A coustically Efficient Origami Based Partitions for Open Plan Spaces

Developing a Design Tool

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The paper investigates the management of acoustic and privacy problems in open-plan spaces through the implementation of lightweight architectural partitions developed by origami tessellations. Integrating knowledge from parametric modelling, acoustics and design for user needs, a design tool for acoustically efficient, flexible, interior partition systems is developed. The paper elaborates on three components of the design tool: form generation, acoustic performance and spatial performance. The form generation component employs parametric models of origami tessellations to generate the partition system. The acoustic performance component employs acoustic simulation and prediction to regulate the containing volume as well as the system's surface materials. The spatial performance component evaluates form and material through qualitative criteria for privacy and flexibility according to user needs.

**Keywords:** Parametric origami, acoustic design, interior partition systems, design tool development

INTRODUCTION

Since Le Corbusier’s definition of plan libre as one of the five points for a new architecture (Curtis 1986) the open-plan has evolved into an influential design principle in Modern and contemporary Architecture. Succeding the iconic projects of the first half of 20th century, open-plan layouts have been widely applied in the design of working and learning spaces, as spatial solutions to the reformative programs in the structure of labor and education after the 70’s. Particularly in the case of office layout, the open-plan has been considered as an innovative solution, efficient both in terms of spatial allocation since it allows increased net usable area, higher occupancy density and ease of reconfiguration (Duffy 1992 in Kim and de Dear 2013) and beneficial to productivity by facilitating communication and interaction between coworkers (Brand and Smith 2005 in Kim and de Dear 2013). Nevertheless post occupancy evaluation studies of office spaces have proved that, open-plan layouts are widely acknowledged to be more disruptive due to uncontrollable noise and loss of privacy (Kim
and de Dear 2013). Similarly, excessive noise levels and lack of acoustic privacy have been frequently identified as the most undesirable aspects of open plan schools (Shield, Greenland and Dockrell 2010).

The standard technical solution to the acoustic privacy problems of open-plan layouts would be a uniform ceiling with acoustic properties. However with standard acoustic ceiling solutions it is difficult to facilitate several activities in the same large room and therefore a spatial-acoustic device is needed need to separate functions into smaller acoustic places. In this framework the research investigates the management of acoustic and privacy problems in open-plan spaces through the implementation of lightweight partitions.

At the basis of the research hypothesis we consider that in comparison with flat paneling, pleated surfaces manifest enhanced acoustic performance. Folding augments the available surface in a given area enabling increase in the quantity of sound absorbent material. Furthermore due to their tortuous morphology pleated surfaces facilitate sound diffusion and reflection. Therefore the form generating presupposition for the definition of the partition system is a set of parametrically defined folded surfaces and origami deriving tessellations specifically.

The acoustic advantages of pleated surfaces are evident in the design of concert halls, best exemplified in the recent Lelystadt Agora Theatre (UnStudio 2007) or the Festspielhaus at Tirol (MHM Architects 2012). However investigations in the reciprocity between acoustic performance and pleated surfaces with applications in open plan spaces are limited in the state of the art. Distortion II (Peters et al 2011) is a small scale architectural partition, designed as an experimental installation that creates visual and acoustic affects within an open-plan space, employing a parametrically designed single surface that responds to two acoustic extremes: a sound-amplified zone, and a sound-dampened zone. In this project a trihedral folded plate unit is adopted leading to a structurally strong system with design flexibility. In the refurbishment of Surfrider Foundation Europe head-quarters, Gardera-D Architecture firm develop a partition in the shape of a pleated 'wave' that isolates two acoustically conflicting programs -an exhibition space and a working space-allowing their cohabitation (Gardera-D 2012). Made of a layering of composite wood panels habitually used in transportation construction the wave allows maximum treatment in term of acoustical insulation and absorption. The convex surface of the partition which is facing the exhibition area is reflective while its concave surface facing the working area is sound absorbing.

Acoustic roofs employing origami deriving pleated surfaces are more common in the state of the art. The resonant chamber (rvtr 2011) acoustic roof paneling system employs the inherent flexibility of the defining geometry, which is a well-known origami archetype invented by Ron Resch, to transform the acoustic signature of a space. Composed of reflective, absorptive, and electro-acoustic panels, the pieces can dynamically adjust their shape to expose or hide these surfaces, thus altering sonic conditions. In a similar manner, tunable sound cloud (fishtnk 2013) is designed as a responsive architectural system that enhances one’s auditory experience of space. The prototype is an interactive, pleated, acoustic roof is composed of triangular panels lined with a series of Arduino micro-controllers.

Considering the state of the art, the distinct identity of the research for 'Acoustically Efficient Origami Based Partitions for Open Plan Spaces', lies in the integration of acoustically regulating formal and material characteristics of the partition system, with a set of user defined performance criteria. The formal presupposition for an origami deriving shape grammar intends to develop a self-supporting, lightweight structure whose kinetic ability can enhance flexibility and adjustability in addition to its acoustic performance.
A DESIGN TOOL FOR ACOUSTICALLY EFFICIENT ORIGAMI BASED PARTITIONS

Methodology

The research intends to develop a Design Tool for structurally efficient, flexible, interior partition walls where evaluation of their morphology according to user needs and acoustic performance is integrated in the design process. The Design Tool integrates computational form-generation, acoustic simulation and prediction and user defined performance criteria. The design assumption for integrating the discrete sets of data is a chaining mechanism between performance, operations and form, considering that certain morphological characteristics of the system facilitate spatial events that satisfy particular user needs.

Figure 1
Conceptual structure of the Design Tool.

Table 1
Conditioning acoustic privacy: spatial boundaries, articulations and enclosures.

The three discrete components of the design tool, spatial performance according to user needs, form generation and acoustic evaluation are elaborated further.

Spatial performance

Definition of spatial performance criteria according to user needs draws knowledge from Post Occupancy Evaluation studies concerning users' satisfaction and comfort in working and learning spaces. Distraction by noise and loss of privacy were identified as the major causes of workspace dissatisfaction in open-plan office layouts (Kim and de Dear 2013). Partitioning has been evaluated as a physical measure that can supports visual and acoustic privacy without obstructing interaction (Shield, Greenland and Dockrell 2010).

The intention behind design of the interior partitioning system is the creation of acoustic sub-spaces which would provide differentiated degrees of privacy to the users of open plan office, education or cultural spaces. The partitioning system ought to be flexible -both by design and by implementation- in order to accommodate the user need for privacy providing boundaries, articulations and enclosures with distinct spatial, visual and acoustic effects. When the partitioning system is curved, the potential acoustic conditions on the convex part of the shell are differentiated from the concave side of the shell. The concave side has less volume, more absorption, and therefore less reverberation time though it would still be strongly acoustically coupled to the main space. Consequently, it becomes obvious that by modifying the curvature of the partitioning system, from a linear to a curvilinear and a circular arrangement different degrees of acoustic and spatial privacy are being achieved. In order to integrate this modification option in the design process parametric modelling is employed to produce curvilinear assemblages of the pleated component.
Form generation

One of the starting points of the research is the development of form finding processes inspired by Origami, the Japanese art of paper folding. Based on simple deployment mechanisms, Origami derivative forms and particularly those based on the Yoshimura and Miura patterns allow a controlled transfer of forces without the need for any secondary support structure. These forms also demonstrate kinetic behavior through translation and rotation. The unique combination of stability and kinematics evident in origami derivative forms renders them appropriate for flexible interior partitioning systems that are self-supporting and deployable. Regular origami patterns can be deployed in the Rigid Origami Simulator developed by Tomohiro Tachi (2007-2009) complementing modelling with Rhino. The shape grammar of origami provides an archive of pleated components that are aggregated into kinetic arrays. Components may be designed according to structural, kinetic and aesthetic criteria, the analysis of which exceeds the scope of the current paper.

![Figure 2](image)

Based on arrays of the pleated component, the partitioning wall is composed as a parametric system with variable adjustment of curvature in plan and elevation. Dimensions of component are defined according to ergonomic data. The number of components is regulated according to the desired volume of the partition. A Grasshopper script is developed to manipulate the form generative curves of the partition system, which we call power curves and distinguish between base and elevation curves. This typology of curves has been defined in accordance with the acoustic and privacy criteria discussed in the previous section. By manipulating the curvature of the array through power curves, each component is parametrically differentiated while maintaining connectivity and cohesion within the partitioning system overall form. Base curves define the spatial configuration of the partition in plan according to desirable degrees of privacy. Elevation curves define the system’s ability for differentiation in response to users’ needs for visual contact, light or in aid of structural efficiency. As proof of concept a series of scaled models are digitally fabricated. Evaluating the physical models we can conclude that the kinetic potential of the origami generated structure augments the versatility of the partitioning system and enables its real time manipulation. Comparing the fabricated prototypes, we can conclude that linear arrays manifest high kinematics; the system is able to acquire multiple curvatures assuming a variety of base curve configurations, while the ones differentiated through elevation curves are less flexible and would rather be considered as static partitions.

Acoustic performance

The main objective of the morphogenetic research is the creation of parametric models for partitioning systems that can adjust their geometry in order to correct the acoustic performance of the containing volume as well as their surface materials. By altering the form generating geometry of the partition system or the material characteristics of the component surfaces in specific ways the acoustic comfort level of the room can be adjusted in terms of ideal reverberation times according to the use and according to the volume of the room. A Grasshopper script is developed in order to improve the acoustic characteristics of the partitioning system including numerical data describing the coating material’s parameters. As it is known in the field of acoustics, each material has its own absorption coefficient of alpha Sabine. Providing that, the designer can calculate the acoustic im-
impact of the object during the design-equivalent absorption area gain, reverberation time modifications, and speech intelligibility indexes—comparing it to the tables of audio data that are given. Thus, an evaluation system is becoming part of the design process and measurable acoustic performance criteria must be set to correspond to the design intent. Designers are enabled to contemplate design options through these evaluative feedback mechanisms.

One can criticize this methodology by arguing that these simple calculations, deriving from the Walter Clement Sabine formula, are valuable for the entire volume and not precise enough. Actually, the form of the partition is only considered in these evaluations by the equivalent absorption area gain that the objet creates and not by its form and position in space. For this reason we wanted to go further and evaluate the partition’s potential to regulate the acoustic performance of the room and also to create small different acoustic spaces in the same room.

**TEST CASE**
The test case intends to verify the acoustic efficiency of a partition developed according to the Design Tool...
methodology, employing acoustic simulation. The goal of the simulation was to evaluate the acoustic performances of an S-curved partition, formed as a space articulating boundary. For that, we use *Pachyderm Acoustical Simulation* (version 1.0b3 by Arthur Vanderhartten, 2011) plug-in for Rhino that simulates the impulse respond of the room and calculates from it several well-known room acoustic criteria used for theaters, operas, concert halls. These criteria are mostly used in a context of artistic representation when we know exactly the position of the sound source (singers, musicians, performers) and the positions of the receivers (audience).

In our context, sources and receivers might be mobile and some criteria often used have no sense to be evaluated such as Strength, Clarity (C80), Definition D(50). They are really valuable for music but less meaning full for ordinary audio-scene in offices (see the interesting discussion developed by Nilsson and Helström, 2010). On the other hand, it was interesting for us to evaluate several reverberation durations that are more linked with the ordinary perception. "Classical" Reverberation times calculated on the decrease of 60 dB on the impulse sound generated give results that are often discussed because we, as listeners, we never experience such a decrease in the "real" life. We hear the reverberation of the room trough a loud and impulsive sound but very quickly another sound will mask the whole decrease of the first one.

For this reason we focus our work on the simulation on short reverberations durations described by the following criteria as: Early Decay Time, T-15 (decrease of the first 15ms) and T-30. They describe the behaviors of the first reflections of the sound source until they reach the listener's ears. Many studies have shown that this first reflections have already all the sound qualities of the room and receivers interpret them properly even they will never hear the whole decrease of the reverberation. We calculated also the reverberation time using the Sabine theory too.

To simulate the acoustic performance of our partition we place it in an imaginary room (15 by 10 meters) and run several simulations:

- **S1**: the room empty (wooden floor aw=0.05, roof and lateral walls are all made of Plaster rough on lath, aw=0.05)
- **S2**: the room with the flat partition with the same materials on both sides as described below.
- **S3**: the room with S-curved partition with a global thickness of 2 cm using on the convex surface common wooden panel (aw=0.10) and on the concave surface sound absorbing perforated wooden panels with mineral wood on the inner side (aw=0.75). Scattering and diffusion factors will also introduced as they are used in the literature and set up depending of the materials used.

We wanted to simulate the potentials given by the S-curved partition. It's why we declared in the model a sound source "far away" from the partition and 2 receiver points, one on the same side of the partition as the source is (receiver 1 or r1), and one on the other size of the partition (receiver 0 or r0), in the most protected place offered by the S-curved partition.

Figure 4
Acoustic simulation of s-curved partition: sound source and receivers positions.
Results

One first result of our simulation is regarding Sabine reverberation time values. In the first scenario average Reverberation Time was approximately around 2.2 seconds whatever the position of the receiver around the partition. With the S-curved partition, the average RT decreases to 1.07 seconds. It means that the global reverberation of the room is divided by a factor 2. In the room, reverberation is more comfortable for any activities related to the ordinary life in open-plan offices (working, speaking, ..). These results from simulation confirm also previous calculations that we’ve developed through the Grasshopper script as we describe previously.

Results from simulations of the Early Decay Time are described as follows:

![Figure 5](image)

**Figure 5**
EDT simulations: 3 scenarios for the reception point r0

![Figure 6](image)

**Figure 6**
3rd simulation scenario for reception points r0 and r1

As shown on the previous chart, decrease of the EDT from simulation 1 to simulation 3 is clearly demonstrated. For all octaves, the EDT decreases about half a second which means that it improves the acoustic qualities inside the partition from a source emitted in the same room but on the other side. It means that, actually, people can easily go inside the S-curved to look for more intimacy if they want to talk with someone or have a personal chat on the phone. Improvements are also demonstrated in comparison with a flat partition (simulation 2) and it can be explained by the fact that the origami based form offers more surfaces which increase the equivalent area of absorption.

The results can be shown also if we compare the EDT value close to the source (receiver 1, direct field) and the receiver protected by the partition (reverberated field) for the third simulation:

Even the global reverberation of the room has decreased, while locally simulation shows how the partition can create two sub-spaces in which acoustic qualities will differ. Similar results were found with the other criteria that we ran in calculation (T-15 and T-30).

To conclude, we can say that the S-curved partition creates locally an acoustic affordance, as James J. Gibson (1977) described it for visual perception, an added acoustic value that future users would have the possibility to exploit.

**DISCUSSION**

The Design Tool for Acoustically Efficient Origami Based Partitions can be useful in a case of collaboration between designer and user since it makes explicit the available design options concerning the form and material of the partition. In terms of computational design, the Design Tool is not seamless at present; it combines different software, scripts and plug-ins. However the criteria are clearly defined and each step in the procedure manifests clear results. The acoustic and visual privacy criteria lead to the definition of power curves which control the overall form of the partition system employing the form generative script. The material selection for the facets of the pleated component employing the acoustic script, defines its acoustic profile. Results
from the scripts entail design modifications and assist the overall design decision making.

From the acoustic point of view, the paper presents the possibility to develop a Design Tool that can evaluate an architectural object as a partition in a room. This first step is very helpful to improve acoustic sensibility for designers that are not aware about acoustics in details. However, it ought to be understood that the introduction of this partition must realize conflicting goals from the acoustic point of view. In this sense, the choice of an origami based folding partition system is particularly interesting in the sense that it is freestanding, rigid and composed of facets. These facets can then be made of sandwich panels which can be made of an absorbent material on one side and a reflective material on the other. This adds a new perspective for architectural design by integrating sound qualities and acoustic potentials in the design process.

Furthermore, it is evident from the test case that we needed to use more precise tools to evaluate the potential of the S-curved partition. On a usual computer, simulation took a lot of time to run the calculation with 2 receiver points. It means that such development can be done only in the final phases of the design when we want to be more efficient and precise. Even results are encouraging, it shows that, one more time, acoustic comes at the end of the project and it use in corrective processes: to validate or not the choices made by the designer considering the form, the position in space, and the materials of the partition. We think that the next step of such studies might be in the development of plug-in or application that can work in parallel with modelling. It would be ideal if calculation could be done instantly, then we could imagine designing form by visualizing acoustic criteria in real time.

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