Tooling Cardboard for Smart Reuse: A Digital and Analog Workflow for Upcycling Waste Corrugated Cardboard as a Building Material

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Abstract. This paper is a description of a hybridized digital and analog workflow for reusing waste corrugated cardboard as a building material. The work explores a combination of digital design and analog fabrication tools to create a workflow that would help designers/builders to negotiate with the material variability of waste cardboard. The workflow discussed here was implemented for designing and fabricating a prototypical modular floor panel using different sheets of waste cardboard combined with repurposed wood. The implementation shows that combining digital and analog tools can create a novel approach to material reuse, and facilitate a design/fabrication culture of *smart* reuse that supports informal building and making at recycling collection centers in developing countries for housing alternatives.

Keywords: Smart reuse · Waste cardboard architecture · Digital analog workflow · Parametric design

1 Introduction

The work detailed in this paper is part of a research agenda that is currently exploring technological methods and tools (from low-tech to digital) for upcycling waste cardboard that is taken directly from the urban waste stream in developing countries, and its reuse/transformation as a resource for architecture. The central thesis presented in this paper is that parametric and other digital design tools can help designers-builders negotiating with the material variability of waste cardboard. This first section of the paper provides an overview of precedents of cardboard architecture including a discussion of the challenges and opportunities of using cardboard as a building material. A brief review of digital design tools used for negotiating variable material is thereafter presented, describing the strategies adopted for this study. Next, in the methods section, the authors describe the workflow proposed for fabricating prototypical modular floor panels reusing sheets of waste cardboard. Finally, the authors analyze and discuss the outcome in the results and conclusion sections.

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1.1 Precedents of Cardboard Architecture in Research and Practice

A systematic review of the literature of cardboard as a construction material in research and practice reveals that the interest in the use of cardboard started in the mid-twentieth century. Nevertheless, it was not until the 1990s that cardboard architecture became noteworthy – especially in the work of Shigeru Ban. Figure 1 illustrates the number of related research publications and buildings that used cardboard products during the last seventy-five years. A possible explanation for this increment might be the emergence of Shigeru Ban's paper buildings in the 1990s and the establishment of research groups in relevant academic centers and universities in the 2000s – particularly Delft University of Technology and ETH Zurich. These research groups; strategically associated either with Shigeru Ban Architects, the paper industry, or engineering consulting companies, developed comprehensive studies on cardboard applications for architecture and structural engineering [1–7].

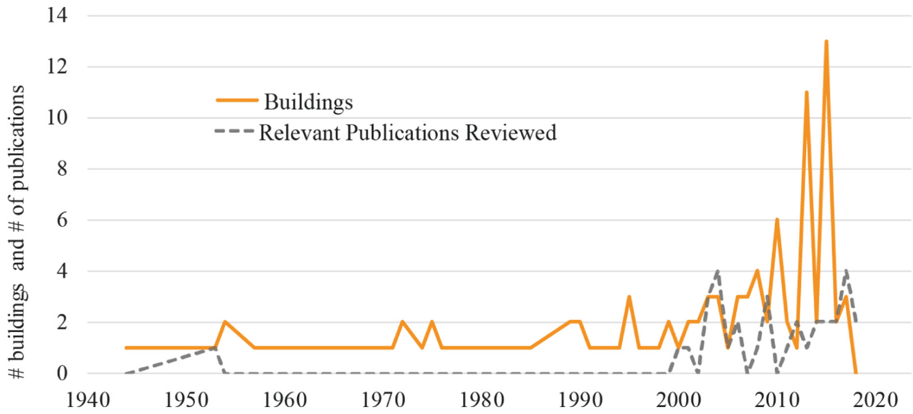

Fig. 1. Cardboard architecture in research and practice

According to the review, architects and engineers were and still are motivated by the eco-friendliness, relative strength, low-weight, and low-cost of the material. 56% of the reviewed publications mentioned cardboard as a sustainable product, and 32% included the reusability and recyclability of the material as an advantage for construction. Other aspects of cardboard products that stand out include the worldwide availability of the material, one that could facilitate a potential mass production system, its fabrication technologies, and its relatively sound acoustic and thermal insulation capacities.

Currently, there is a wide range of applications of cardboard products in building construction. The most common application of cardboard products – specifically paperboard, paper tubes, corrugated cardboard, honeycomb boards, and L and U-shape profiles – is in the fabrication of composite walls panels for walls (for both load and non-load bearing), floors, and roof. This application is found in short-span structures in small residential and commercial buildings. The second most common application, particularly for paper tubes, is for constructing arches, barrel vaults, domes, shells, and formwork for columns. This application is found in short and long-span structures. The most common type of buildings on which these applications are found are mostly temporary pavilions for exhibitions (26%), public buildings (26%), emergency shelters (21%), and housing and multifunctional buildings (15%) among others.

Overall, there has been extensive formal research into the use of cardboard products as a building material. However, the focus has typically been on brand-new and engineered cardboard produced by the paper factories, and geographically located in developed countries (50% in Europe, 21% in North America, and 17% in Japan) where the recovery rate of waste cardboard is very high – above 90% in North America, West Europe, and Japan [8]. On the other hand, waste cardboard has a different story in developing countries where it is commonly underutilized; the recovery rate is very low – barely above 60% in Latin American countries [8], there has been very little formal research about used cardboards potential reuse for designing and producing waste cardboard architecture.

The research described in this paper focuses on how a combination of digital and analog tools could facilitate reinserting waste cardboard collected from the urban waste stream in developing countries into a "smart" reuse process for housing alternatives. The work includes a case study developed in an academic setting that is intended to be tested in Asuncion, Paraguay, where the formal recovery system of recyclable materials including waste cardboard is deficient or non-existent [9], and there is a population that needs housing and cannot afford building using conventional materials.

1.2 Reusing Waste Cardboard – Opportunities and Challenges

Waste corrugated cardboard occupies a large volume of the residential and commercial municipal solid waste produced globally – particularly in urban areas – and it is also one of the least valuable products among all collected recyclables [10]. This situation, in addition to associated material advantages mentioned previously, presents an opportunity for the potential use of waste cardboard as a building material for the construction of affordable housing systems in places (cities) where cardboard is a common waste and the material is insufficiently recovered or recycled.

In some developing countries, for example, waste cardboard is commonly recovered by an informal network of self-employed collectors or "cardboard pickers" who eventually use this material for building temporary shelters. Although the material is highly available and almost free, the vulnerability of cardboard against the elements, and the lack of technologies and knowledge for processing and improving the material on-site, prevents pickers from using it for constructing long-term use buildings.

Upcycling waste cardboard, however, presents several challenges, ranging from advancing collection methods, improving the mechanical properties of the material – cardboard, for example, loses resistance to puncture and long-term loads – and improving its resistance to humidity and fire, to negotiating with the variability of the material for designing building parts (waste cardboard, as opposed to brand-new cardboard, is heterogeneous in size and thickness). In this paper, we present a design and fabrication workflow for upscaling waste cardboard as a building material, using digital tools to negotiate with the variability of the material. The goal is to fabricate building parts using sheets of waste cardboard that are taken directly from "the street". Additional aspects considered for this work were the structural limitations of the material and the potential constraints of the target context – urban areas in developing countries with little or no access to digital fabrication tools.

1.3 Incorporating Digital Design Tools

Digital design tools can be used for negotiating the variability of non-standardized or irregular materials in frameworks where the final design is conditioned by the existing material. One strategy is to incorporate material feedback in design and automated fabrication processes. An example of this approach is presented by Amtsberg et al. [11] were the authors developed a digital setup to adapt non-standard parts to a predefined geometry using 3D scanning and nesting tools. Other more theoretical studies explored flexible and adaptable systems to incorporate indeterminacy in materials and machine processes as an advantage for design [12].

Another group of studies developed parametric tools for dealing with the variability of reclaimed materials. Here the literature includes: parametric scripts that accommodate shifting dimensional variables in reclaimed materials for reusing lumber from an old barn to configure new building components such as building skins [13]; insertion of digital information into material system for reusing waste sheet manufacturing products into a flat-pack building system [14]; parametric scripts for designing foldable trusses made from sheet steel using two-dimensional CNC fabrication tools for minimizing waste [15]; and negotiating inherent irregular geometries with unconventional technologies – industrial robotic arms—for designing and fabricating large capacity structures made of forked tree limbs [16].

Together, these studies indicate that combining variable materials and digital design and fabrication tools requires a workflow that can adjust to the indeterminacies of non-standardized materials without compromising their efficiency, stability, and aesthetics. The main strategies adopted in the described studies, such as parametric tools for minimizing waste and design algorithms for accommodating the variability of reclaimed materials, serve as precedents for this study.

1.4 Proposing a Hybridized Digital/Analog Workflow

Our study proposes a digitally-aided workflow for both designing and fabricating cardboard architectures using waste cardboard. The digital tools developed with this workflow aid the materialization of the cardboard elements using analog means. In other words, while the design part of the workflow relies on parametric design tools, the fabrication process is very much manually made, using (common) low-tech tools. With this combined use of digital and analog strategies, we argue for the need to develop decentralized and accessible fabrication tools that are to be physically associated with recycling environments, where the access to automated machinery might be limited.

In this context, we propose a hybridized digital/analog workflow to support the design and fabrication processes of building components made with waste cardboard in combination with other standard building materials – primarily repurposed plywood or particle board. Our workflow was designed to be applied in a recycling environment in a developing country. The novelty of this approach relies both on the use of waste material (waste cardboard collected from the urban waste stream as opposed to brand new cardboard provided on demand by paper manufacturing companies) and the methodology – incorporating digital design and fabrication tools into the workflow combined with low-tech methods and tools.

2 Methods

As explained in the introduction, the proposed workflow relies both on digital and analog strategies. In the workflow, we use parametric tools for helping design with non-standard building materials and for providing materialization instructions for fabricating cardboard architectures. Previous studies have also used parametric tools for aiding materialization processes. For instance, Çapunaman et al. [17] developed computer algorithms in Grasshopper for Rhino to generate patterns for (hand) making three-dimensional objects previously modelled using CAD software. Another study used parametric design tools for creating templates to help materialize a parametric wall using low-tech masonry techniques [18]. These studies demonstrated how computer algorithms and parametric tools can help translate design from digital environments to fabricated elements, by providing materialization instructions and guides rather than fabrication technologies.

As a proof of concept, a case study was developed (in an academic) setting where we repurposed sheets of waste cardboard collected from a university waste stream, in combination with common, repurposed wood and conventional hardware for producing a prototype of a modular floor panel. The floor panel consists of a "sandwich structure" comprised of two particle boards sheets with a core made of structural ribs that are fabricated with folded sheets of repurposed waste cardboard. What follows is a description of the workflow, detailing the tools developed in each step.

The workflow, illustrated in Fig. 2, includes (1) **material collection**; (2) the **documentation** and inventory of the collected sheets of waste cardboard; (3) **digital design tools** for designing the panel with structural ribs of waste cardboard, adapting available material to the designed component, and for providing materialization instructions; (4) **fabrication** of the structural ribs of waste cardboard using digital and analog tools to produce the floor panels; and (5) manual **assembly** of the floor panels. Through the implementation of a workflow for producing simple building components made of waste cardboard, this paper provides a reflective account of digital and analog techniques for reusing and upcycling common waste into building elements.

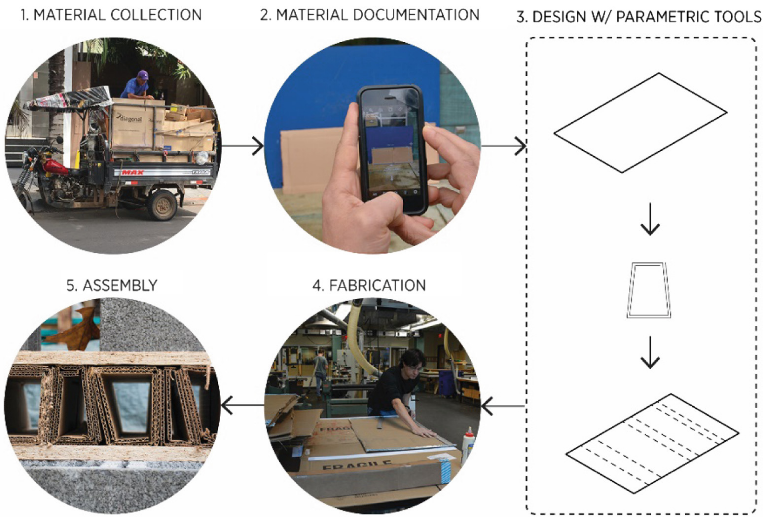

Fig. 2. Proposed workflow

2.1 Material Collection

The first step, ***material collection***, involves recovering and sorting sheets of waste cardboard that are not contaminated with food or medical waste, wet, and torn. This process is intended to be developed in association with waste collection systems available in the local context. For instance, in Asuncion, Paraguay – where we are planning to apply this workflow – the municipal collection system does not segregate neither residential nor commercial waste sending everything to landfills. Consequently, the recovery system of common recyclable materials, including waste cardboard, is dependent upon the work of self-employed collectors who harvest recyclables from the streets (Fig. 3). According to Medina, an specialist on informal recycling in the region, these unofficial collection systems "have been essential for the paper industry in Latin America" contributing to increasing the recovery rate of waste cardboard in, for example, Mexico and Brazil (see p. 21 in [19]).

Fig. 3. Self-employed collectors in Asuncion, Paraguay

In Paraguay, however, recycled cardboard only contributes 30% of material to the local production of new cardboard products and, according to a representative of the largest paper factory in the country, there are no expectations that this amount will grow in the near future [20]. Consequently, waste cardboard has the lowest value among local recyclable materials and collectors receive only between 5–10 cents (US Dollars) for each kilogram of recovered waste cardboard. We can compare this to at least double the amount for white, color or mixed paper, and ten times more for aluminum [21]. In an effort to imbue both collecting waste cardboard, and the material itself with more value, we are proposing that this workflow could support upscaling waste cardboard as a recyclable with a combination of digital and analog tools.

2.2 Material Documentation

The second step, ***material documentation***, is shown in Fig. 4 and it consists of recording the dimensions of the recovered sheets of waste cardboard. The documentation is made by assigning an identification number to each sheet (variable a) and recording its length (variable b), width (variable c), and thickness (variable d). The scanning process of these variables is made by the user, employing a smartphone with a common tape measure application. In this research, we used a mobile app called *EasyMeasure* – as smartphones are widely available in the deployment context and this application is very inexpensive.

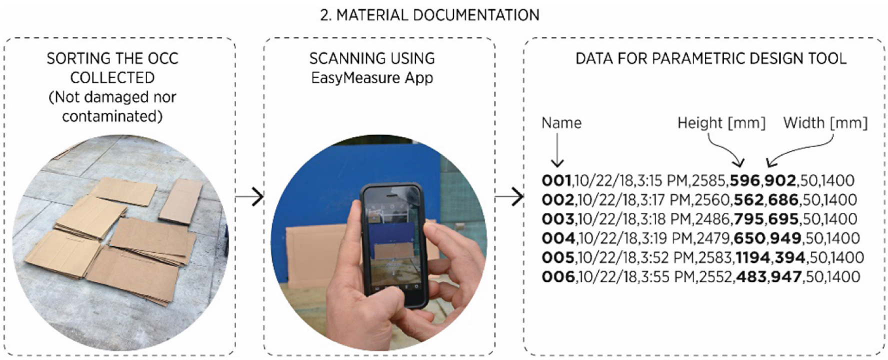

Fig. 4. Material documentation process using the *EasyMeasure* mobile app

The user simply places the sheet on a board and records the first three variables using the camera of the phone. The thickness is taken manually using a regular tape measure or similar measuring device. The material information recorded using the application is then exported to a text file, and this data is imported into a parametric script (detailed in the next section). The script selects the data needed from the text file and excludes all other information provided by the application that is not required. This documentation procedure automates the creation of a database that in turn facilitates the next step of the process when the designer needs to choose the appropriate sheet(s) of waste cardboard for the building component needed.

2.3 Designing with Digital Tools

The material documentation provides all the information needed for the next step in the framework, where we use ***digital design tools*** to produce a prototypical modular floor panel using a parametric tool, and for providing materialization instructions for the next step. The parametric design tool is a script developed in the Grasshopper plugin for Rhinoceros. The script facilitates the design of building elements with cardboard pieces of different shapes and thickness, where the final design emerges in the interplay between the constraints set by the user and the shape of the material that is available. The script allows the user to define limits to the solution space of the waste cardboard elements to assess different configurations with the aim of maximizing material reuse. The digital design tool also automates the generation of materialization instructions; cutting and scoring paths for geometries that are necessary for the fabrication process, according to the configuration of the building element.

Figure 5 illustrates the logic of the parametric design tool. The inputs for the script are the dimension of the sheets of cardboard obtained in the documentation process, and a group of design variables established by the user. The variables defined by the user (user input) are the thickness of the cardboard sheet, the minimum and maximum values for the dimensions of the cross-section of the waste cardboard rib, the profile type, and the number of cardboard walls each profile has. The cross-section of the profile can be either quadrangular, rectangular, trapezoidal, or triangular. The length of the waste cardboard ribs is also defined by the user, as per the desired width of the panel and the available material.

Based on the variables and input described above, the algorithm creates a series of possible profiles and automatically selects the appropriate profile for each cardboard piece available, so as to maximize material reuse. The algorithm outputs a preview of the panel by placing the selected profiles side by side until completing the desired length of the panel. The algorithm also produces scoring and cutting paths on each one of the sheets of cardboard and places tag names to identify the sheets facilitating the work during fabrication. The script also shows the amount of waste for each design iteration.

The user can then read (on each sheet) the amount of waste in millimeters and if it is deemed as an excessive amount of waste, the user can adjust the user input variables and redesign the profiles. This step can be repeated as many times as needed. Simply put, the user designs with the digital tool, adjusting the parameters and assessing how much material is wasted, in an iterative design process.

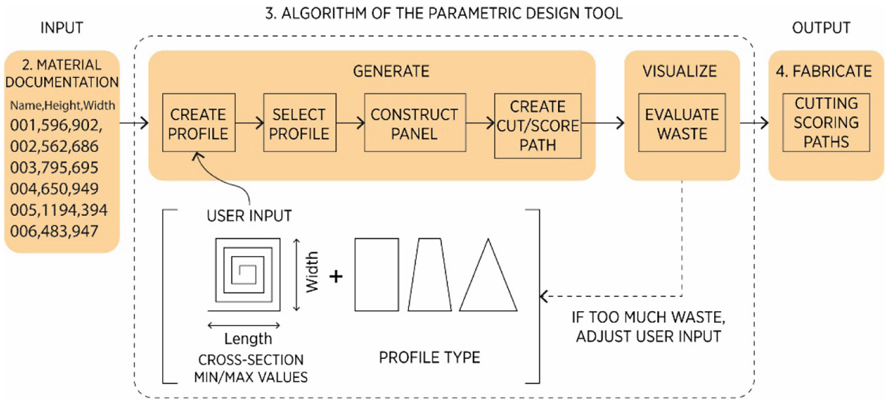

Fig. 5. Logic of the parametric design tool

Figure 6 depicts how the script creates a preview of the panel showing the flat (unfolded) waste cardboard ribs with the scoring paths and the waste generated by the design. The output of the parametric script are the materialization instructions, in the form of cutting and folding path geometries that can either be printed out as templates in paper, or simply be the geometries used to laser-cut the pieces. The workflow continues with the fabrication of the waste cardboard ribs and assembling the panel.

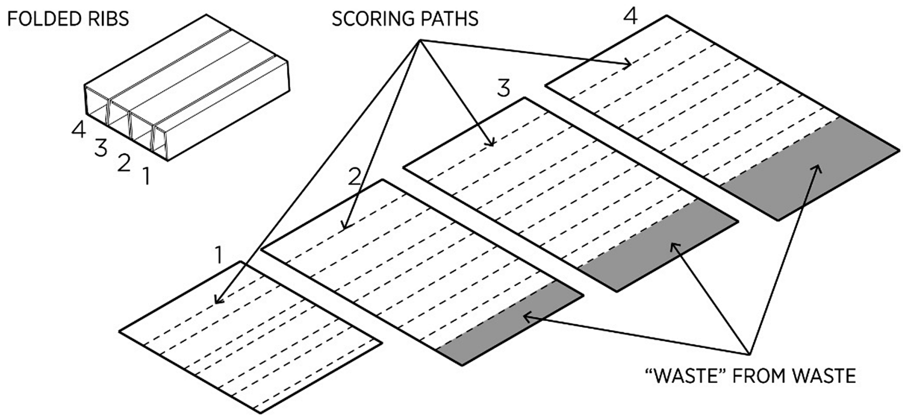

Fig. 6. Visualization

2.4 Fabrication of Building Parts

The third step, the ***fabrication*** process, combines digital information obtained from the previous step and analog fabrication methods associated with cardboard construction, such as scoring, cutting, and/or folding, aiding the user in producing the building components needed. At this point, the cutting and scoring paths obtained with the digital design tool need to be translated onto the cardboard pieces. Different methods can be used at this point: translating the scoring and cutting paths using printed templates, or directly laser/drag knife cutting the cardboard pieces. Figure 7 illustrates how the translation can be done with the help of printed paper templates generated by the script. Using a cutting surface, the paper template is positioned accordingly by the user as a guideline for cutting and scoring.

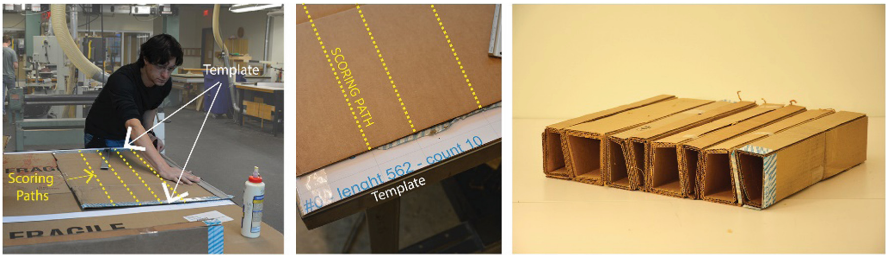

Fig. 7. Fabrication process

2.5 Assembly of Building Parts

The last step, the ***assembly*** of the panel, is realized manually using hand and power tools. The plywood/particle board is placed on top of a flat surface and the waste cardboard ribs are joined to it using a water-based adhesive. Then, the second particle board is placed on top and the panel is clamped until the adhesive is completely cured. Depending on the humidity level, the panel can be ready in between 60 to 120 min. The waste cardboard ribs can be randomly placed by the user, as the profiles are designed to have the same angle. In future studies, we intend to optimize the placement of the profiles in the panel, arranging the different profile sizes to improve the mechanical performance of the cardboard elements.

3 Results

As a proof of concept, we implemented the workflow in an academic setting for designing and fabricating a floor panel. The panel (Fig. 8) was designed to be 2400 mm long, 450 mm wide, and 150 mm high, resulting in a sandwich structure of two particle board sheets with a core fabricated from thirty-five folded sheets of six different dimensions of repurposed waste cardboard. The finished panel is intended to be moved/placed by two people. The panel is supported by two joists running on the longest side of the panel. The folded sheets act as structural ribs and they are oriented in parallel to the width of the panel and perpendicular to the joists. The particle board sheets and waste cardboard ribs are joined using a standard and inexpensive water-based adhesive.

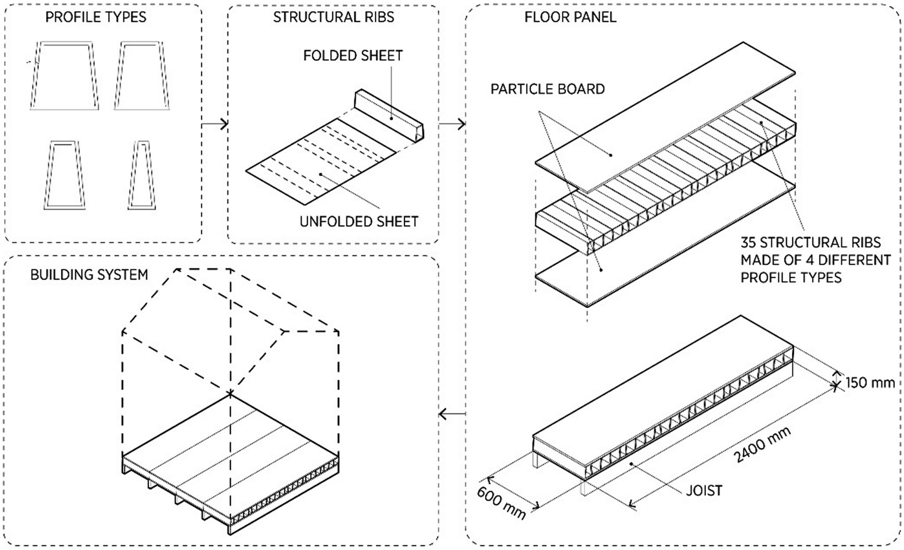

Fig. 8. Prototype of floor panel

The material collection process consisted on recovering sheets of waste cardboard from the university waste stream. We collected around forty sheets of waste cardboard, of six different dimensions, in a couple of hours in a common week day and, as mentioned above, we use thirty-five sheets for building one single floor panel. Although the reusing rate for this experiment was very high (almost 90%), we did not quantify the numbers of sheets found that did not qualify because they were contaminated, wet, torn, or were not large enough to be use as structural ribs.

The material documentation was effortlessly made by one person using the *EasyMeasure* app. We had fifty-two waste cardboard pieces of six different dimensions; the creation of the database helped in organizing and processing this information. The margin of error of the app – roughly 2.5 cm – is considered acceptable since it does not significantly affect the final dimensions of the panel profile. The app creates a database as a *.csv* file that is imported into the parametric script. Rather than manually entering the information into the parametric model, the proposed method facilitates and speeds up the recycling process by automating the creation of a database. The documentation process could also be done manually. However, the availability of smartphone applications for measuring surfaces or perimeters and its accessibility make this a viable alternative for automating the process.

The parametric tool was successfully used to design the panel as to maximize material reuse. Overall, the reusing rate of the each one of the thirty-five sheets was above 90%. The designed panel has four different dimensions of trapezoidal rib profile types, ranging from very thin ones used for the small pieces of waste cardboard, to thick profiles for the larger pieces. All the profiles have at least two cardboard walls as minimum thickness. To improve mechanical properties, this wall thickness could be increased to three or more. In this case, the cardboard pieces were not long enough to do so. One interesting aspect we discovered is that, while the parametric tool automates the creation of the profiles, the visualization of the panels, and the cutting-scoring paths, the user still is very much in control of the design process. The user defines the solution space and conditions the outcome of the system, optimizing the design so as to use as much material as possible.

In the illustrated workflow, we fabricated the panel using printed paper templates to translate the cutting and scoring paths, a utility knife and a cutting edge. Although this process can easily be made using a large laser cutter machine or a sample maker machine with a drag knife (commonly used in the packaging industry), we decided to keep the process as simple as possible considering that the access to such technology will not be easy in a context of scarce resources. Therefore, the tools used for cutting and scoring were very conventional and common. An alternative digital way for translating the scoring/cutting paths on the sheet of waste cardboard could be using virtual superimposition methods to replace templates or standard set up and measurement systems as seen in [22].

Finally, to have an idea of the structural performance of the panel, we performed an empirical load resistance test (Fig. 9) placing concrete blocks on top of the panel, taking into consideration the standard uniform live load used for residential floor designs, which is around 195 kilograms per square meter. After loading, we measured the deformation and the relative humidity levels over the course of several days. Although the waste cardboard used for building the panel did not have any protection against humidity, the panel did not show substantial deformations; however, further tests are needed to have a complete characterization of the panel's mechanical properties.

Fig. 9. Empirical load resistance test

4 Conclusions

This paper presented a workflow for upcycling waste cardboard using digital and analog tools. We propose a method for reusing waste cardboard – rather than 'new' cardboard—as a building material. The novelty of this approach relies on using digital design tools to "inform" and upscale a waste material for fabricating building elements; waste material that otherwise would be used only for producing new cardboard, or filling landfills.

Generally speaking, in the presented case study, the use of waste material with its heterogeneous nature is not evident in the resulting aesthetics of the constructed building part. Although this is not required, highlighting the heterogeneity of the material could enhance the overall aesthetics of the architecture. A variation to this approach would be to use algorithms to design a more heterogeneous building element where the formal configuration indicates the existence of materials of different sizes and thicknesses. Further studies for different application will explore this alternative. The described approaches are schematized in Fig. 10.

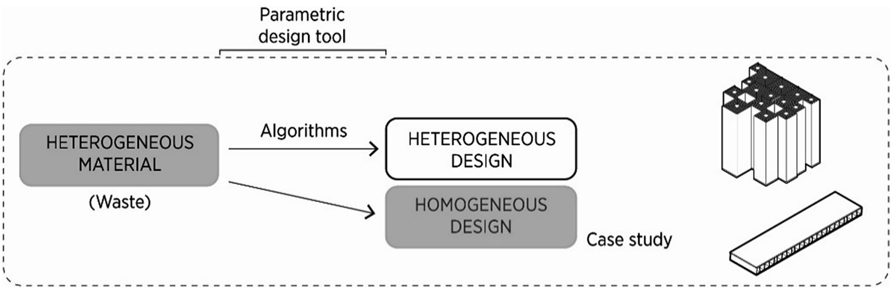

Fig. 10. Proposed approach for upscaling waste material

The reuse rate of sheets of waste cardboard for this experiment was very high (90%). However, the percentage of waste cardboard that did not meet the conditions required for the experiment was not measured. Further analysis in this aspect is, therefore, an essential next step in confirming the real impact of the project in the recovery rate of waste cardboard.

The material documentation method, using the mobile app, allows for the rapid creation of a database that is imported into a parametric model. Although the margin of error of the measurement app is around 2.5 cm, this is still acceptable considering that the edges of the sheet of waste cardboard need to be trimmed. Additionally, the proliferation of smartphones, and the low-cost and user-friendliness of the app allows almost everyone to use the tool.

The design phase of the workflow makes the process faster and more precise, giving inherent "smartness" and new value to the collected waste cardboard pieces. The algorithms of the parametric tool help transform a waste material that has variable shape and form into a relatively conventional construction component, in this case, a floor panel. The design tool also helps translating the cutting/scoring/folding paths from the digital to physical by offering printable templates that can be used without the need of a computer. Although the parametric tool works satisfactorily, the only parameter that it provides the user with for evaluating the different design iterations is how much material is wasted. Further work is required to incorporate other evaluation parameters into the parametric tool, such as an indication of the designs' mechanical performance.

The fabrication phase can be adapted to the available resources of the target context: urban areas in developing countries. The fabrication can be done either by translating the digital information into the physical realm with the use of templates – this would be the simplest way – or by using laser/drag knife-cutting machines to cut and score the cardboard pieces in situations where these tools are available. Parts of the workflow are automated, such as the creation of the database and the generation of cutting and scoring paths. Nevertheless, the automation does not mean relinquishing control over the design outcome of the cardboard architecture. Rather, the digital tools are conceived as to make the design and fabrication process faster and more efficient.

On the other hand, since cardboard is essentially a packaging material, more work could be done to determine the compatibility of the proposed tools with existing structural packaging design and fabrication tools. The existing standardized methods for fabricating packaging components and its associated tools could help inform more efficient design-fabrication workflows for repurposing waste cardboard.

Finally, the application of the workflow proposes that the combination of digital tools – increasingly ubiquitous around the world and more affordable as they proliferate – and analog tools to create a novel approach to material reuse, producing architectural and structural elements while simultaneously accommodating for waste cardboard's inherit material indeterminacies. We argue that methods that can record, and accommodate for, indeterminacies in (found, collected) waste materials will facilitate a culture of *smart* reuse that supports informal building and making at collection/recycling centers.

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