Exploring Low-cost Acoustic Panels with Origami Patterns for Classrooms

Principal Author[1], Second Author[2], Third Author[3]

[1]First Institution, City, State Abbreviation
[2]Second Institution, City, State Abbreviation
[3]Third Institution, City, State Abbreviation

ABSTRACT: The goal of the work presented in this paper was to provide an alternative method to improve the acoustic conditions of classrooms in public schools in low-income contexts by designing, fabricating, and testing low-cost and modular acoustic panels. The panels used are shaped with Origami-patterns, and they were made of waste cardboard sheets collected from the urban waste stream. The exploratory work combined physical prototyping and simulation using Pachyderm, an acoustic simulation plugin for Rhinoceros-Grasshopper. While prototyping focused on assessing fabrication workflow, simulation focused on determining Reverberation time of three types of three-layered Origami-based panels. Fabrication results showed that all panels were easy to produce with simple tools. The simulation confirmed that panels with a denser pattern decreased Reverberation time between 27% to 48% for 125, 250, and 500 Hz frequencies. Further research will explore increasing panels layers and adding alternative and recycled materials to test sound absorption. The solution presents promising results for low-income contexts with a high need to improve the physical conditions of classrooms and other buildings.

KEYWORDS: Waste Cardboard, Origami, Acoustic Insulation, Classrooms

INTRODUCTION

Climate change challenges everyone to create innovative and more affordable ways to increase buildings resiliency. This challenge is challenging for those living in low-income contexts which cannot afford to build using conventional and high-quality materials. The study described in this paper is part of research that explores waste cardboard applications for architecture and provides guidelines to design and fabricate low-cost and modular insulation panels using Origami patterns and waste cardboard sheets as the primary material.

The goal is to improve the acoustic performance of classrooms in primary public schools in developing countries, commonly characterized by poor internal conditions. A primary public school located in Paraguay was selected as the case study selected for the exploration. The school represents a common case of building that requires substantial improvements in the physical infrastructure to help children improve their education environment.

The work is based on two strands of research. There is a body of literature that investigates Origami patterns for structural and non-structural purposes including acoustic panels, such as the work by Turco et al. (2017). There is algo work by Kang et al. (2021) where researchers proposed multi-layered and perforated flat cardboard panels to improve acoustic performance of housing apartments in Seoul.

In this work, we followed a mixed-method approach combining prototyping and simulation. In the first part, the authors designed panel templates using the Miura-ori pattern –one of the simplest and more common Origami patterns. The digital templates were used to test the fabrication process and perform simulation using the Pachyderm Acoustical Simulation for Rhino Grasshopper. Simulation evaluated the Reverberation time of designed panels, and the results allowed to obtain adequate design parameters for prototypes improvement.

We conclude that using waste cardboard sheets obtained from urban waste and fabricated following an Origami pattern can work for acoustic panels. The guidelines offered in this work are intended for both professionals and laypeople who have access to waste cardboard and need low-cost alternatives to improve the acoustic conditions of classrooms. Future work will focus on housing in similar socio-economical contexts that require improvements to fulfill acoustic requirements. The study contributes to the growing body of research that utilizes smart geometries for architectural applications and studies exploring sustainable materials to mitigate buildings' impact on climate change.

1.0 BACKGROUND

The background information that supports the project is presented in three parts. The first part contextualizes the situation of primary public schools in Paraguay, where there is an urgent need to improve classrooms infrastructure where acoustical conditions are an overlooked issue. The second part comments on recent advances in Cardboard Architecture, highlighting the opportunities to use this material. The third part provides a brief overview of Origami engineering and why this geometry is helpful for acoustic panels.

Paraguay suffers one of the highest deficits in educational building infrastructure in Latin America, negatively impacting the educational development of children between 5-14 who attend public schools (Murillo and Román 2011). The deficit is both quantitative and qualitative, seriously affecting rural areas where public primary schools do not have enough classrooms and suffer from problems in the structure of buildings (Yanes-Pagans, Bedoya, and Zarza 2018). As an example of local efforts to improve the current situation, Mauricio Villalba, an architect from Paraguay, worked on a project that sought to improve the physical conditions and thermal performance of roofs in public primary schools in rural areas (Villalba 2021). Simulations on the thermal performance of the lightweight and modular roof system proposed by Villalba indeed showed improvements in the indoor conditions of classrooms that currently do not have any thermal insulation. However, there are no ongoing projects that look at the acoustic conditions of classrooms in rural schools considering there is no treatment whatsoever in existing buildings. In this context, this work aims to contribute to local efforts by proposing a low-cost and lightweight acoustic panel system made of waste corrugated cardboard that can be easy to fabricate, transport, assembly, and recyclable. The acoustic condition addressed in this work is Reverberation time.

Recent published architectural research about acoustical conditions of multi-use educational spaces pointed out the importance of acoustical qualities to support better learning (Butko 2021). Butko proposed porous concrete material as an alternative to improve absorption and diffusion qualities of spaces where users manifested acoustical issues. Absorption and diffusion are essential to assuring good communication in educational spaces, and designers commonly use materials such as wood or foam panels to tackle these issues. Although Butko's research reported improved speech legibility, clarity, and sound reflection, porous concrete materials could be costly for low-income contexts and challenging to transport to remote areas.

Cardboard materials are paper-based products that are not typically used in building design. Nevertheless, work by Shigeru Ban has increasingly brought attention to the material since the 1990s, showing the potential of cardboard in works such as the Nomadic Museum in various locations (2005), the Cardboard Cathedral in New Zealand (2013), and the Concert Hall in France (2017). In the Concert Hall, the architect used paper-based materials as acoustic elements creating a warm and intimate spatial character. A recent publication by the author on Cardboard Architecture has drawn attention to the use of cardboard products during the last eight decades as both structural and non-structural building components (Author, 2021). The review summarized research into cardboard architecture in academia and professional practice, identifying different cardboard structural systems such as active vector and active surface structures. The main advantage of using cardboard as a building material is its low cost, relatively good mechanical properties, and ease of recycling (Latka 2017). In terms of applications in building construction, cardboard can be used in several ways, for instance, to build formwork for casting panels (Authors, Year) or make tubes for chairs and furniture, as seen in the work of Shigeru Ban.

Cardboard can also be used for making panels for thermal and acoustic insulation for buildings. A group of studies has found positive results in terms of performance and cost. Asdrubali et al. (2015), for example, measured transmission loss and thermal conductivity and reported that cardboard works for light thermal insulation panels for non-structural and internal partitions. Similarly, a comprehensive review on insulation materials that compare conventional, alternative, and advanced insulation materials (Schiavoni et al. 2016) pointed out that although sound absorption results are unfavorable due to its inner structure, cardboard is a remarkable material for sound insulation. Two other seminal works for this project investigated sound absorption and insulation performance of perforated and non-perforated cardboard panels, including panels with multi-frequency resonators reporting excellent results as stated by the authors (C. W. Kang and Seo 2018; C.-W. Kang, Kim, and Jang 2021). In these works, authors tested flat panels made of three corrugated cardboard sheets with different perforation configurations for housing purposes.

Origami is a craft technique that is concerned with folding paper. This is a method for creating three-dimensional structures from flat surfaces, appealing for engineering applications. A comprehensive review by Sorguc et al. (2009) describes origami applications in architecture and how the technique can be a medium for inquiry in design. Regarding Origami patterns, the design is typical for structural components and panels. Designers commonly use Origami patterns because they are simple and effective in fabricating rigid elements with flat materials, facilitating a minimum number of elements, and being easy to transport (Gattas and You 2016). In this sense, the work by Turco et al. (2017) applied Origami techniques for adjustable acoustic panels made of cardboard and wood to fit acoustic and visual requirements. Their results showed that shape variation and size increase could improve acoustic panels' scattering/diffusing properties at lower frequencies. Another remarkable precedent that used Origami patterns for acoustic panels developed a computational method to integrate design and acoustic engineering, including parametric design, acoustic simulation, and optimization (Takeanada and Okabe 2013).

The work presented in this paper adds to the literature on Cardboard Architecture by exploring Miura-ori origami patterns with different design variables to build acoustic panels using waste cardboard sheets. Furthermore, it uses a case study of primary schools in rural areas to argue that these origami acoustic panels could be an economical way of improving the performance of such buildings.

2.0 METHODS

2.1 Design and Prototyping

In this project, design variables for acoustic panels included Reverberation time (RT), modularity, cost, ease of fabrication, transportability, and recyclability. Acoustic performance variables include absorption and diffusion

requirements. We focused on diffusion, specifically on RT measured in seconds, considering this is a crucial classroom issue. We relayed in previous research by Asdrubali et al. (2015) and Secchi et al. (2016) for sound transmission and sound insulation.
Modularity allows for adaptation to different uses in interior spaces of different dimensions (e.g., wall and/or ceiling). We intend to keep the system low-cost and easy to fabricate to help people with little money and little experience to obtain the materials and tools needed to produce the panels. In this case, we used sheets of waste cardboard that can be picked up for free from the streets and are free of contamination and in good shape, any cutting surface, knife, ruler, pencil, and conventional water-based glue. Water-based glue counts to make these panels easy to recycle or repurpose. The templates were created using parametric design software (Grasshopper); therefore, they can be generated in different shapes and dimensions as printed guidelines to facilitate the fabrication process.

2.2 Selected Case Study of Housing

In this paper, we adopted a case study methodology, where we designed and tested acoustic cardboard panels for a classroom for a primary public school in Paraguay. The room measures 7.2 x 7.2 meters and is 3 meters high (155.52 m3). The case study is a typical sample of a government-sponsored school in Paraguay, and Figure 1 illustrates the building layout. The school is built with concrete floors, brick masonry walls of 15 cm thick and no plastering, and corrugated steel panel roofs (no ceiling) supported with a steel structure. Classrooms have no thermal/acoustic insulation in the walls or under the roof. The room sizes define the design conditions for panel size and modularity, which is critical for efficiency and low costs. All doors are made of metal sheets, and windows have a single layer of tempered glass with metal framing. Studies reported poor quality conditions of classrooms physical conditions harming children's education and development (Murillo and Román 2011).

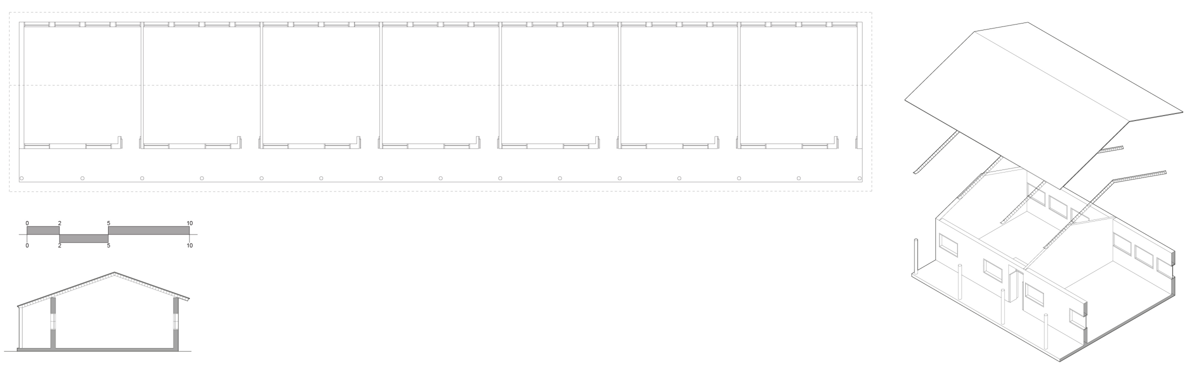


Figure 1: Floorplan, section, and partial axonometric view of a *Colegio Nacional Los Primeros Colonos del Chaco* new Loma Plata in the Chaco Region, Paraguay. Source: Mauricio Villalba

2.3 Simulation

In this research, we conducted a simulation study to assess the acoustic properties of the origami-shaped cardboard panels. While there are many indicators of acoustic performance, we focused on Reverberation time, measured in seconds, as this parameter is used in many standards, such as LEED and ANSI standard S12.50.2002. Reverberation time is defined as the time it takes for a sound to decay to a specified level, typically 60 dB. We used Pachyderm, an acoustic simulation plugin for Rhinoceros-Grasshopper, to measure the Reverberation time. This software can be used to predict noise and create a visualization of sound propagation, and it is intended to aid designers in developing spaces with good acoustic performance.
The simulation settings are shown in Figure 2. The basic simulation settings include defining a sound source and a receiver. These were set on opposite sides of the room. The interior walls were defined in the simulation as a standard indoor partition, and conventional materials were selected for the floor, walls, and roof. To simulate the acoustic performance of the cardboard panels, we obtained values for absorption coefficient from work by Kang, Kim, and Jang (2021). In a seminal study, the authors experimentally characterized the absorption coefficient of triple-layered-panels cardboard panels using the method of an impedance tube and calculated the noise-reduction coefficient. One limitation of the software we used is that it is difficult to make calculations using materials with exceptionally low absorption coefficients: the simulation tends not to converge since the sound takes too long to decay. We, therefore, are limited in the material selections for the simulation.

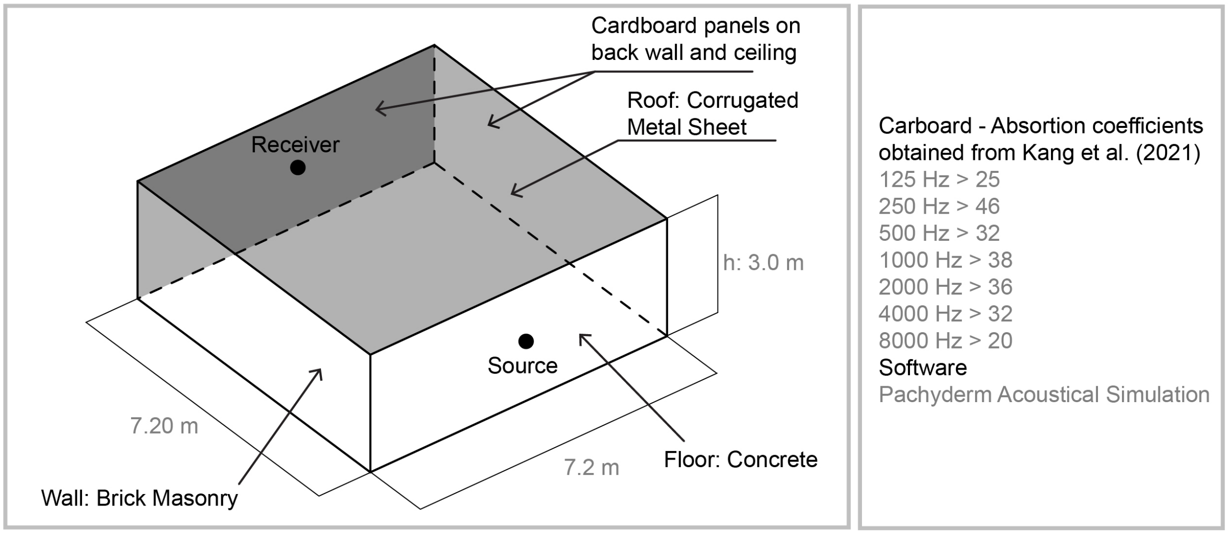


Figure 2: Simulation settings. Source: Authors

3.0 RESULTS

3.1 Fabrication

Figure 3.1 illustrates panel templates, modules, and finished panels. Templates include folding lines as mountains and valleys. All panels fit in a 457 x 812 mm frame for laser cutter fabrication; however, frame size can be adjusted to available cardboard sheets if necessary. We tested panels with large, medium, and small size modules to measure fabrication time. Figure 3.2 shows the prototype panels, each made with three layers of 3 mm thick sheets or single wall glued with a conventional water-based adhesive applied by hand with a spatula. The cutting time difference between panels is irrelevant if done with a laser cutter; nevertheless, the smaller the module, the more difficult it is to mount with time variation between 2-4 minutes for Panels 1 and 2 and 8-12 minutes for Panel 1. The work can be done entirely by hand, and although this will increase fabrication time, it will make the process low-tech and low-cost affordable for anyone or have access to the templates and material. We tested making perforations in Panel 3 following the same method used by Kang et al. (2021) 2.5 mm perforations were done quickly using an electric drill.

These panels can be attached to the wall or ceiling using adhesive strips, hot glue, or tape. The modularity facilitates their assembly, and they can be cut easily with a knife or handsaw to fit irregular spaces. Cardboard surface is easy to paint with either water-based or oil-based paint allowing households to use whatever they have at hand to decorate the panels.

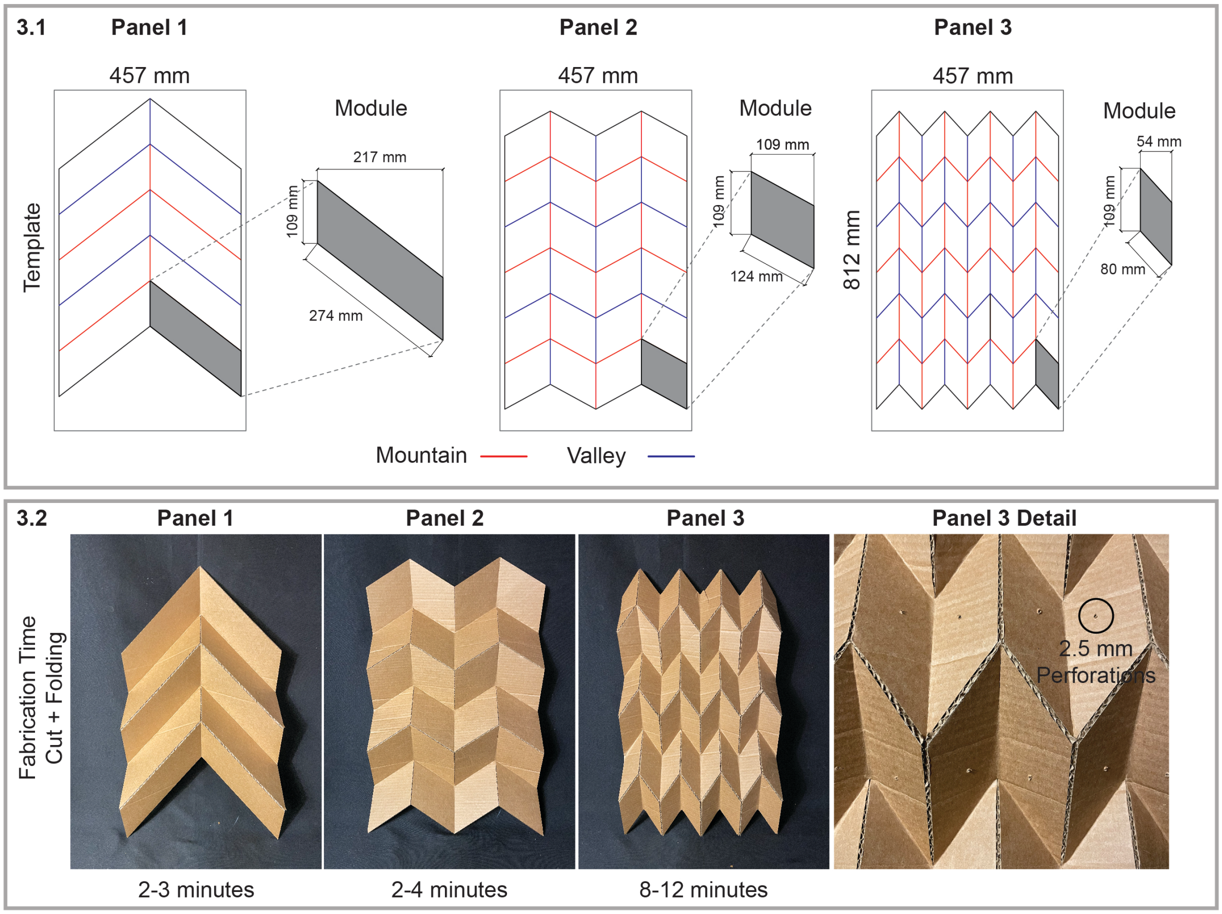


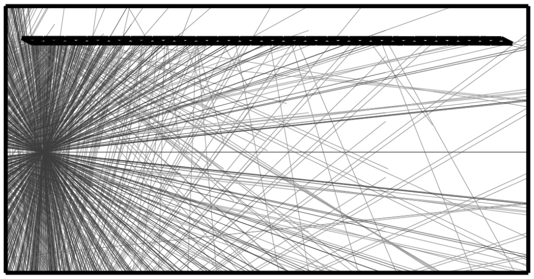
Figure 3: Templates and finished panels. Source: Authors

3.2 Simulation

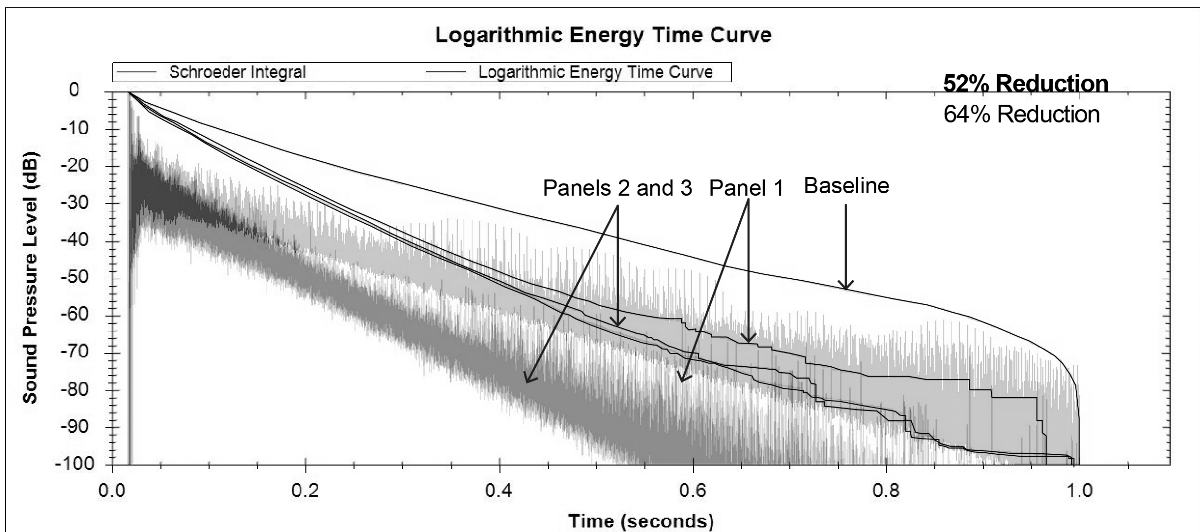
Figure 4.1 shows a visualization of sound propagation in the room, with the left-hand side depicting the first moments and the right-hand side showing the sound waves as they reflect into the panels and the walls. The sound pressure simulation results are shown in Figure 4.2. We simulated the acoustic performance of a baseline case with no panel to assess how the introduction of the panels helped improve or not the acoustic performance. As shown in the graph depicting sound pressure levels (dB) vs. time in seconds, the panels overall help considerably improve the acoustic performance and decrease RT in the room. Overall, all panels present similar acoustic performance, with Panels 2 and 3 presenting the best performance. The reason might be related to their design, which has a denser pattern, which makes the sound waves diffuse more than the other prototypes. Panel 1 has the most 'open' Origami pattern; however, reverberation decreased -45%, -37%, and -22% for 125, 250, and 500 kHz wavelengths—speech frequency levels range. The table below Figure 4.2 compares the reverberation times for the three panels and the baseline case with no panel.

An interesting observation that emerges from the data comparison of the three panels and the baseline case is that there is not much of a difference in the acoustic performance of the different origami panels. Taken together, the simulation results indicate that there might be other characteristics that more greatly affect acoustic performance other than pattern design. These can be, for instance, material characteristics and layer count of the cardboard panels. One way that has been proven effective to improve the acoustic performance of cardboard panels is to make perforations into corrugated cardboard, as shown in a study by Kang et al. (2021). As shown in section 3.1, we tested fabricating non-perforated and perforated panels following the study; however, our simulation corresponds to non-perforated panels for now. Another alternative is increasing cardboard layers and arrangement of the cardboard panels, as proposed in an experimental study by Asdrubali et al. (2015). It is also possible to combine layers of cardboard with other recovered materials with high acoustic absorption, such as recycled paper, textiles (denim or towels), jute, or hemp fiber. Nevertheless, for the target case study of a classroom, the panels sufficiently improve the acoustic performance, and the results indicate that it is up to the abovementioned standards.

4.1



4.2



	Htz	Baseline	Panel 1 Seconds	Panel 1 % Reduction	Panel 2 Seconds	Panel 2 % Reduction	Panel 3 Seconds	Panel 3 % Reduction
	62.5	0.87	0.49	-44%	0.46	-47%	0.47	-46%
Speech	125	0.89	0.49	**-45%**	0.49	**-45%**	0.46	**-48%**
Frequenz	250	0.59	0.37	**-37%**	0.34	**-42%**	0.34	**-42%**
y Range	500	0.45	0.35	**-22%**	0.32	**-29%**	0.33	**-27%**
	1000	0.31	0.26	-16%	0.24	-23%	0.23	-26%
	2000	0.24	0.21	-13%	0.18	-25%	0.18	-25%
	4000	0.76	0.23	-70%	0.21	-72%	0.22	-71%
	8000	0.82	0.5	-39%	0.48	-41%	0.47	-43%

Figure 4: Simulation results. Source: Authors

CONCLUSION

The goal of the exploratory work presented in this paper was to explore alternative materials to improve the acoustic conditions of classrooms in primary public schools in developing contexts by making low-cost insulation panels made of waste corrugate cardboard sheets and conventional glue. The study tested the fabrication of three types of cardboard panels designed with origami patterns and simulated the acoustic performance using the Pachyderm software for Rhinoceros. All designs decreased reverberation time considerably for different wavelengths suggesting the panels could work. Although the differences between the three versions do not appear to be significant, ranking the panels with a denser pattern the most efficient (Panel 2 and 3), the findings suggest the potential positive impact of the system for classrooms at a meager cost. Fabrication workflow was also considered to assess panels design, and in this case, the panels with the less dense pattern were the easiest to fabricate (Panels 1 and 2).

In order to improve the acoustic performance even more, future research can try out other strategies to improve the performance of the panels, such as layering more sheets of cardboard, perforating them, combining layers of cardboard with other recycled material to increase sound absorption (e.g., shredded paper, denim, toweling fabric, and natural fibers). Although these additions might increase fabrication complexity and cost, they could make panels more efficient.

One limitation of the work is that we only focused on the Reverberation time. Future research can simulate or test the thermal efficiency of these cardboard origami panels, which is also critical in these types of buildings located in hot and humid climates.

Finally, we are looking to extend the use of these prototype panels for housing in developing contexts with poor building qualities, high reverberation time, and low thermal performance. In this way, we hope to increase buildings resiliency and take advantage of urban solid waste like corrugated cardboard that is currently underutilized.

REFERENCES

Asdrubali, F., A. L. Pisello, F. D'Alessandro, F. Bianchi, M. Cornicchia, and C. Fabiani. 2015. "Innovative Cardboard-Based Panels with Recycled Materials from the Packaging Industry: Thermal and Acoustic Performance Analysis." *Energy Procedia* 78: 321–26. https://doi.org/10.1016/j.egypro.2015.11.652.

Butko, Daniel. 2021. "A Sound Approach to Concrete: Transforming Concrete Through Shape and Porosity for Acoustical Reflection, Diffusion, and Absorption." *Technology|Architecture + Design* 5 (1): 46–58. https://doi.org/10.1080/24751448.2021.1863673.

Gattas, J. M., and Z. You. 2016. "Design and Digital Fabrication of Folded Sandwich Structures." *Automation in Construction* 63: 79–87. https://doi.org/10.1016/j.autcon.2015.12.002.

Gönenç Sorguç, Arzu, Ichiro Hagiwara, and Semra Arslan Selçuk. 2009. "Origamics In Architecture: A Medium Of Inquiry Or Design In Architecture." *METU Journal of the Faculty of Architecture* 26 (2): 235–47. https://doi.org/10.4305/METU.JFA.2009.2.12.

Kang, Chun-Won, Mina K. Kim, and Eun-Suk Jang. 2021. "An Experimental Study on the Performance of Corrugated Cardboard as a Sustainable Sound-Absorbing and Insulating Material." *Sustainability* 13 (10): 5546. https://doi.org/10.3390/su13105546.

Kang, Chun Won, and Yung Bum Seo. 2018. "Sound Absorption and Sound Transmission Loss of Perforated Corrugated Board." *Palpu Chongi Gisul/Journal of Korea Technical Association of the Pulp and Paper Industry* 50 (4): 32–39. https://doi.org/10.7584/JKTAPPI.2018.08.50.4.32.

Latka, Jerzy F. 2017. "Paper in Architecture: Research by Design, Engineering, and Prototyping." Delft University of Technology.

Murillo, F Javier, and Marcela Román. 2011. "School Infrastructure and Resources Do Matter: Analysis of the Incidence of School Resources on the Performance of Latin American Students." *School Effectiveness and School Improvement* 22 (1): 29–50. https://doi.org/10.1080/09243453.2010.543538.

Schiavoni, S., F. D'Alessandro, F. Bianchi, and F. Asdrubali. 2016. "Insulation Materials for the Building Sector: A Review and Comparative Analysis." *Renewable and Sustainable Energy Reviews* 62: 988–1011. https://doi.org/10.1016/j.rser.2016.05.045.

Secchi, Simone, Francesco Asdrubali, Gianfranco Cellai, Elisa Nannipieri, Antonella Rotili, and Irene Vannucchi. 2016. "Experimental and Environmental Analysis of New Sound-Absorbing and Insulating Elements in Recycled Cardboard." *Journal of Building Engineering* 5 (March): 1–12. https://doi.org/10.1016/j.jobe.2015.10.005.

Takeanada, Tsukasa, and Aya Okabe. 2013. "A Computational Method for Integrating Parametric Origami Design and Acoustic Engineering." In *Computation and Performance – Proceedings of the 31st ECAADe Conference*, edited by Rudi Stouffs and Sevil Sariyildiz, 2:289–95. Delft: TU Delft. http://papers.cumincad.org/cgi-bin/works/paper/ecaade2013_203.

Turco, Massimiliano Lo, Ursula Zich, Arianna Astolfi, Louena Shtrepi, and Matteo Botto Poaola. 2017. "From Digital Design to Physical Model: Origami Techniques Applied to Dynamic Paneling Shapes for Acoustic Performance Control." *ECAADe* 2: 77–86.

Villalba, Mauricio. 2021. "Contribuciones a La Cultura Del Diseño Paramétrico y La Fabricación Digital En Paraguay Con Énfasis En Un Ejercicio de Diseño y Simulación de Cerramientos Superiores. Caso:Colegio Nacional Los Primeros Colonos Del Chaco." Universidad Nacional de Asuncion.

Yanes-Pagans, Monica, Juan Bedoya, and Dalila Zarza. 2018. "Paraguay. Invertir En Capital Humano.: Una Revision Del Gasto Publico y de La Gestion En Los Sectores Sociales." http://documents1.worldbank.org/curated/en/145651542655422647/pdf/132203-replacement-Chapter-Education-final1.pdf.