Tooling Cardboard for Smart Reuse

Testing a Parametric Tool for Adapting Waste Corrugated Cardboard to Fabricate Acoustic Panels and Concrete Formwork.

Julio Diarte[1], Elena Vazquez[2], Marcus Shaffer[3]
[1,2,3] The Pennsylvania State University
[1,2,3] {jcd40|emv10|mus39}@psu.edu

The study presented in this paper is part of ongoing research that is exploring how digital design tools and technologies can support waste cardboard reuse for manufacturing architectural elements in a context of scarcity. For this study, we explore the use of a parametric design tool to design and fabricate three different architectural components using waste cardboard sheets: acoustic panels and two types of formwork for concrete. This design tool maximizes the smart reuse of a waste material and aids in the fabrication process by outputting instructions for cutting, scoring, and folding. This paper also demonstrates how parametric design tools can help reuse non-standard (dimensions variable) waste materials, mediating between measurable material conditions and desired material targets for designs.

Keywords: *Cardboard Architecture, Reusing Waste Cardboard, Material Reuse Processes, Parametric Design Tools*

INTRODUCTION

Dealing with urban waste is a major problem worldwide, especially in developing countries where formal waste recovery systems are insufficient. In some Latin American countries, for instance, only 57% of urban waste is recovered and the rest is “processed” in open air dumpsites, through open-air burning, or in streams and rivers; with consequences for the environment (Tello Espinoza et al. 2010). In this context, we believe that our role as architects and designers is to develop methods and tools to increment material reuse in buildings and decrease the amount of waste in the environment.

This paper is part of ongoing research that is exploring how digital design tools and technologies can support designers through reusing urban waste for manufacturing architectural elements (Diarte and Shaffer 2018). The research focuses on waste corrugated cardboard; one of the largest components of the urban waste composition worldwide (Silpa Kaza et al. 2018), and explores its potential as a building material based on its advantages for construction: availability, low-cost, acoustic/thermal properties, and strength relative strength in certain loading conditions. The increasing use of cardboard in design and architecture in the last three decades confirms its potential (Cripps 2004; Eekhout et al. 2008; Ayan 2009; Pohl 2009; Salado 2011; Sekulic 2013; Latka 2017). Nevertheless, this building interest has mostly focused on new/engineered/purposedesigned cardboard, while waste cardboard has received less attention - downgrading it to recycling and production of more cardboard.

On the other hand, it has been demonstrated that parametric design tools can be a powerful ally when designers (or would-be designers) need to create a variety of options instead of single "finished" objects, therefore expanding the design-space exploration (Reas et al. 2010). Furthermore, parametric tools can also help in dealing with non-standardized materials in producing design alternatives (Vercruysse & Self 2017). With waste cardboard, the designer must negotiate with non-uniform sheets - diverse perimeter dimensions and thickness - to produce standardized (modular) elements. We, therefore, argue that parametric tools can aid the design process of reusing non-standard materials such as waste cardboard.

In a recent paper - currently in press - (Diarte et al. 2019) we presented and described a hybridized digital/analog workflow for reusing waste cardboard as a building material. The workflow aimed to facilitate the work of designers/builders when documenting and mediating with the variability of waste cardboard using a digitally-aided process. The workflow included the material collection and documentation of waste material for creating a database, a design component using parametric tools and a digitally aided fabrication process. As a proof of concept, we tested the workflow for the design and construction of a prototypical floor panel.

In this study, we extended the application of the digital design component of the workflow, to fabricate other architectural elements - either made with waste cardboard or whose fabrication process could be dependent on waste cardboard. More specifically, we developed digital design tools that use waste cardboard of variable dimensions as a material to fabricate acoustic panels and concrete formwork. The digital design tool is a parametric script that aids the design of architectural elements to maximize the use of the material (waste cardboard). The script also aids the fabrication process, by outputting cutting, scoring, and folding paths.

We present three different iterations of the digital design component that aid the design and fabrication of acoustic panels with triangular profile tubes, concrete formwork with triangular profile tubes, and concrete formwork with prismatic molds. In describing the digital tool developed, and by demonstrating its application in the fabrication of cardboard architectures, we present a research-by-design exploration that aims to incorporate waste cardboard into architectural elements. This paper also demonstrates how parametric design tools can help reuse non-standard waste materials, mediating between existing material conditions and desired target designs.

METHODS

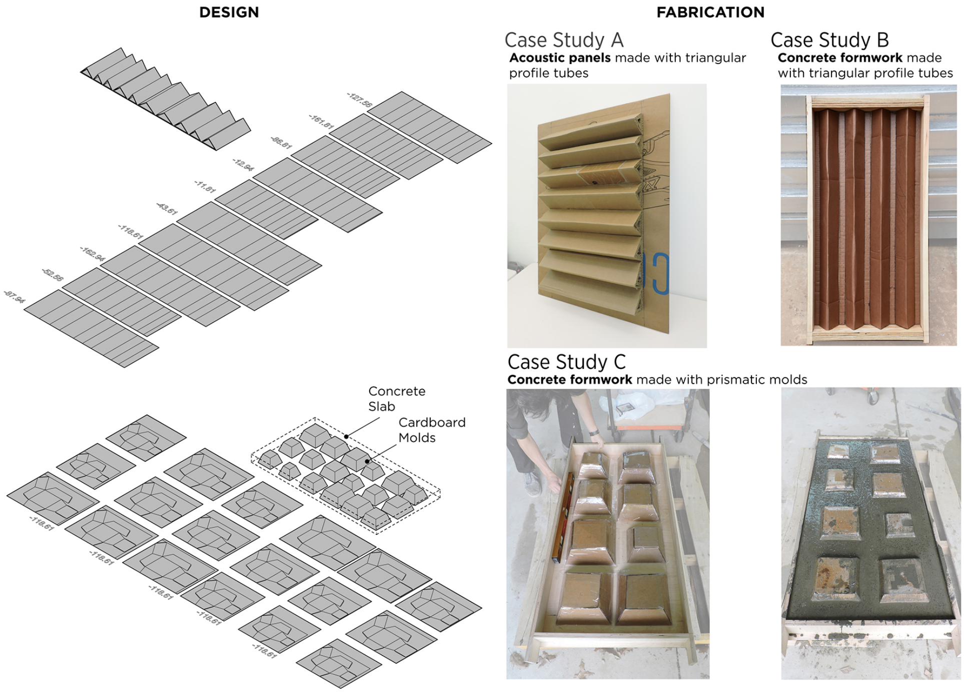
In this paper, we present a prescriptive study developed through an iterative cycle of inductive design and development, where the outcome of the research are design and fabrication principles. Research, within this approach, is done by developing digital and physical prototypes. The resulting design principles are encoded in the developed digital tools for creating cardboard architecture. The general aim of this process is to find ways in which waste cardboard can be incorporated into 1) finished architectural elements made with waste cardboard, and 2) incorporating cardboard into fabrication processes.

As stated above, we extended the application of the digital design component presented in previous work. We developed parametric tools and tested its implementation in aiding the design process and providing fabrication instructions for three different case studies, illustrated in Figure 1.

Parametric Design Tool

The parametric tool utilized in this work is developed in a way to accommodate the variability of waste cardboard sheets into building parts. In all the parametric tools developed, the script allows the designer to adapt a n number of different sheets of waste cardboard to fabricate the parts. The tool is composed of

Figure 1
Case Studies A, B, and C



the following parts: 1) generate; 2) visualize; and 3) fabricate. Figure 2 depicts the algorithmic logic of the parametric design tool, applied for the three different case studies.

The digital design tool is composed of the following components: The **generate** component of the tool combines two sets of data. First, the user's input with the dimensions of the triangular profiles or truncated square pyramids, and second, the material documentation data that contains the size (length and width) of the sheets of waste cardboard available. The component creates a series of design options and calculates the best match with the existing material. The **visualize** component shows a tridimensional view of the selected design options and displays the cutting and scoring paths on the sheets. The designs displayed shows the amount of material used allowing the user to readjust the dimensions if necessary. The **fabricate** component outputs the information for cutting and or scoring the sheets to create the tubes or truncated square pyramids. In other words, the output of the parametric tool are the fabrication instructions.

RESULTS

The following section describes the implementation of the parametric design tool in the design and fabrication of the three case studies described above. We develop three different prototypes of building components, to test the implementation of the digital tool in both the design and fabrication processes. The first two used triangular profile waste cardboard tubes and the third used waste cardboard molds based on truncated square pyramids. We used ply-

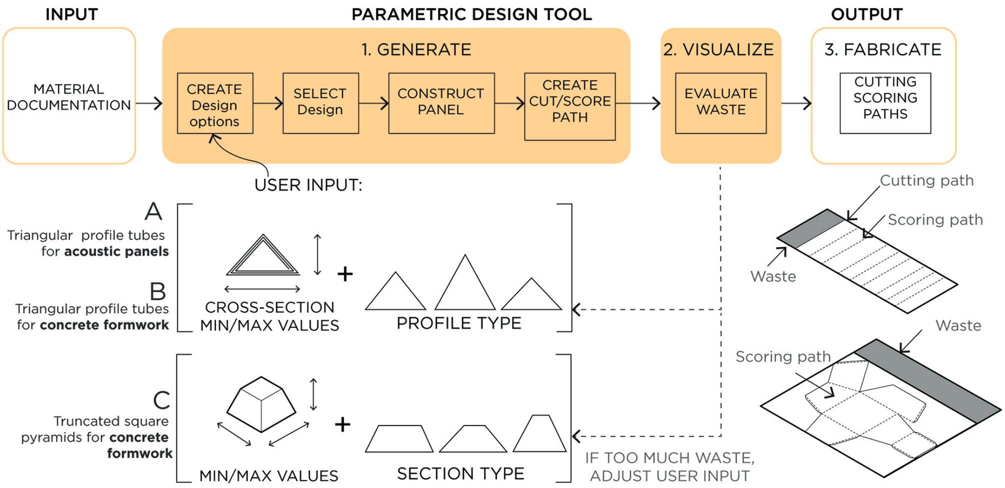


Figure 2
Algorithmic Logic of the Parametric Design Tool

wood elements to complement the fabrication of formwork for the prototypes for case studies b and c.

CASE STUDY A: Acoustic Panels made of Waste Cardboard Tubes

Previous research developed by Asdrubali et al. (2015) has demonstrated that panels made of corrugated cardboard sheets have promising acoustic insulation properties. Asdrubali's team tested different cardboard panels, concluding that the insulation property of the panel increases with the thickness, and the panels with concordantly oriented flutes perform significantly better than samples with perpendicularly oriented flutes. Following these design principles, we fabricated an experimental acoustic panel to reduce the transmission of sound from inside to outside, while acting as a sound diffuser.

Using the parametric tool, we accommodated sheets of waste corrugated cardboard of two different sizes (610 x 500 mm and 750 x 500 mm) and thickness 5 mm to fabricate several acoustic panels of size 600 x 800 mm. The panels were made of triangular profile tubes glued to a board made of two corrugated cardboard sheets that can be attached to a wall or ceiling. All tubes have triple-wall and the same cross-section dimension: 75 millimeters of base and height. The length of all tubes is 400 mm. Figure 3 illustrates the design of the tubes, panels, and application concept.

To determine the insulation capacity of the cardboard panels, we performed a preliminary experiment comparing the performance of the panels to a standard stone wool insulation product. To do this, we used the panels to cover the interior of a soundproofing test box. Then, we reproduced three different frequencies (1 kHz, 2.5 kHz, and 5 kHz) in the interior of the closed test box and measured the decibels out of the box for three different settings: a) the test box without any insulation; b) using stone wool insulation; and c) using cardboard panels.

To reproduce the frequencies, we used an online tone generator and a noise meter application to measure the decibels. The results, as shown in Figure 4, indicate that although the stone wool insulation performs much better, the cardboard panels still shows promising insulation properties. For instance, for the 1 kHz frequency, the stone wool re-

Figure 3
Case Study A.
Components and
Application
Concept

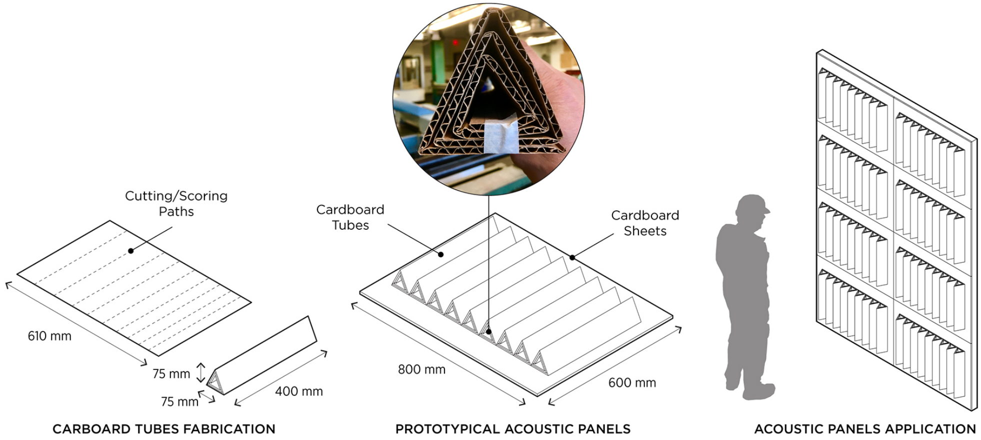
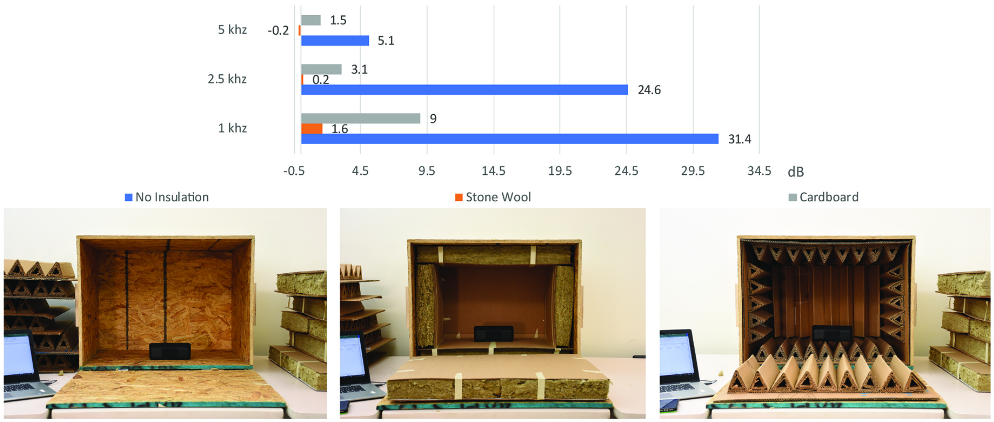


Figure 4
Case Study A.
Preliminary Sound
Insulation Test



duced 94.9% of the sound and the cardboard panels reduced 71.34%. The results for 2.5 kHz and 5 kHz showed similar outcomes suggesting a promising use of these cardboard panels for interior spaces.

CASE STUDY B: Concrete Slab Fabricated with Plywood and Waste Cardboard Tubes Formwork

The use of paperboard, paper tubes, and corrugated cardboard for formwork in concrete casting is not new and there are several commercially available products. However, most of the existing products are for forming concrete columns and made of brand-new cardboard. In this project, our goal was to produce a modular concrete slab that can be part of a flooring system, but one fabricated through the use of waste cardboard. The process consisted of two parts, design and fabrication of the formwork, and the manual concrete placement. The formwork was prepared by combining a plywood frame and a board with triangular profile tubes - similar to those described in the Case Study A. The size of the slab is 400 x 800 x 100 mm and it is supported by two joists running perpendicular to the direction of the ribs. The size allows two people to transport the slab without the use of heavy machinery. Figure 5 below shows the components of the formwork and the assembly concept of the flooring system.

Some of the aspects considered for the concrete casting process were, first, to keep the process as tactile and low-tech as possible, and second, protect the cardboard components from contact with water. Regarding the first aim, the concrete casting process was indeed completely manual and did not require more than a single person to perform the work. This is important considering that the project is intended for scarcity contexts. Furthermore, the task of moving the slab can be done with only two persons. To address the water issue and facilitating removing the formwork, we applied several layers of a standard waterproofing for wood to both the plywood frame and the cardboard panel and covered it with a conventional plastic sheeting material before placing the concrete. Both materials are readily available and low-cost. Figure 6 below show images of the making process and the outcome.

CASE STUDY C: Concrete Screen Fabricated with Plywood and Waste Cardboard Molds Formwork

In this case study, the goal was to fabricate concrete screens that can function as a partition or shading devices. Similar to Case Study B, the system consisted of a formwork composed of a plywood frame and cardboard molds. We adapted the parametric design tool to create cardboard molds based on a truncated square pyramid instead of triangular profile tubes described before. In the construction industry, this type of mold is commonly made of plastic and used to cast waffle concrete slabs. Here, we propose to fabricate the molds using folded sheets of waste corrugated cardboard to replace the plastic ones.

The dimension of each mold is a consequence of the combination of the size of cardboard sheets and the user/designer input values. That is to say: bottom and top base length and width, the height of the pyramid (this is a constant number determined by the thickness of the slab), number of mold options, and the incremental step between each option. For this study, we produced eight cardboard molds of four different base sizes. We cut the mold templates generated with the parametric script using a laser cutter but they can be easily done by hand. The molds were assembled using conventional packaging tape and placed on a plywood board with a water-based adhesive.

The size of the screen was established on 600 x 1200 x 80 mm so it can be easily transported and assembled by two people. Before casting, we applied several layers of a standard waterproofing for wood to both the plywood frame and the molds. Additionally, we sprayed conventional cooking oil on the formwork to act as a release agent. Figure 7 illustrates the process for this case study.

Although the cardboard molds were slightly wrinkled after removing the formwork, there were still in good conditions for further casting. Another aspect we noticed is the fact that the molds need more reinforcements to support the weight of the wet concrete and to improve the quality of the outcome. As can be seen in Figure 8 below, there are several flaws in the form of the concrete screen but this can also be considered as a particular aesthetic feature considering that we are reusing a waste material.

In the three case studies, the parametric tool facilitated the design process, and provided fabrication instructions, in the form of cutting and scoring

Figure 5
Case Study B.
Components and Application Concept

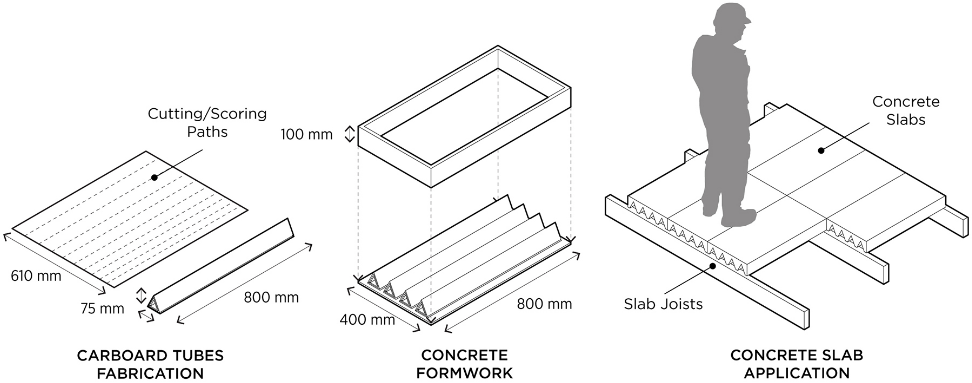


Figure 6
Case Study B.
Making Process and Outcome

paths. The fabrication process was mostly manual, where the cutting and scoring paths generated were translated into the cardboard sheets with the help of printed templates or directly as cutting/scoring paths for a laser cutter. The fabrication process was greatly facilitated by the digital design tool, despite the analogue nature of the fabrication process. The digital tool also allowed for testing several design iterations, evaluating them as according to how much the design solution maximizes the use of the waste cardboard material.

CONCLUSIONS

This paper summarizes the development and testing of parametric tools designed to adapt waste corrugated cardboard to the fabrication of acoustic panels and concrete formwork. The design explorations suggest the advantages of the tools in adapting a readily available and variable waste material (one taken from the waste stream, post-consumer) to create relatively standardized building elements. One of the more significant results was the satisfactory performance of the tool in matching the existing material to the different versions of the base geometry. This situation is applicable either for the tubes or the molds.

We fabricated three different prototypes of architectural elements where waste cardboard was used either in the fabrication process only - as in the case of the concrete formwork -, or conforms the finished

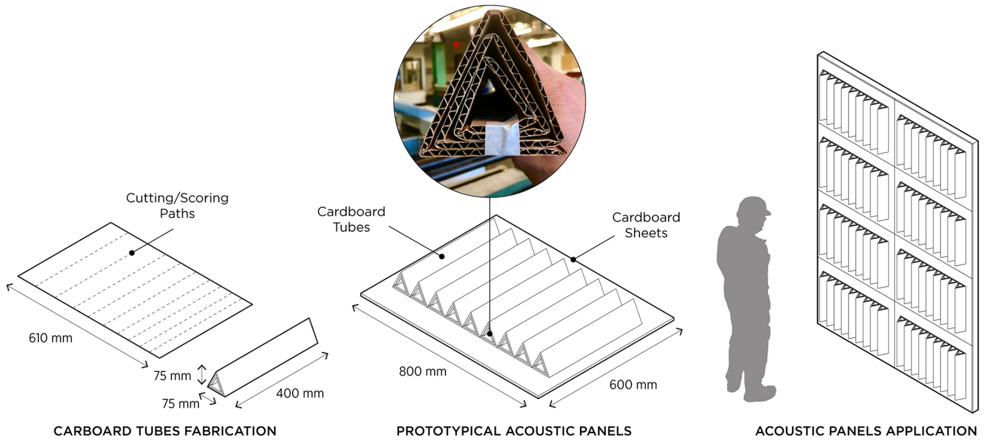


Figure 7
Case Study C.
Components and Application Concept

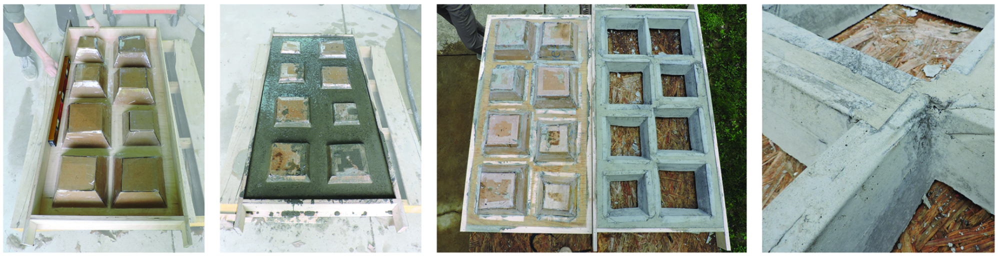


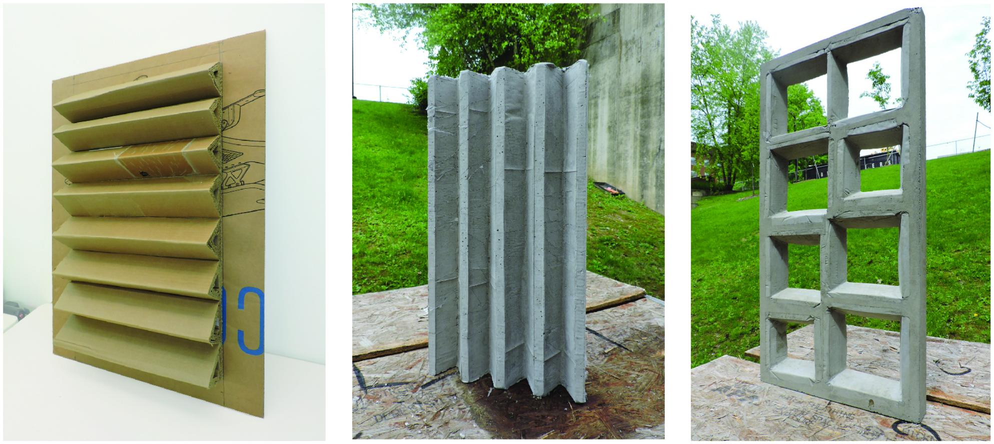
Figure 8
Case Study C.
Making Process and Outcome

building element, like in the acoustic panels (Figure 9). The fabrication process was aided by the cutting/scoring paths created with the digital design tool. The feasibility and ease of fabrication indicate that waste cardboard has the potential of conforming novel architectural elements and aiding fabrication processes, replacing other conventional materials.

Future work includes incorporating performance feedback into the digital design tools. The current version of the digital tool does not account for any performance indicator. Currently, the selection of the design iterations i.e. selection of profile and section types relies only on the visual feedback of how much waste material is being used, or on a design decision made by the user of the tool. Future work will look at incorporating performance feedback into the design iterations, which will be related to the function of the architectural element. For instance, structural analysis can inform the selection of profile type and cardboard component dimensions for adequately supporting the concrete formwork.

Finally, this study argues for the development of new methods and tools that use digital design technologies to take advantage of waste material and its implementation in making new building com-

Figure 9
Architectural
Element Prototypes



CASE STUDY A:
ACOUSTIC PANELS

CASE STUDY B:
CONCRETE SLAB
APPLICATION

CASE STUDY C:
CONCRETE SCREEN
APPLICATION

ponents. Reusing waste corrugated cardboard as a building material, instead of brand-new cardboard, in scarcity contexts proposes a new potential for designers and architects. In this new potential, we aim to see designers and architects not just as creators of buildings using pre-established materials but designing buildings through the development of material processes/tooling. We believe this could be an important contribution to architecture in the current 4th industrial revolution.

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REFERENCES

Asdrubali, F, Pisello, AL, D'Alessandro, F, Bianchi, F, Cornicchia, M and Fabiani, C 2015, 'Innovative cardboard-based panels with recycled materials from the packaging industry: Thermal and acoustic performance analysis', *Energy Procedia*, 78, pp. 321-326

Ayan, O 2009, *Cardboard in Architectural Technology and Structural Engineering*, Ph.D. Thesis, ETH Zurich

Cripps, A 2004, 'Cardboard as a construction material: A case study', *Building Research & Information*, 32(3), pp. 207-219

Diarte, J and Shaffer, M 2018 'Urban Recycling Intervention: Devising Low-Cost Tools for Transforming Old Corrugated Cardboard into Building Elements and Construction Materials', *Proceedings of 10th International Conference on the Environmental and Technical Implications of Construction with Alternative Materials WASCON 2018*, Tampere, pp. 362-366

Diarte, J, Vazquez, E and Shaffer, M 2019 'Tooling Cardboard for Smart Reuse: A Digital and Analog Workflow for Upcycling Waste Corrugated Cardboard as a Building Material', *In Lee JH. (eds) Computer-Aided Architectural Design. "Hello, Culture". CAAD Futures 2019. Communications in Computer and Information Science, vol 1028. Springer, Singapore*, pp. 384-398

Eekhout, M, Verheijen, F and Visser, R (eds) 2008, *Cardboard in Architecture*, IOS Press, Amsterdam

Tello Espinoza, P, Martinez Arce, E, Daza, D, Soulier Faure, M and Terraza, H (eds) 2010, *Regional Evaluation on*

Urban Solid Waste Management in Latin America and the Caribbean: 2010 Report, Pan American Health Organization, Inter-American Association of Sanitary and Environmental Engineering, Inter-American Development Bank
Silpa Kaza, L, Bhada-Tata, P and Van Woerden, F (eds) 2018, *What a Waste 2.0 A Global Snapshop of Solid Waste Management to 2050*, International Bank for Reconstruction and Development / The World Bank, Washington DC
Latka, JF 2017, *Paper in Architecture: Research by Design, Engineering, and Prototyping*, Ph.D. Thesis, Delft University of Technology
Pohl, A 2009, *Strengthened corrugated paper honeycomb for application in structural elements*, Ph.D. Thesis, ETH Zurich
Reas, C, McWilliams, C and Barendse, J 2010, 'Parameterize', in Reas, C, McWilliams, C and Barendse, J (eds) 2010, *Form+Code in Design, Art, and Architecture*, Princeton Architectural Press, pp. 92-117
Salado, G 2011, *Painel de vedacao vertical de tubos de papelao: Estudo, proposta e análise de desempenho*, Ph.D. Thesis, Universidade de Sao Paulo
Sekulic, B 2013, *Structural cardboard: Feasibility study of cardboard as a long-term structural material in architecture*, Master's Thesis, Polytechnic University of Catalonia
Vercruysse, E and Self, M 2017, 'Infinite Variations, Radical Strategies', in Sheil, B, Menges, A, Glynn, R and Skavara, M (eds) 2017, *Fabricate 2017*, UCL Press, pp. 30-35