From digital design to physical model

Origami techniques applied to dynamic paneling shapes for acoustic performance control

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The recent trend toward non-standard and free form architecture has generated a lot of debate among the Scientific Community. The reasons can be found in the renewed interest in organic shapes, in addition to recent and powerful capabilities of parametric platforms. In this regard, the Visual Programming Language (VPL) interface gives a high level of freedom and control for conceiving complex shapes. The geometric problems in identifying a suitable shape have been addressed by relying on the study of Origami. The control of variable geometry has required the use of algorithmic models that ensure fast changes and free control of the model, besides a physical one made of rigid cardboard to simulate its rigid-foldability. The aim is to present a prototype of an adaptive structure, with an acoustic application, to control sound quality and perception in spaces where this has a central role, such as theatres or concert halls.

Keywords: *parametric modeling, generative design, shape and form studies, acoustics conditions, digital Representation*

INTRODUCTION (MLT UZ)

Over the last several decades, the recent trend toward non-standard and free form architecture has been deeply discussed by the Scientific Community. The reasons can be found in the renewed interest in organic shapes, in addition to recent and powerful capabilities of parametric platforms. In this regard, the Visual Programming Language (VPL) interface gives a high level of freedom and control for conceiving complex shapes.The geometric problems in identifying a suitable shape have been addressed by relying on the study of Origami: the terms derives from the Japanese "ori" (fold) and "kami" (paper), which has already been used for engineering applications. The control of variable geometry has required the use of algorithmic models to ensure fast changes and free control of the model, by defining the rules that control folding geometries and the succession of folds found in nature: it is possible to apply these principles to the architecture and engineering sectors to obtain an analogous mechanism for similar functionalities.The mix of different variables can generate a wide variety of possibilities that can be used to study possible applications and efficient adaptive structures. The project analyzes a proposal for an adaptive structure able to change its spatial conformation and to address changing external acoustic conditions.The aim of this research is to present a prototype of an adaptive structure related to acoustic models, to control sound quality and perception in spaces where this has a central role, such as a theatre or concert hall.

STATE-OF-THE-ART AND REFERENCES (MLT MBP)

One of the main recurrent issues related to the architecture field is the international debate on Smart Cities: this topic encloses the vision of experts about how the city will be in the next future considering the effects of the massive diffusion of the digital technologies. At the regard, experts previsions suggest that both the cities and the single buildings (Smart Buildings) will be more and more populated by sensors able to optimize consumptions and to improve the life quality of the inhabitants. According to the diffusion of these systems, different experiments have been performed to understand how parametric shapes and structures can react to some external variable conditions (Smart Structures). A lot of focus has been put into the Adaptive Structures able to change their shape or to change their own geometrical or material (Smart Materials) features to answer to the environmental changes.The whole surface of the Deployable Structures (Pellegrino, 2001) undergoes a unique movement generated by the application of an actuating force in a single point, whereas transformable structures limit their movement to single elements located inside fixed supporting frames and so this requires a distributed actuation systems.Such adaptive capability is often realized by folding mechanisms of a certain surface performed by a precise distribution of elements and forces. The theme of adaptiveness has been faced at first with a biomimetic analysis, studying the geometries and mechanisms of deployable structure that are present in nature.The dynamism of an origami model, intended as the result of rules that control folding geometries and the succession of folds, is recognizable in some dynamics of recent architectural projects. We propose some issues:1. This building designed by H. Larsen Architects presents a peculiar shading system made by a composition of movable triangular panels, mounted through supporting hinges that allow them to move by changing their degree of openness. The panels are moved by different small electric motors controlled by a network of sensors which measures the external lighting conditions and the air temperature (Figure 1.1). *Al Bahr Towers* is an office tower designed by Aedas Architects in Abu Dhabi. The double skin system has been designed by taking into consideration the sun path and the inclination of the solar rays on the façade in the different periods. The layout of the skin is inspired by a hexagonal origami pattern. Triangular panels are hinged on fix frames that allow them to perform their rotational movement (Figure 1.2) . *Theme pavilion EXPO Yeosu* has been realized for the 2012 Expo in Korea by SOMA. The theme is "The living Ocean and Coast": in fact it is characterized by a dynamic façade, composed by vertical strips, whose changements reproduce the waves' movement, favoring the maintenance of optimal internal conditions and reducing the energy consumption of the building (Figure 1.3). *Resonant Chamber* has been built using digital modelling and manufacturing tools, acoustic performance simulation, material tests. The first prototype has been developed by the studio RVTR, and installed at the University of Michigan Taubman in 2012. It is an indoor interactive system able to modify the acoustic surroundings throughout the transformation of the geometry and the use of electroacoustic technologies and materials. This system allows to modify the degree of acoustic exposure of the surfaces. The software simulates the physical behavior of the structure, giving the possibility to study both the acoustic response related to different posi-

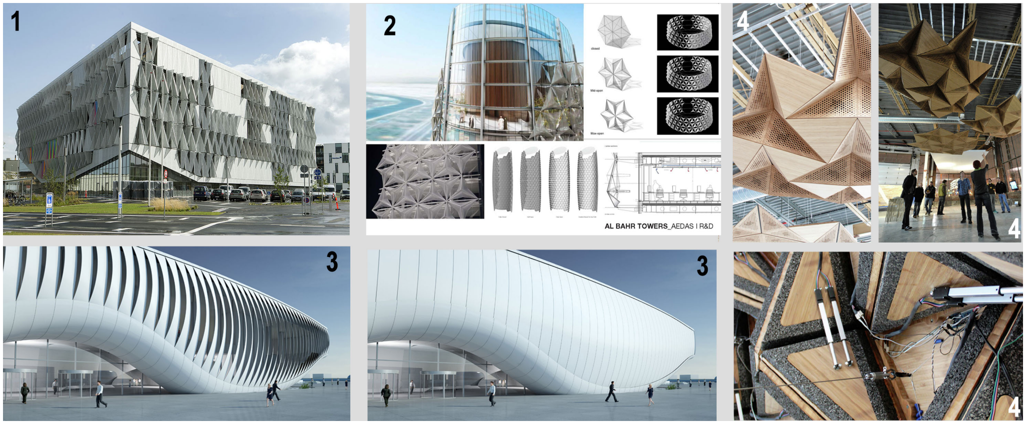


Figure 1
(1) The façade is composed by 1600 elements of perforated sheet metal. Al Bahr Towers (2) presents a shading system to control the solar rays, as for the structure of the EXPO pavilion (3): (4) the kinetic system of the Resonant Chamber governs the sound level and the reverberation time.

tions and the deployment paths of the points to design the actuation system (Figure 1.4).

THEORETICAL BASES

Origami (UZ)

In traditional origami, folds determine the shape and constitute the essence also through its transformation over time, by linking together 2D and 3D. Each bend, its repeatability and its possible reversibility, becomes part of the structure of the form that has been defined during the transformation process. Born to be a paper and/or tissue modeling tool, origami has rapidly evolved into rigid material management in accordance with Huzita-Hatori's axioms (Tachi, 2010). As said, in a rigid origami the rotation axis between flat surfaces, and hence a hinge is recognizable in its folds: at the regard, the choice of material used further defines the constraints. Working with paper means taking into account a sequence of steps bound by trying not to tear the material. Working with rigid materials - having a defined thickness that results in an increase in the section on each layer overlap - can lead to work with modular elements to reduce the number of folds and to simplify the shape. In this case, the modularity of the components explored in several modifications, offers further flexibility to the project.The starting point is a flat surface constituted by a sheet of paper, so performing the deployment movement by distributing the forces applied in one point thanks to the folding patterns. The category of the rigid foldable ensures the possibility to realize them with rigid material. Different pattern of tessellation -all the points are moving approaching or departing on non-linear paths and the surface extension changes along the movement- were taken into consideration: their deployment movement were controlled through the Rigid Origami Simulator by Tachi. Doing that, the Miura-Ori pattern, considered as of the simplest and most diffuse rigid origami pattern, has been analyzed. It has already been used in engineer application which creates a periodical corrugation with increasing depth during the folding procedure, till reaching the flat folded condition.

Computational, Parametric and Algorithmic Design (MLT)

New design and representation options, better known as parametric and algorithmic procedures, are characterized by two computational design methods: computation means mathematical, so it implies a method related to logic and calculus. Computerization instead is related to the power of a computer system, used to enter and process data. Computation

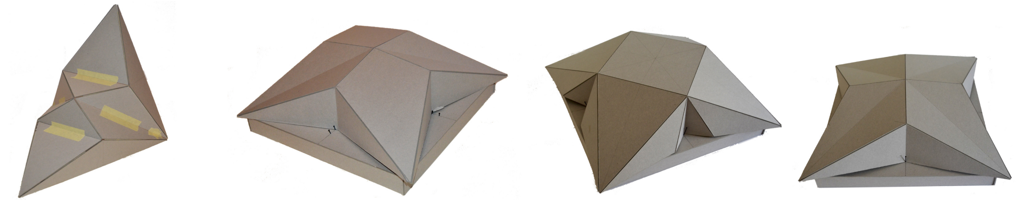


Figure 2
Different solution of rigid cardboard to simulate its rigid-foldability. Each folding line represents a discontinuity point and it can't be realized with the same material. Two solutions: a) creating the joints by using hinges or other mechanical linkages but it occurs an air gap between the panels; b) using a different material such as a membrane that should be flexible enough to bend but also give the rigidity stability to the system: here the vertices are characterized by multiple folding lines touch: these are critical points in which the presence of material interferes with the movement and usually it is removed to ensure a smoother movement.

has introduced new opportunities in several fields, from design to fabrication, from construction to management. Parametric design can be defined as the capability to control and develop a project through parameters (De Kestelier et al. 2013), set since the beginning of the design process, then controlled and managed at any stage of the design development. This implies a rigorous mental process useful to correctly set both the parameters and the constraints (Kolarevic et al. 2013).The resulting design solution therefore is not unique, but there is a whole list of variations generated by several combinations of the parameters.One of the main advantage relies on the possibility to perform variations: the resulting geometry can be obtained in real-time, allowing a dynamic and interactive optimization process. It is possible to identify two categories of parametric models that are commonly used in practice: the first one (parametric variation - PV) provides the generation of different design instances by the variation of parameters that control the shape. A previous design phase has been required to set correctly the parameters and to obtain the desired variations; the result is called parameterized modeling schema: the same geometry in fact could be ruled by different schemas.The second category is known as parametric combinations (PC) or associative geometry models. It works with the composition of different geometrical entities according to set rules; the design options are the result of several combinations of the defined starting shapes. Finally, the merging of these two methods creates hybrid parametric models where the combination of parametrized base entities allows shape variations, useful for the geometrical exploration and the definition of the final design solution.Regarding to the Algorithmic Design, the final model is defined by a succession of operational steps that can be expressed through an algorithmic language. An algorithm is a procedure to obtain a certain result following a defined process composed by a finite list of basic and simple actions.The results is a well-defined list of successive instructions and a graphic representation of the resulting geometry. These operations can be manually written or performed by a computer: in the latter case the algorithm has to be written in a specific language, with the support of a scripting editor, linked to a 3D modeler or graphic software able to display the result (Figure 2). Some visual programming editor can be used to write an algorithm through nodes (the operations) and links (dataflow between the nodes).Another possibility, enabled by the parametric and computational tools, is to modify the design by integrating the results of different analysis, realized aiming to evaluate the performance of the building. The flexibility of the model, in fact, guarantees its easy manipulation at different design stages; the optimization process for the building efficiency thus becomes faster, resulting in an easier way to produce different design solutions. These are called evolutionary algorithms and they calculate the geometrical solution that best fits to the set variables defined in the first phases (Mendez et al. 2014). In this case the designer does not draw directly the shape, but he designs the process and the rules necessary to generate it (form-finding process).

DESIGN DEVELOPMENT (MLT MBP UZ)

The 3D geometry traditionally conceived had to be considered in a new dynamic dimension (4D) that best satisfies the environmental requirements.One of the more unexplored aspect of architecture design is the acoustic component; the research around sound and all the related aspect is still ongoing and a lack of tools, both for design and tests, complicates acoustic designer life, reducing the quality of the product; so, the aim of this work is the design of a prototypal adaptive structure, able to be critically evaluated by an acoustic application, to control sound quality and perception in spaces where this has a central role, such as theatre or concert hall. The topic is the control of reflections by creating surfaces with variable conformation: flat conditions generate specular reflections, while rough states generate scattering effects. The structure requirements that drove the design process have been developed through the following steps: *1. Flat starting condition and rough final condition; 2. Rigid deployment movement and imple actuation system; 3. Need to cover a large surface; 4. Application suitable for different orientations; 5. Aesthetic features*.

Geometry selection, tests and assesments

As said, the geometry definition was based on the study of the Origami. Different pattern were taken into consideration. According to the Miura-Ori pattern is quite interesting to notice that the resulting support structure would have been too complex and visible in some condition, revealing moreover a background surface. A sort of second acoustic skin that with an air gap behind with a low reflection capacity would be necessary.The problems emerged from the analysis of a tessellation pattern drove the research to simpler pattern relevant for matrix configurations that can be used as bases for more complex origami.Different patterns have been tested through digital simulation and paper folding. The first pattern analyzed shows an intermediate state between the open and flat fold condition, with a geometric configuration that could determine scattering effect. Its displayed a critical issue: the volume included in the intermediate state has not a closed profile that can be lied on a surface; this aspect could cause a great sound absorption, which should be avoided in scattering objects. A new form has been found out by simplifying a larger one, keeping the central scheme that still constitutes a flat and rigidly foldable pattern. The new simulation points out that the external edges of the surface constitute a profile able to generate a closed volume with no gap. The resulting shape has a cross conformation with the points on the external edges move on linear trajectories while the central point that moves vertically and it can be considered the actuation point for the whole movement of the geometry.Similar features have been conceived in the third pattern which has a central square instead of a single point and a greater amount of folding lines and vertices with high degree value so with more lines converging in (Figure 3). The digital simulation with Grasshopper has revealed a slight deformation on the quadratic faces during the deployment movement; this has led to add two folding lines to split them in triangular faces ensuring more flexibility to the whole geometry.The selected pattern has a squared shape composed by 16 triangular faces of two types; the faces of the same type are coupled and one is specular to another. The starting input of the algorithmic model used for movement simulation and geometric analysis is a mesh composed by faces equivalent to the faces of the pattern; the folding lines are divided into mountain and valley folds. The physic engine of the plug-in Kangaroo, through a dedicated tool for the Origami, reproduces the folding movement. Within the digital environment it is possible to set other acting forces or to indicate constraints that limit or guide the movement; they have been applied to ensure that the external points can move on rectilinear trajectories and to reproduce the actuating force on the central point. Adding constraints it is possible to observe the behavior of the structure by simulating the real installation with anchor points and obliged movements. The use of an algorithmic ensured the mathematical management applied to each point of the movement, beside the graphic representation of the geometrical entity and its animation. Doing that, it is possible to measure

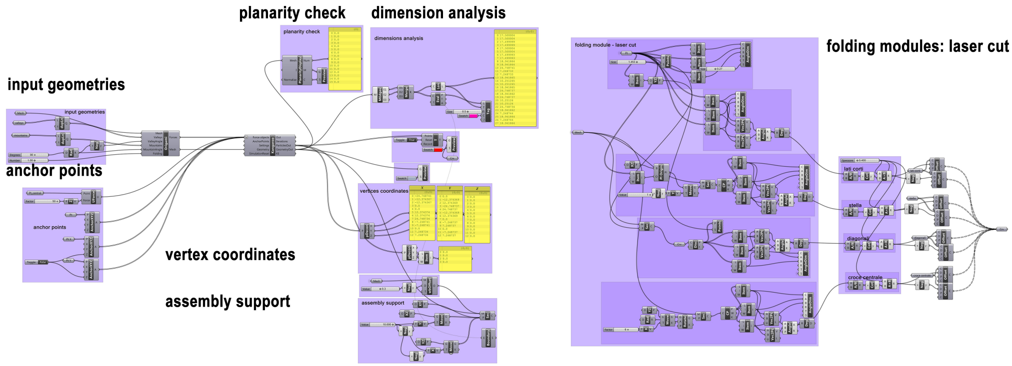


Figure 3
Part of the algorithm used for the origami simulation: it has been developed using Grasshopper software and the plug-in Kangaroo. The algorithmic model is based on the input elements of the geometry constituted by the mesh and the folding lines, divided in mountain and valley.

the folding angles between every face, a very crucial data useful for modeling thick panels of the structure. The planarity of the faces during the deployment can be tested to evaluate if the rigidity is kept. The algorithmic model moreover allows to scale the geometry, a precise dimension of the base panel therefore can be defined after acoustic considerations; the reflecting surface thus would be composed by the repetition of this base module, each of them will require a distinct actuation system that permits to control the amount of scattering surface in the space, answering to the changing needs.The squared shape ensures a complete cover factor of a flat surface without leaving empty space between close modules in the flat condition. Then, the coaching of several components defines the aesthetic aspect of the wall and its acoustic behavior.

Digital model

The algorithm virtually folds the mesh according to the folding, angle applying rigidity and stiffness to the side of the faces. Other forces can be added to the model creating anchor points or obliged movements. The output is calculated per each frame of the deployment movement and it is constituted by the folded mesh and the points positions from which it is possible to extract their coordinates and trajectories. It allows several operations related to the output geometries in order to perform the necessary tests and obtain the desired information. A planarity test for the faces of the panel has been applied as the display of the side's lengths, to check their deformation along the deployment.The same model has been used to calculate the folding angles between each face at the final condition to draw the faces and to realize a functioning prototype of the module using real dimensions, avoiding the issues related with the thickness of the material by following the tapered panel method by Tachi.

Physical prototypes for acoustic tests (LS AA)

The test samples have to guarantee a low value of absorption factor (α) to produce good results, thus they should be realized both with rigid material and with a specific thickness that avoids dispersion for resonance effect. Different material and techniques have been tested for the acoustic tests, aiming to find the best mix of material and production effort. The first attempt has been realized gluing wood panels on a cardboard engraved on the two side to reproduce the different folding lines.It has been used a 3D print to obtain a precise model. The physical model presents (l = 7 cm) some printing defects, thought these could be corrected, the time necessary to realize one piece took about 2 hours with a very low thickness of the external surface, that could cause a bad acoustic performance: for these limits

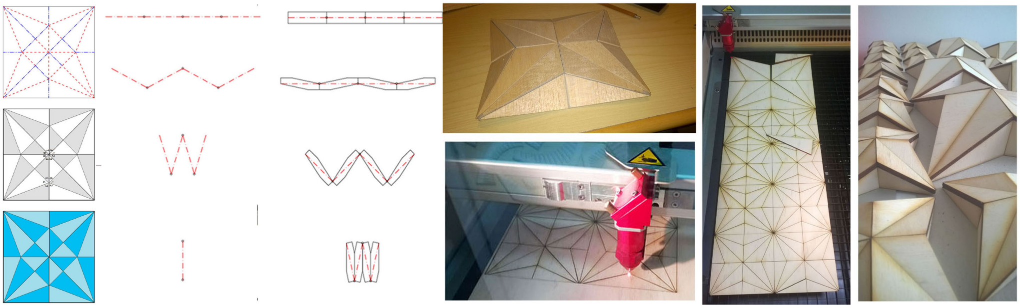
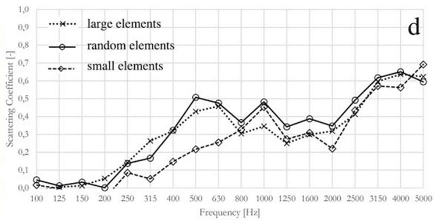


Figure 4
From the left: flat foldability rules and thick rigid origami methods; wooden fixed panels and the laser cut process and the assembled modules.

the 3D printing have been discarded.The wood has very good acoustic properties for its rigidity and density, furthermore it is largely appreciated by architects for its visual aspect. Each of the 45 panels necessary for the acoustic measurement is composed by 16 faces for a total amount of 720 single pieces that needed to be cut and then joint together in the correct position with a good precision. Laser-cut machines provide very sharp cuts of different material, guaranteeing a fast production. The geometries have been exported directly from the algorithmic model by sectioning the surface, in its open state to obtain the profiles of the surface that constitute the supporting element for the faces (Figure 4).Then, the samples have been assembled for the acoustic measurement. To ensure sharp edges and no gap between the panels, the internal edges of the mountain folds have been smoothed. The faces in fact have been mounted considering from the ideal surface an internal extrusion to generate the thickness of the panels. In this way the inner side of the faces in correspondence of mountain valley would have collided without any smooth operation. All the panels have been varnished with a transparent finishing to enhance the reflectiveness of the surface.The design process of the surface studied in this work has been mainly focused on its sound diffusion characteristics, i.e. scattering properties. Contrary to the acoustic absorp-



f

Scale 1:1							Scale 1:5	
Dimensions		Distance		Frequency f (Hz)			Dimensions	
l (m)	b (m)	d (m)	D (m)	$c/2b$	$c/2d$	$c/2D$	l (m)	b (m)
1	0,25	0,42	0,71	680	405	239	0,2	0,05
0,9	0,225	0,378	0,639	756	450	266	0,18	0,045
0,75	0,188	0,315	0,533	907	540	319	0,15	0,038
0,5	0,125	0,210	0,355	1360	810	479	0,1	0,025
0,45	0,113	0,189	0,320	1511	899	532	0,09	0,023

Figure 5
Sample with (a) large, (b) small and (c) random elements; (d) measured scattering coefficients values for the three samples; (e) and (f) evaluation of the dimensions of the irregularities with regard to the lower limit scattered frequencies.

tion properties, the diffusive characterization of different surfaces is less pursued and very often leads to inaccurate objective evaluations of the acoustic parameters for different environments. However, these surfaces have been extensively studied subjectively and objectively in concert halls where their effects influence the reduction of echoes and sound concentration, and help in improving the uniformity of the sound quality distribution among the audience area (Beranek, 1996). Beside the tangible effects on the perceptual aspects of the sound field within a space (Torres et al. 2000; 8 Ruy et al. 2008; Shtrepi et al., 2015), the assessment of the diffusive properties result crucial for the accuracy in acoustic simulations based on the geometrical acoustic principles (Vorländer, 1995). This evidence has led to the standard (ISO 17497, 2004) for acoustic measurements of the diffusive properties. ISO 17497 defines the scattering and the diffusion coefficients, which are related to a quantitative and a qualitative description of the diffusive properties, respectively. In this work the scattering coefficient properties, which represent the energy ratio between the diffusively reflected and the total reflected energy, have been considered since they are used in acoustic simulation software as input data. Thus, by using this standard, valid databases can be generated and used in the preliminary phases of the design process to make evidence based choices that could guide a performance-based design and become helpful to a multidisciplinary panel of practitioners.Variable acoustic properties have been used extensively for performance spaces in order to recreate different conditions based on the purpose of the performance. One of the well-known examples is the ESPRO hall at IRCAM(Peutz, 1978; Shtrepi et al., 2016), where the variable acoustics is obtained by rotating triangular prisms with different acoustic properties as well as diffusive conditions.Since the spectral properties of the sound sources, i.e. musical instruments and voices, in concert halls cover almost the entire range of audible frequencies, it is suggested to maximize the sound diffusion at all frequencies. Therefore, the design of diffusive surfaces should aim to increase the scattering properties at a broad range of frequencies. This objective has guided the design of the diffusive surfaces configurations in this paper based on geometrical design rules, i.e. the scattering phenomenon is more likely to be generated when corrugations are of the order of magnitude of the wavelength.

ACOUSTIC MEASUREMENTS (LS AA)

The acoustic analysis consisted of both acoustic measurements and simulations. The measurements, which aimed to characterize the absorptive and scattering properties, have been performed for three different samples based on the recommendations of ISO 17497-1. The simulations have been performed for a small multipurpose hall ("Aula Magna Giovanni Agnelli" at Politecnico di Torino) by applying the acoustic properties of the measured samples in the model of a hybrid acoustic software named Odeon.

Scattering properties

The measurements have been performed in the 1:5 scale reverberation room (Figure 5, a, b, c) at the Applied Acoustics Lab at Politecnico di Torino. Three square samples (0.54x0.54 m) have been built using the same scale factor. The samples differ from each other with regard to the dimensions of the diffusing elements, i.e. with regard to the lowest scattering frequency limit (Figure 5, f). The first panel is made of the largest elements (Figure 5, a), the second is made of the smallest elements (Figure 5, b), and the third is a random combination of the largest and the smallest elements (Figure 5, c).The results of the scattering coefficients measurements (Figure 5, d) showed that the use of randomized irregularities (sample 3) could improve its properties at lower frequencies similarly to the sample made of the largest elements (sample 1). However, the diffusive properties of these samples have been largely influenced by the properties of the fiberboard used in their production. It could be expected that more reflective materials (e.g. plastic) could lead to higher values of scattering coefficients.

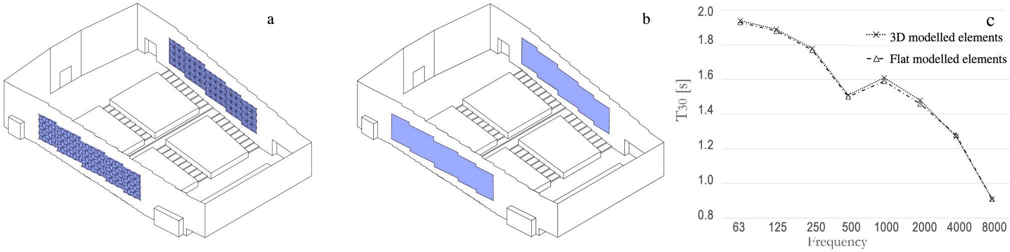


Figure 6
(a) Diffusive surfaces modeled as 3D elements; (b) Diffusive surfaces modelled as flat surfaces with a scattering coefficient assigned from measured values; (c) comparison between reverberation times (T30) obtained in case (a) and (b).

Odeon Simulations

In order to have a more complete understanding of the behavior of the adaptive panel, it has been applied in the lateral walls of the Odeon model of "Aula Magna Giovanni Agnelli" at Politecnico di Torino. The room has a fan-shaped plan and a tilted audience area. Its length is 31 m and its width varies from 17 m at the front to 21.5 m at the rear. The hall has been formerly characterized acoustically through in situ measurements which resulted in a reverberation time of 1.58 s at mid frequencies.Odeon is a hybrid simulation model that takes into account the diffusive properties of the surfaces by applying the scattering coefficient values to flat modeled surfaces or by directly modelling the diffusive patterns (Christensen, 2013). Both these modelling methods (Figure 6, a and b) have been used in this study in order to investigate the accuracy of the simulations based on the modelling method and availability of the scattering input data. The results (Figure 6, c) showed that both methods lead to similar results. Therefore, an accurate evaluation of the acoustic properties of the diffusive surfaces could be helpful to diminish the efforts regarding modelling details and consequently reduce the evaluation time in the design workflow.

CONCLUSION

The work started with an analysis of the state-of-the-art and related professional applications on the theme of adaptive structures. Then, some principles were analyzed: foldable geometries, modeling and prototyping process as well as the capability to manage the development of the project considering all the issues involved. The project took into consideration the acoustic theme, aiming to produce a proposal of an adaptive structure able to increase the efficiency and versatility of close environment, with a specific regard to conference and music halls. To solve specific issues, the reading and the understanding of important scientific publications (i.e. thick rigid origami) was crucial. In addition, the laboratory measurement was essential to determine the scattering coefficient of a surface covered with the selected geometry necessary to answer to this need. The deep study of the specific application contributes to enhance the completeness of the work, giving a description of its behavior that often lacks in the presentation of similar solutions.In order to provide a more complete and wide work, after having measure the scattering coefficient of the panels, an installation inside an existing space has been simulated; this study was crucial to understand their real effect on a sound field, by comparing the obtained results with the reference case. The analysis shows an evident change in the distribution of the energy which ensures a real impact of the scattering diffusion on the environment perception. Music and speech require different reverberation times to provide suitable clarity and definition levels. A static space will always provide the same conditions; the choice of adaptive panels ensures the possibility to modify the space and the acoustic response of the surfaces. Such versatility opens up new ways to conceive structures including the dimension of time. The traditionally conceived three-dimensional geometry had to change in the fourth dimension: in fact, the proposed solution is an adaptive panel able to modify its spatial configuration by provoking a change in sound reflection which rebound on the acoustic of the room.The research and the examples are still in their preliminary phase, the effects of a massive introduction of adaptive products in all the aspect of human life are difficult to predict, but of course they will generate a significant innovation affecting our society, our habits and our cities.At this days, we are seeing the evolution of the relationship between thinking and making, which originally was attended in the action of the hand of the craft-person artist and then was expressed by the design; Drawing plays its role from making to thinking and the coming back to its early conception as technical language no more simply considered as an active tool of the creative process (Lo Turco et al. 2016).

REFERENCES

Beranek, L 1996, *Concert and Opera Halls: How They Sound*, Acoustical Society of America, Woodbury, NY

Christensen, CL 2013, *Odeon Room Acoustics Program, Version 13.0, User Manual*, Industrial, Auditorium and Combined Editions, Lyngby, Denmark

Cumino, C, Frigerio, E, Gallina, S, Spreafico, M and Zich, U 2014 'Modeling Vaults in Origami: A Bridge between Mathematics and Architecture', *Proceedings of Origami6.II. Technology, Art, Education. International Conference on Origami Science and Tecnology*, Tokyo, Japan, pp. 571-582

Mendez Echenagucia, T, Sassone, M, Astolfi, A, Shtrepi, L and Van Der Harten, A 2014, 'EDT, C80 and G Driven Auditorium Design', *Building Acoustics,*, 21 (1), pp. 43-54

Kasem, A, Ghourabi, F and Ida, T 2011 'Origami axioms and circle extension',, *Proceedings of the 2011 ACM Symposium on Applied Computing. ACM*, New York, p. 1106–1111

De Kestelier, X and Peters, B 2013, *Computation works: the building of algorithmic thought*, Architectural design - John Wiley & Sons, New York

Kolarevic, B, Peters, B and Peters, T 2013, *Parametric Evolution, Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design*, Wiley & Sons, New York

Pellegrino, S 2001, *Deployable Structure*, Springler Verlan, Wien

Peutz, VMA 1978 'The variable acoustics of the Espace de Projection of IRCAM (Paris)', *Proceedings of AES 59th Convention*, Hamburg, Germany, p. 1–8 paper 1310

Ryu, JK and Jeon, JY 2008, 'Subjective and objective evaluations of a scattered sound field in a scale model opera house', *J. Acoust. Soc. Am.*, 124(3), p. 1538–1549

Shtrepi, L, Astolfi, A, D'Antonio, G and Guski, M 2016, 'Objective and perceptual evaluation of distance-dependent scattered sound effects in a small variable-acoustics hall', *J. Acoust. Soc. Am.*, 140, p. 3651–3662

Shtrepi, L, Pelzer, S, Vitale, R, Rychtarikova, M and Astolfi, A 2015, 'Objective and perceptual assessment of the scattered sound field in a simulated concert hall', *J. Acoust. Soc. Am*, 183(3), p. 1485–1497

Tachi, T 2010 'Geometric considerations for the design of Rigid Origami Structures', *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium. Vol. 12.*, Shanghai, China

Torres, R, Kleiner, M and Dalenbäck, BI 2000, 'Audibility of 'diffusion' in room acoustics auralization: An initial investigation', *Acta Acust.*, 86(6), p. 917–925

Lo Turco, M and Santagati, C 2016 'From SfM to Semantic-Aware BIM Objects of Architectural Elements', *Proceedings of EuroMed 2016*, Nicosia, Cyprus, pp. 600-612

Vorländer, M 1995 'International Round Robin on room acoustical computer simulations', *Proceedings of 15th International Congress on Acoustics*, Trondheim, Norway, p. 689–692

Vorländer, M 2008, *Auralization: Fundamentals of Acoustics, Modeling, Simulation, Algorithms and Acoustic Virtual Reality*, Springer, Berlin, Germany

[1] http://www.langorigami.com/

[2] https://github.com/oripa/oripa