored in recent years (Reinhardt et al., 2016).

The field of robotic architecture is largely build on the pioneering work of Fabio Gramazio and Mathias Kohler from ETH Zurich (Gramazio, Kohler and Willmann, 2014) and on the activities of international networks such as the Association of Robotics in Architecture (Brell-cokcan and Braumann, 2017). The versatility and adaptability of industrial robotic arms and their potential for exploring new building techniques and engaging with new materials has fostered a plurality of methods and design processes. One of these processes is Subtractive Manufacturing, where 3D objects are created by the removal of material. This process covers standard industrial techniques such as

milling (Jung, Reinhardt and Watt, 2016) and hot-wire cutting, but recent work has also implemented chiselling (Steinhagen et al., 2016) and carving techniques (Clifford et al., 2014).

Recent work by (Reinhardt et al., 2016) combines acoustic performance and robotic milling in a search for “acoustic effects of complex architectural geometries”. Their research proposes an iterative design process consisting of the following steps:

“(i) specification of the architectural design parameters, along with the acoustic design aims (e.g. scattering coefficient spectrum); (ii) computational design of specific surface micro-geometries; (iii) fabrication of physical scale model test samples in the form of discs; (iv) acoustic measurement and analysis of sample performance; and (v) refinement of the design with potential further iteration.” (Reinhardt et al., 2016)

In their work the designs of the specific micro-geometries are informed by the theoretical knowledge of acoustic scattering and specular reflection, while the robotic manufacturing process is tested through digital simulations before the actual robotic manufacturing of the sample discs occurs. Driven by the physical measurements of the acoustic performance of the sample discs the next iteration can be further improved and refined.

With the continuously improving software for parametric design found in the CAD-software Rhinoceros 3D (McNeel, 2018) and its embedded plugin for editing graphical algorithms Grasshopper, as well as the functionalities of the Grasshopper add-ons Pachyderm Acoustics (Harten, 2018) for acoustic analysis and KUKAprc (Brell-Çokcan and Braumann, 2010) for robotic simulation, this software package now supports the development and investigation of new design methods. Methods that supports architects and students of architecture in a design exploration of performance driven geometries based on acoustic analysis and robotic manufacturing.

By following a primary generator methodology, where aspects are successively investigated (Foged, 2018a), the work presented in this paper seeks to establish a design method that incorporates simulation of acoustic performance and robotic fabrication of milled wood panels.

The potentials and challenges involved in adopting the established design process is investigated through its implementation in a design studio with architectural master students - thereby investigating the challenges that non-experts meet when exploring a design space for which possible solutions can be simulated and tested against specific performance criteria. Through evaluation of the students' final design solutions and based on qualitative observations conducted during the design studio the research project also seeks to record the impact that the design process has on creativity and the associated cognitive processes.

This paper will present the established design method, including the processes of generating geometric variations, visualization of expected output of the milling process, performing acoustic simulations, and the generation of robotic toolpaths and the visual simulation of running these toolpaths. With the design method being implemented in a design studio on architectural master level, the paper will also present selected student work along with the physical 1:1 prototype of a mobile library structure that concluded the studio. The paper will also elaborate on the potentials and limitations of acoustic and robotic simulation, and reflect on the design method's impact on the creative and cognitive process of designing performative wood panels.

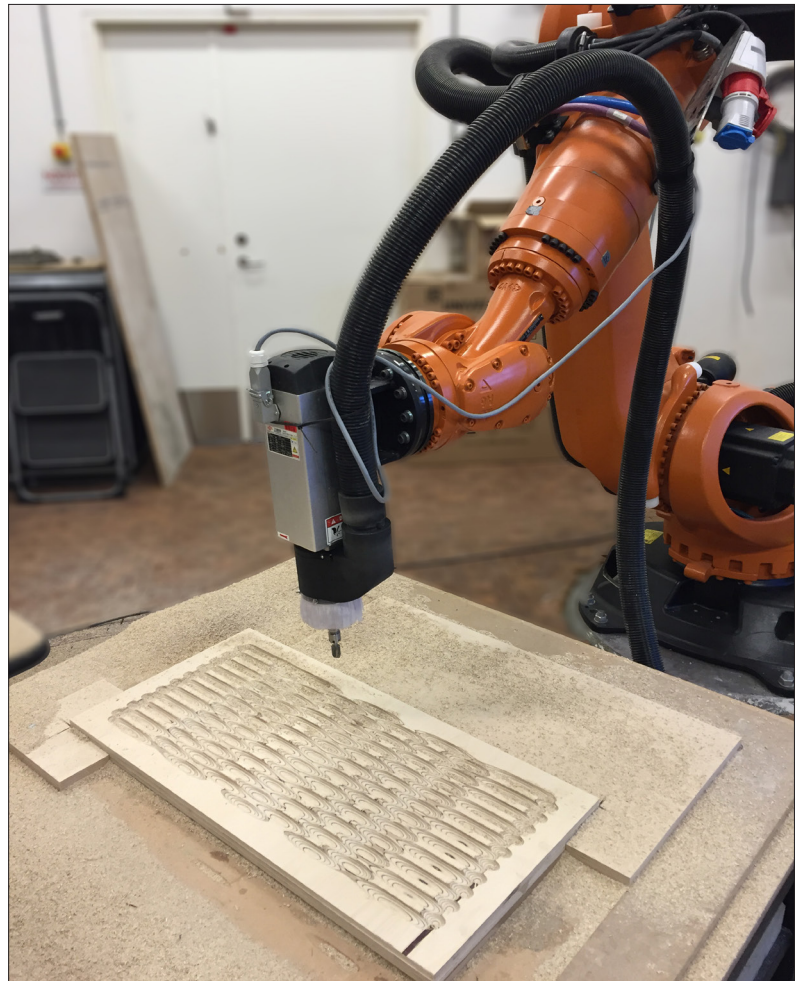


Figure 1.

Robotic milling of prototype for acoustic panel.

Photograph by Jacob Hilmer.

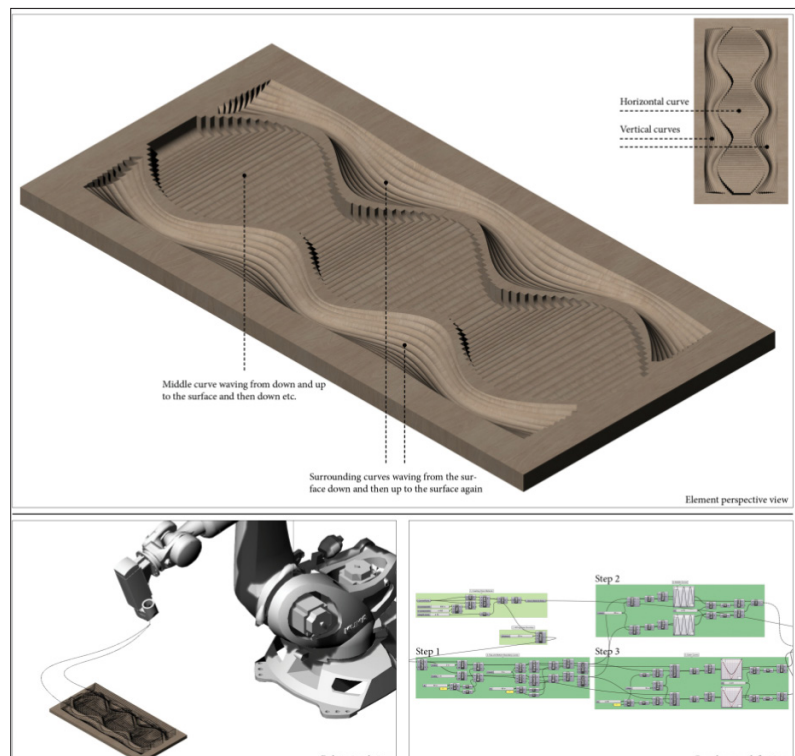


Figure 2.

Image showing a parametric design system (bottom right), with one out of many possible geometric compositions (top) and the corresponding simulation of the robotic fabrication.

Credit: student Maria Møller Salling.

2. Methods

The reason for developing a new design method was to enable a design process where geometric composition, acoustic performance, and robotic fabrication could be explored in parallel. To achieve this the design method is constructed such that the designer, through direct manipulation and design of digital curve geometry, receives the geometric solution that results from milling a wooden plate using the selected curves as milling paths. These milling paths and the given geometric solution allows for both a simulation of the robotic milling process and an acoustic analysis of the milled wooden plate – both simulations holds the potential of acting as valuable feedback for the next iteration of re-designed and increasingly informed curve geometry.

To examine the design method's ability to assist in the exploration of acoustic geometries and robotic milling of wood panels, the method was implemented in a 3-week design studio with architecture students on their master level. The aim of the design studio was to explore and apply architectural acoustics in the early design processes through to robotic manufacturing processes and the production of 1:1 prototypes. Structured in three phases the first week explored spatial- and material systems, robotic manufacturing constraints, and parametric modelling. The second week architectural acoustics was introduced together with robotic simulation. During the last week, the students explored their own design systems and iteratively improved the acoustic and manufacturing performance of their geometric solutions. Each student worked towards a final design for a mobile library shelf system consisting of empty shelves for books and shelves containing their acoustically performative plywood panels. The studio ended with each student fabricating one panel of their own design for mounting in a 1:1 prototype of the mobile library. The design method consists of a computational design system and a physical robotic setup.

The Robotic Setup

The robotic setup consists of an industrial robotic arm (KUKA KR300R2500) with a 7.5KW CNC spindle mounted as its end effector (see figure 1). With a ball nose milling bit (19 mm. diameter) attached to the spindle this setup allows for a milling angle of up to 25 degrees away from the vertical axis (z-axis in this case) without colliding with the 800x400x24mm plywood plates that were chosen for the acoustic panels.

The Computational Design System

The computational design system is constructed in Rhino+Grasshopper, and consists of four parametrically related sub-systems, or clusters, named: Path Generation, Geometry Generation, Acoustic Analysis, Robotic Simulation.

In the Path Generation cluster, users can directly interface or manipulate with the curve-based milling paths, the paths that the milling robot will follow during fabrication, thereby indirectly controlling the appearance of the resulting milling geometry. Design of the milling paths is a three-dimensional design challenge as the curves can be defined as moving through varying xyz-position, thereby defining their location on the wood plate and the depth they are moving down into the wood plate. There are numerous ways to generate and control curves, making this area open for a creative and explorative design process.

The Geometry Generation cluster performs the subtractive process of removing material. Using the milling paths, their connected planes, the cross section of the chosen milling bit, and the stock

material (plywood plate) the cluster performs boolean (subtractive) operations and graphically visualizes the resulting milling simulation (see figure 2).

In the Acoustic Analysis cluster the Pachyderm Acoustic plugin is utilized to simulate the acoustic performance of the geometric shape from the Geometry Generation cluster (see figure 3). Depending on the acoustic aim (ex. low reverberation time, high scattering coefficient, high absorption level) varying geometric shapes can be compared and the search for a better acoustic performance can inform the generation of new milling paths, thereby creating new and acoustically improved geometric shapes.

The cluster containing the Robotic Simulation largely consists of components from the KUKAprc package. Specifying the model of the robotic arm, the tool that it is equipped with (in this case the spindle) and the base coordinates (the robots position relative to the plywood plate) this cluster can simulate and visually represent the exact movements of the robotic arm by following the planes that are generated in the Path Generation cluster. Another important output is the estimated time that the robot needs to fabricate a given design – together with the results from the acoustic analysis the fabrication time can contribute to the overall performance of a given design solution.

An important aspect about the computational design method is that all feedback is visualized graphically (see figure 1). The dynamic simulation of the robotic movements, the visualization of different geometrical compositions for the acoustic panels, and the graph-based visualization of the results from the acoustic analysis, all serves as visual feedback that supports an iterative exploration of design solutions.

Design Studio Observations Setup

The results of applying the design method on non-expert users was gathered through qualitative observations during the day-to-day interaction with the students as well as observations gathered during the final presentation and evaluation of student projects. The author's role as teacher and supervisor during the design studio made observations overt and with a shifting role of the observer, as defined by Gold R. L. (Gold, 1958), between 'observer-as-participant' and 'complete observer'. Assisting students with design questions regarding tectonics, aesthetics, robotic manufacturing, acoustics, etc. as well as technical/mathematical issues of parametric modelling and geometrical understanding, means the observer will participate in, and thereby influence, the observed situation. These participant observations were complemented with non-participant observations where the author observed the design process of the students from a distance and without interaction.

Based on the experience from previous explorations of computational-based design method (Jensen and Foged, 2014; Foged, Pasold and Jensen, 2014; Foged et al., 2012) the processes and issues of interest were already narrowed in and the participant observations could be conducted through 'focused observations' (Spradley, 1980) centred on the following research questions:

"Can students with little or no experience in parametric design thinking or architectural acoustic establish a creative and explorative design process using the proposed design method?"

"How will the technical challenges influence the design process and the design qualities of the physical outcome?"

"To what degree will the proposed design method enable a parallel exploration of acoustic architecture, parametrically generated geometries and robotic manufacturing?"

To complement the qualitative observations a quantitative method was applied. Based on observations deducted from the final presentation of student projects an anonymized score board was constructed, showing performance within six different categories: Tectonic Design Quality, Implementation of Design Method, Parametric/Fabrication Level, Acoustic Integration Level, Analytical/Reflective Level, and Representation Level. The scoreboard, with its six grading dimensions for each student, was analysed using the statistical procedure Principal Components Analysis (PCA). The aim of running this analysis was to explain the variation in scores and expose any pattern that could assist in further improvements to the proposed design method. An example could be that if high performance in acoustic integration had a negative impact on the fabrication level then improvements of the design method could be made to ensure better integration between these two performance aspects.

3. Results

Evaluation of the proposed design method should be based on both the technical aspect of establishing the computational system and its impact on the creative and cognitive processes when adopted by non-expert architectural students.

Design and development of the computational system has shown that it is technically possible to combine the generation of geometric patterns, acoustic analysis, and robotic simulation in an integrated computational workflow. Clustering the computational system into four sub-systems simplified the workflow and enabled the user to iteratively shift focus between the four clusters, for instance working on the geometric composition of the path curves in the 'Path Generation' cluster and when satisfied enabling the other clusters to witness the effects. Although aiming for a continuous data flow between the four clusters it was not technically possible to implement the acoustic analysis in the Grasshopper environment with the consequence of having to transfer the geometric output to Rhino and running the simulation there. This resulted in a break in the data stream and the need for repetitive manual work for each design iteration.

The qualitative observations of the 3-week design studio, including the robotic manufacturing of the acoustic plywood panels, shows that, with only few days of parametric design teaching, it is possible for non-experienced students to adopt the proposed design method and explore the design and fabrication of acoustic panels. The clear structure of the design process – create milling curves, generate milling surface, analyse acoustic performance, simulate robotic fabrication, (repeat process) – allowed all students to iteratively explore various designs while searching for better performing versions. The fact that each part of the process was graphically visualized increased the students' understanding of their own design choices and the consequences thereof – making clear the limitations and potentials of the design system.

A challenge facing many students was the transition from exploring the geometric system of curves that were given to them during the introduction of the design method, to designing their own geometric system. For most students, the design of a new geometric system was not based on the idea or concept of a system, but instead on an aesthetic-driven concept for the appearance of the final geometry. This often resulted in students exploring a design system with a very narrow solution space and with aesthetic performance as the main design driver, as also witnessed in the studies by I.V.V. Foged (Foged, 2018a).

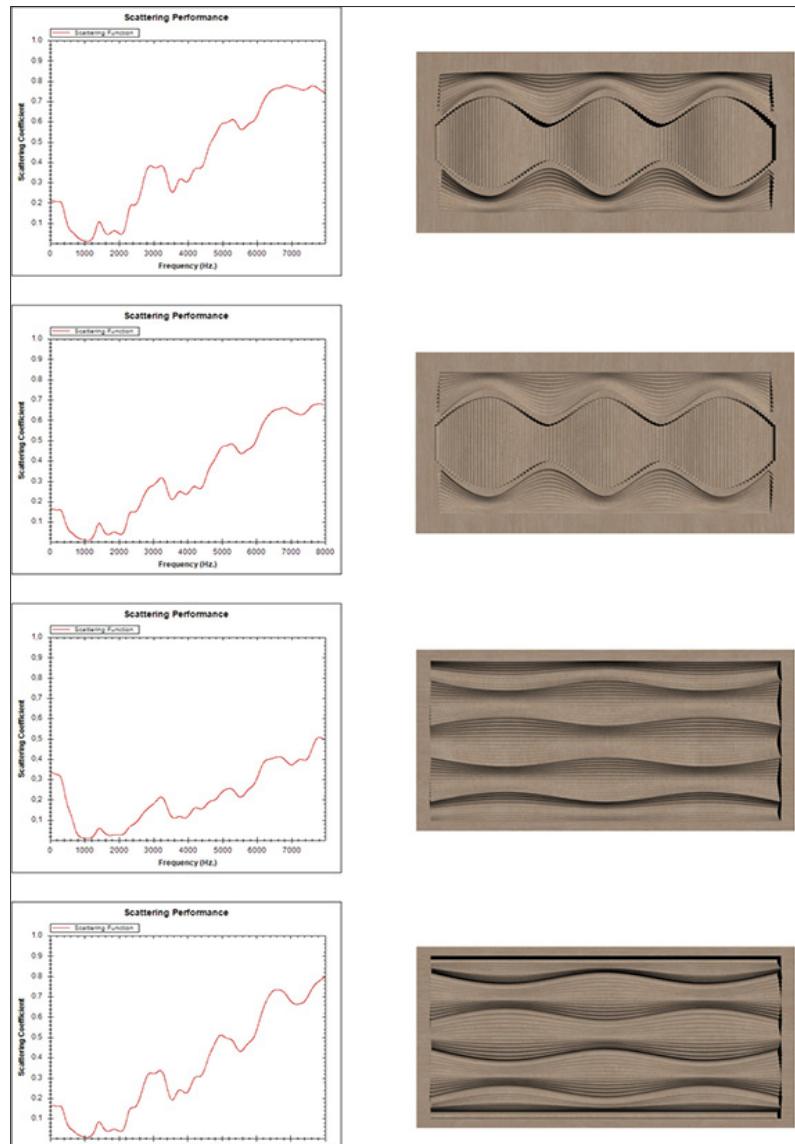


Figure 3.

Image showing the acoustic performance (scattering values) of the corresponding geometrical composition.

Credit: student Maria Møller Salling.

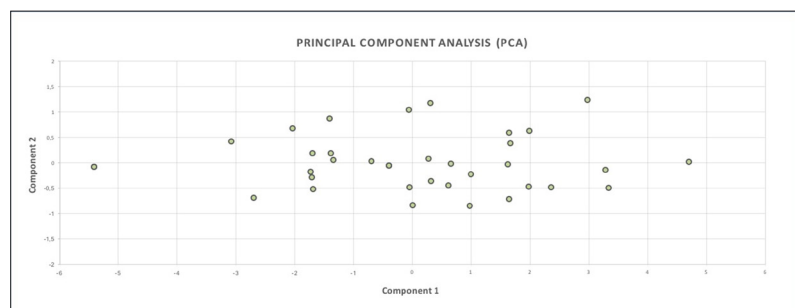


Figure 4.

A scatter graph showing the result of the PCA with the most influential principal component (Component 1) on the x-axis and the second principal component (Component 2) on the y-axis.

Observing the design process also made it clear that there was a general unwillingness among the students to initiate their design exploration with geometrically simple systems, but instead more advanced designs were pursued, often leading to more time being used on solving complex geometrical problems than on iteratively exploring the design system.

Another challenge for students with only little experience in parametric modelling was their lack of knowledge regarding geometric modelling techniques and methods available in the parametric software. This often resulted in a very limited exploration of geometric systems or in design trajectories with unsolvable geometric challenges. For both scenarios, a negative result on the creative flow was observed as either no new design potentials were recorded by the student or the speed of each design iteration was too slow for upholding a suitable - and thereby creative - flow. As opposed to these scenarios, for the more experienced and skilled students a much smoother creative flow was witnessed, where the geometric solution and performance of one design iteration lead to quick changes of established design parameters or to the creation of new parametric relationships within the design system.

The result of applying the proposed design method can also be witnessed in the full-scaled physical prototype for the mobile acoustic-driven library (see figure 5). The library structure consisted of one robotic-milled wood panel per student and the geometric variation across the panels is an indicator of the explorative potential of the design method. Another important observation made during the fabrication phase was that when each student started the robotic milling of their own wood panel they expressed a clear expectation to the sequence of movements to be made by the robot. The continuous computer simulations of the robotic fabrication process meant that even with no prior experience with industrial robotic arms or with milling as a fabrication process, the students were in control not just of the final shape of their design, but also of the process in which it was made.

The results of conducting the PCA on the six quantifiable performance aspects used in the score board, was that the first principal component, a weighted average of all grades (eigenvalue > 1), explained 85% of the variation within the grades (see figure 4). The second principal component was the contrast between the scores given for "Tectonic Design Quality & Parametric/Fabrication Level" and "Experimental Method Level & Analytical/Reflective Level" (eigenvalue = 0.3). This second component explained another 5% of the variation.

4. Discussion

Based on the setup of the computational design system it is evident that several design aspects (generation of geometry, architectural acoustics and robotic manufacturing) can be explored through an integrated parametric workflow. Except for a full parametric implementation of Pachyderm Acoustics, an issue that is more than likely to be overcome with future software updates, the parametric workflow enables an interrelated and parallel exploration of selected primary design drivers.

Insights based on the qualitative observations of the 3-week design studio showed that students with little or no experience in computational design quickly adopted the design method, but also that some student struggled with technical challenges and that this led to less successful explorations of potential design solutions. This points towards the need for a certain skillset and experience, not just with the technical aspect of computational design, but also within computational design

thinking. As the best student projects showcased, there's a huge potential in a parallel exploration of performative design drivers, but harvesting this potential requires dedicated teaching of skills and competencies in the field of computational design.

With the analysis and simulation methods implemented in the proposed design method, it is possible to explore geometrical variation and complexity based not merely on aesthetic motivations, but also performative qualities on means of fabrication. During the design studio, most students iterated through the design method numerous times and by starting with simple geometric solutions they were able to understand the results of their acoustic simulations, relate these acoustic performance values to the given geometry, and merge this knowledge with the theory of acoustic taught in the beginning of the design studio. The design studio was constrained to acoustic performance and robotic milling, but both the design method and the affordance of the robotic setup serves as a framework capable of adapting to the exploration of a wide variety of performance aspects and fabrication methods.

The implementation of the robotic arm and the visual-based simulation of the movements it would perform during the milling process resulted in a fabrication process that was highly integrated in the early design process. From observations during the fabrication of the students' final prototype it was clear that a very valuable insight concerning the robotic fabrication was present even before their first actual hands-on encounter with the robotic arm. Due to the limited time schedule of the design studio the students were only given the chance to produce one milled prototype of their wood panel, but based on their reflections a lot of production and material knowledge was gained during this fabrication process, which could potentially be fed directly back into their design system and further inform their design process. The fabrication of multiple prototypes based on continuously improved design solutions therefore shows to have a huge potential for informing the design process.

Introducing the principal component analysis (PCA) as a supplement to the quantitative observations showed that the variation in grades could be explained by the average of all six grades - if a student is performing good in one category, for instance Tectonic Design Quality, the student is also likely to perform on the same level in the other five categories. This pattern could be explained by the computational-based skills and design capabilities of the student - if a student doesn't succeed in creating and exploring complex computational design systems he/she is unlikely to conduct a good exploration of the acoustic integration and the robotic fabrication aspect.

5. Conclusion

Based on the results of the qualitative observations of the 3-week design studio it is evident that the proposed design method enables non-expert architecture students to conduct an explorative and creative design process that integrates acoustic performance and simulation of robotic fabrication.

The observations also exposed that the capacity and level of computational design thinking, including technical software skills and geometrical understanding, had a significant impact on the students' creative flow during the design process. When iteratively exploring new ways of generating complex and performative geometries the students are continuously faced with new geometric and parametric challenges and not being able to solve these, results in a very limited design exploration where only few design parameters were investigated.

The studio also showed that integrating simulation of robotic fabrication had a very positive impact on the design process and ensured a seamless transition between designing and the production of prototypes (or final products). The implementation of robotic simulation revealed interesting potentials for further exploration and questioning in future work: What skills are needed to engage in a parallel design exploration between a human designer and a sensing robotic arm? If the robotic arm can sense its environment how could this information be implemented in new creative design processes?



Figure 5.

Physical measurements of the acoustic performance were performed on varying configurations of the students' milled plywood prototypes. Image credit: Isak W. Foged.

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