BUILDING FROM WASTE CARDBOARD

A Grammar for the Design and Fabrication of a Customized Modular House with Waste Cardboard and Wood-framed Panels

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Abstract. The project presented in this paper is part of a research project that investigates the reuse of waste cardboard as a building material for low-cost housing. The study combines craft-based production and digital-based tools. It implements a shape grammar formalism as a tool for structuring the design of a modular, customized house, including the generation of fabrication instructions for some building parts. In this paper, we present an implementation of the grammar for designing the floor plan of a single-story house.

Keywords. Material Reuse; Waste Cardboard Upcycling; Shape Grammars; Modular House; Sustainable Architecture.

1. Introduction

Waste corrugated cardboard is one of the most significant components found in the urban waste stream, and it is among the least valued recyclable materials. Waste cardboard is usually underutilized in developing countries where if it is not recycled for producing more cardboard, it ends up in landfills or dumpsters, increasing the impact of humans on the environment. In Asuncion, Paraguay–the case study for this project, for example, recycling rates are one of the lowest in the region–below 5% according to (IADB 2015); therefore, the implementation of novel and more sustainable methods for upcycling urban waste is critical.

Precedents of cardboard architecture occur in both research and practice. Since the 1940s, many investigations have analyzed and documented the many advantages and potential applications of cardboard products as building materials. Some of the most prominent studies can be found in (Eekhout et al. 2008; Pohl 2009; Salado 2011; Latka 2017). Following the same direction, in the last three decades, architects and structural engineers have experimented using cardboard products for humanitarian purposes–being the work of the Japanese architect Shigeru Ban the most noticeable in this area (Luna and Gould 2009). However, most of these works focused on using brand-new cardboard products, and little research has explored alternative applications of the waste cardboard that self-employed collectors recover from the streets in developing countries.

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The project presented in this paper is part of a research that investigates alternative use of waste cardboard as a building material in developing parts of the world. The research includes: (a) experimental tools combining craft-based and digital-based methods for designing and prototyping building elements with waste cardboard–e.g., acoustic panels, concrete formwork molds, and wall panels (Diarte et al. 2019a, 2019b); and (b) hands-on work with waste cardboard collectors in Paraguay testing the feasibility of the workflow for building a prototype unit with panels made of waste cardboard and plywood (Diarte 2020).

This project aims to advance this research agenda and to continue building upon previous investigations on cardboard architecture by proposing a modular building system for housing that apply wall panels made of waste cardboard sheets and wood framing. The system uses shape grammars as a tool for (1) formalizing the design system of a customized modular house typology based on local precedents; (2) developing a structural system of the house; and (3) proposing a fabrication system that generates the fabrication instructions for producing the waste cardboard panels.

2. Practicalities of the Material

The research focuses on the waste cardboard that is collected from the urban waste stream by self-employed collectors in the metropolitan area of Asuncion, Paraguay. Material parameters include variability of size, thickness, and quality. However, the project uses only the waste cardboard that not contaminated with food or medical waste, wet or torn. After selection, the sheets are organized by size and thickness and documented. A construction workshop held in Asuncion in August 2019 and published in (Diarte 2020) showed a high percentage of waste cardboard reuse–80% of reuse rate from a total 1.2 tons of collected waste cardboard-for building a prototype unit of 11.3 m2 with panels made of waste cardboard sheets and plywood. This project follows the same criteria for material assessment.

3. Design Principles of the Modular House

The definition of the archetype for this house was based on the “sausage-house” typology. This is a traditional urban house typology found in Asuncion that is a derivation of the porch-house. This typology has its roots in the Spanish colonial tradition, and its design and materiality have been successfully adapted to the climate and local culture, according to Gutierrez (1983) and Morra (2000). The typical floor plan of a sausage-house follows a succession of rooms containing the public and private areas along a corridor facing an interior patio. The depth and articulation of these spaces may vary in different cases, but in general, they are built in narrow and deep lots. Another reference used for defining the housing system was the regulation regarding the design of social housing in Paraguay. (SENAVITAT 2011).

The house developed for this project have three sub-systems: (a) the foundation or plate consisting of shallow foundations of reinforced concrete square footing or bricks masonry. The foundation or plate will help to adapt the house to moderate slope situations and terrains with high humidity lifting the construction above the existent ground level; (b) the envelope, which consists of load-bearing and non-load bearing wall panels made of waste cardboard and wood frames and reinforcements; and (c) The roof made of conventional corrugated metal panels with wood or steel trusses. The shape grammar presented in this paper supports the design of the sub-system b.

The modularity facilitates adapting the house to different situations. The system works by addition or subtraction of modules, offering the alternative of customizing the floor plan of the house. However, the modules are limited to variations of squares and rectangles. This concept facilitates the production, transportation, assembly, and, more importantly, incremental construction that is critical in urban areas in developing countries. If the system, based on modular and dry construction, is easy to understand and practical to execute, the owners would be able to build using fewer resources and technical assistance compared to traditional masonry or concrete framing. An easy disassemble process could allow reusing the components and reducing waste in case of transformations or demolition.

4. Methodology

The project implements a shape grammars formalism as a tool for structuring the design and fabrication of the building parts for the envelope of the house using waste cardboard and wood frames. Shape grammar is a ruled-based algorithmic system used to create and understand designs through the computation of shapes and to define design languages (Knight 1989). This methodology has been extensively used to depict the construction logic of existing architectural elements as well as to generate new designs. The literature includes examples of modular systems (Duarte 1993), housing (Duarte 2005; Benros et al. 2011), masonry wall types (Vazquez 2017), among others. This project builds on this existing body of knowledge and proposes a novel application of shape grammars to describe the design and fabrication of cardboard architectures with the goal of upscaling a waste material. Table 1 illustrates the structure of the grammar for better understanding. This paper first describes the proposed shape grammars, and then we provide an initial validation of the grammar by an internal test through the design of a house.

Table 1. Structure of the Proposed Grammar.

Stage	Design Grammar	Rules	Fabrication Grammar	Rules
1	Lot Definition and First Room Placement	0 and 1	Walls Reinforcement Placement	8.1 to 10.5
2	Spatial and Structural Grid Design	2.1 to 2.8	Wall Panels Floor Plan Configuration	11 to 12.2
3	Function Definition	3.1 to 7.4	Wall Panels Elevation and Doors/Windows Placement	13.1 to 14.6
4			Wall Panels Construction Details	15.1 to 15.3

5. Modular Grammar

In *stage 1* of the *modular grammar*, the designer defines the size of the lot and places the first room (rules 0 and 1). The local regulation does not allow a lot with less than 360 m2 with few exceptions and establishes a width of between 10 m and 14 m. The program brief of this project includes a living room (12 m2), kitchen (8.5 m2), dining room (4.5 m2), bathroom (4 m2), master bedroom (15 m2), secondary bedroom (11 m2), bathroom (4 m2) and interior circulation (around 10% of the total surface). The next step is the placement of the first room in the lot. Rule 1 establishes specific parameters related to the size of the room-minimum width 2.5 m and maximum with 5 m-and its distance to the perimeters of the lot. For example, the minimum distance between the first room and the front limit is 3 m, and the minimum distance to the sides and back limits is 1.5 m.

Stage 2 of the *modular grammar* (rules 2.1 to 2.8) defines the spatial/structural grid of the house. This set of rules defines the spatial organization of the house. Stage 2 starts with the placement of the porch on the side of the first room and follows with the longitudinal growth of the house (rules 2.1, and 2.2). Lateral growth of the grid beside the placement of the porch is not allowed in this project. The rules also allow placing "gaps" in the grip to create small patios or to divide the house into two if necessary (rule 2.3). Rules 2.4 and 2.5 permit the designer to modify the grid by shrinking or enlarging a specific room. Rules 2.6 and 2.7 create subdivisions inside a room to give space for a corridor for internal circulation. Rule 2.8 integrates two adjacent spaces.

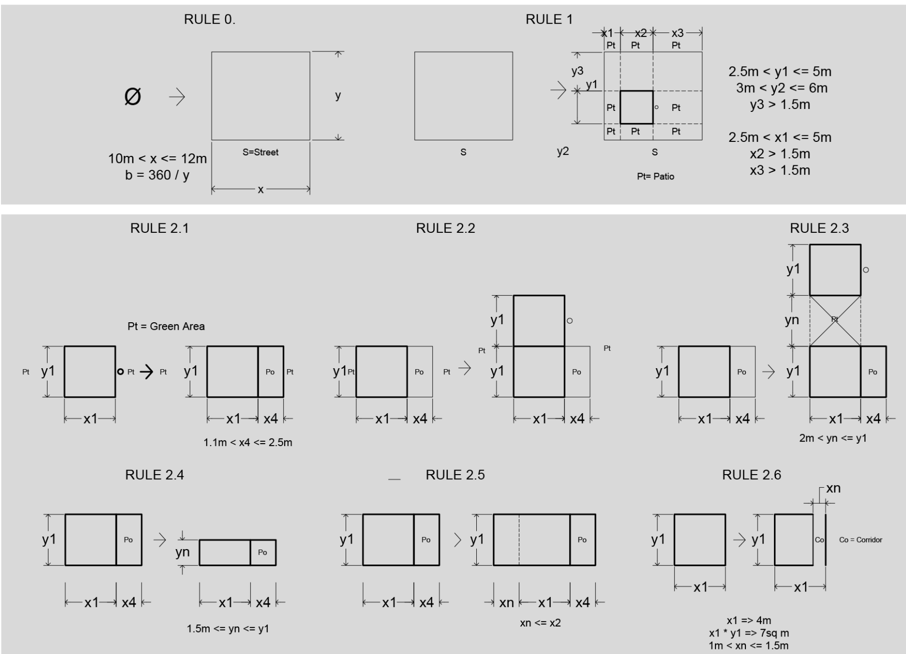

Figure 1. Partial rules for stages 1 and 2 of the modular grammar.

Stage 3 of the *modular grammar* includes rule 3.1 to 7.4 and deals with adding function to each one of the modules of the grid. This project considered five main functions: Living area (rules 3.1 and 3.2), kitchen (rule 4), dining area (rules 5.1 to 5.4), bedroom (rules 6.1 to 6.5), and service unit that includes the bathroom and laundry area (rules 7.1 to 7.4). The living area connects to the dining room and kitchen, and the bedrooms can be placed either in connection to the living or the kitchen. The service unit can be linked to a bedroom or a kitchen only. Take note that the porch goes along the house always, and eventually, part of it can be enclosed and transformed into a living extension, dining room, or bedroom extension.

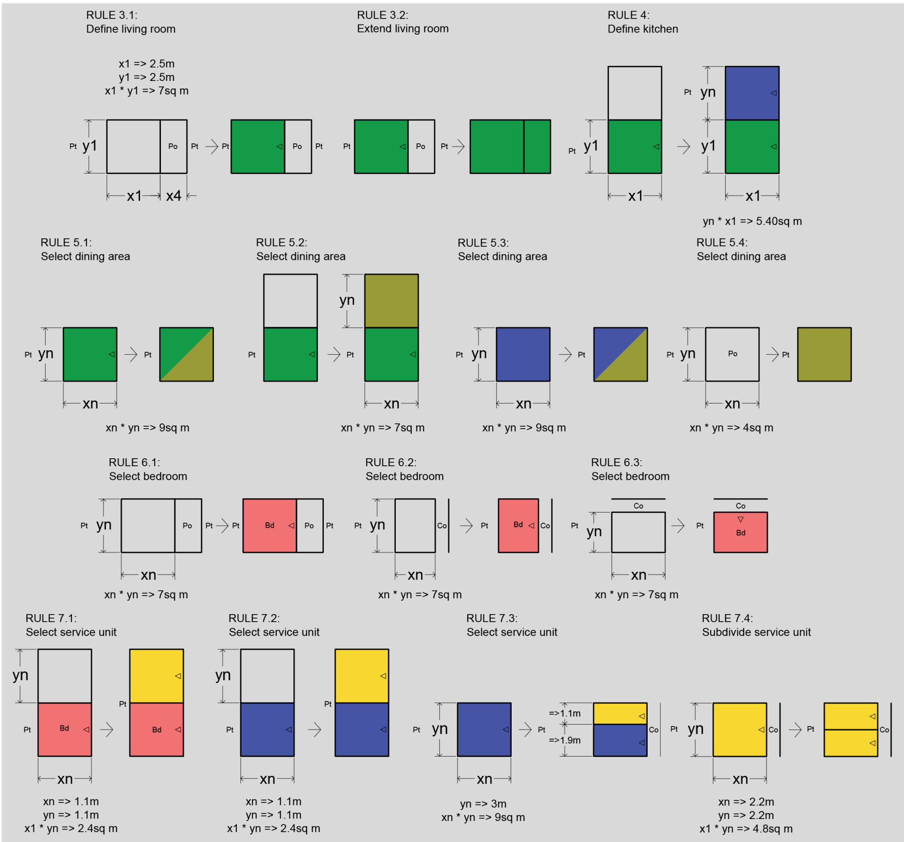

Figure 2. Partial rules for stage 3 of the modular grammar.

6. Fabrication Grammar

Stage 1 of the *fabrication grammar* focuses on the placement and definition of the columns for reinforcement (rule 8.1), definition of thicknesses of walls (rule 8.2), placement for doors (rules 9.1 to 9.5), and modification of the design of the walls (rules 10.1 to 10.5). The size of the columns depends on the material used; however, each side of the column can vary between 10-30 cm. The columns are placed at the intersection of the segments that form a module. The thickness of the walls varies between 5-20 cm, depending on the function of the wall. For partition walls, the thickness is between 5-15 cm, and for load-bearing walls, the thickness is between 15-20 cm. The placement and position of doors are restricted by the size of the room and the location of the corridor next to the room. The modification of the walls allows the designer to integrate rooms to create larger spaces and to control the level of openness of the porch. The outcome of the first stage is a floor plan of the house showing the spatial and functional configuration.

Stage 2 of the *fabrication grammar* deals with the constructive part of the wall system. Rule 11, for instance, takes each segment of the wall between columns and subdivide it into panels. These panels can have thicknesses between 5-10 cm, 10-15 cm, and 15 and 20 cm. The thickness of the panel constrains its length, and this can vary between 0.25-0.50 m for the first category of walls, 0.50-1.0 m for the second category of walls, and 1-1.25 m for the third category of walls. Rule 12.1 and 12.2 control the placement and length of windows that can vary between 0.40-1.60 m wide and occupy the length of one or two panels. Stage 2 offers a detailed floor plan illustrating all wall panels of the house. Figure 3 shows some of the rules of stages 1 and 2.

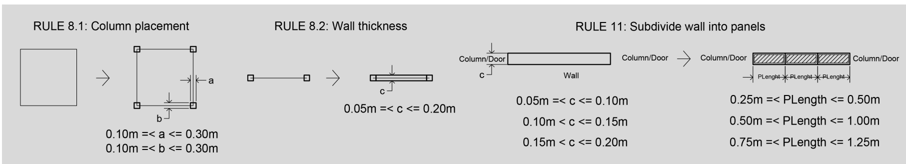

Figure 3. Partial rules for stages 1 and 2 of the fabrication grammar.

The rules in *stage 3* determine the elevation of each segment of the walls of the house. Rules 13.1 to 13.4 produce the elevation of columns, doors, and windows. The next group of rules (rules 14.1 to 14.6) take the floor plan of the panels given by the previous stage and produce the elevation of the frame that forms the panel. The dimensions of the frame vary depending on the condition of the panel. This project considered three situations: a panel between panels, the panel between a column and a panel, and the panel between columns. Constructively, the adjacent wall panels share vertical studs except when they are next to a window or door. Panels that are part of the windows or doors have their vertical studs.

Stage 4 includes rules 15.1, 15.2, and 15.3. These rules advance the details for the manufacturing of the panels. The goal is to subdivide the panels into triangular profile tubes using sheets of waste cardboard. These tubes are glued together to form the cardboard panels that will be used to fill and reinforce the wood frames. The criteria for defining the dimension of the triangular profile tubes rely on the thickness of the panel. Rule 15.1 controls this configuration and then rules 15.2 and 15.3 places and multiply the profiles until completing the total length of the wall panel.

The *fabrication grammar* concludes with the application of the parametric grammar presented in (Diarte et al. 2019a). The parametric grammar takes the dimensions of the triangular profile tubes and determines the cutting, scoring, and folding patterns to produce the tubes for the cardboard panels. The parametric grammar, in combination with the modular and fabrication grammar, produce the instructions for the fabrication of the cardboard panels. Figures 5, 6, and 7 show the rules 13.1 to 15.3.

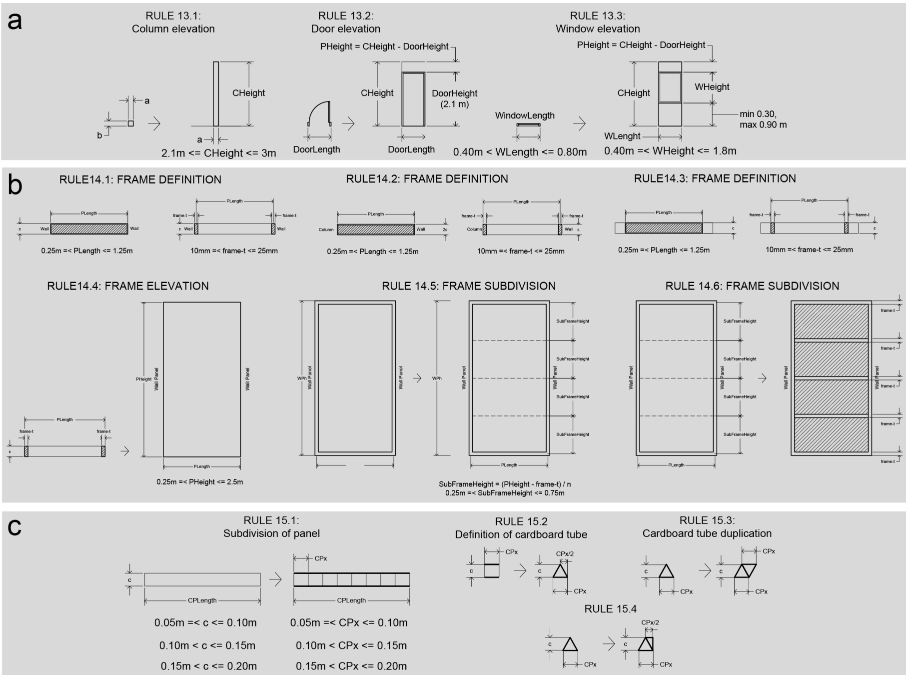

Figure 4. (a) Elevation rules (b) Frame design rules (c) Cardboard panel fabrication rules.

7. Results

The grammar was implemented to show possible design iteration generated with the rules. For this purpose, we produced the floor plan of a single-story house of 84.4 m2 for a lot of 360 m2. The design follows some of the criteria found in the sausage-house typology, especially the linear organization of the rooms along a porch facing a patio. However, certain aspects differ from the precedent, for instance, the separation of the house from the left limit of the lot–to allow cross-ventilation of interior spaces–and the partial occupation of the porch for extending the bedroom or placing the dining room. The outcome represents a variation of the precedent within the language of the original typology.

Some features that could be improved in the *modular grammar* are the following: First, the integration of the rules for designing the structural/spatial grid with the assignment of functions. An alternative for doing this is by having a library of pre-set spaces with the established minimum dimensions and in different configurations to help synthesize the design of the scheme for the floor plan. Second, the rules for modifying the grid can be useful for trained designers who use the grammar; however, it is not certain these rules can be helpful for non-designers who want to take advantage of the grammar for designing their own houses. Third, although the final floorplan presented in this paper can be considered satisfactory in terms of architectural qualities, the grammar does not prevent undesired outcomes, which is crucial for future computer implementation of the grammar. To control undesired outcomes is necessary to include more specific rules to restrict certain relations between spaces. Figure 8 illustrated the derivation of the rules of the *modular grammar*.

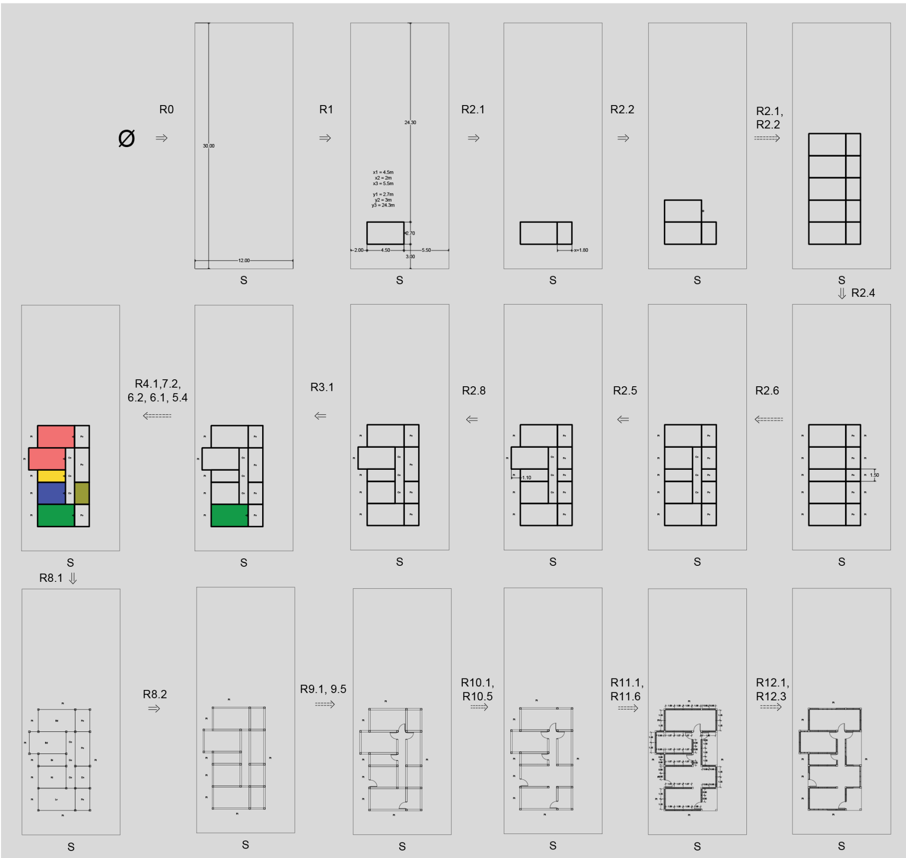

Figure 5. Derivation of rules of the modular grammar.

The *fabrication grammar* allowed for the definition of some construction details for the wall system and the outline of the facades, including wall panels, windows, and doors. The *fabrication grammar* also provided templates for cutting and scoring the sheets of waste cardboard. However, some details could be added to the grammar. First, the grammar facilitated the design of the floor plan of the wood frames and offers the elevations for each wall but still needs more rules that depict more clearly fabrication instructions. Second, the design and fabrication criteria for the interior and exterior facing of the panels are not included in the grammar yet. Third, a step-by-step assembly instruction process needs to be included to make possible the actual production of the building parts. Four, although the integration of the parametric grammar produced in a previous study is useful and contributes substantially to this project, we still need to test the integration of both systems. Further work will investigate the integration of both tools in a single case study. Figure 9 shows the derivation of rules of the *fabrication grammar*.

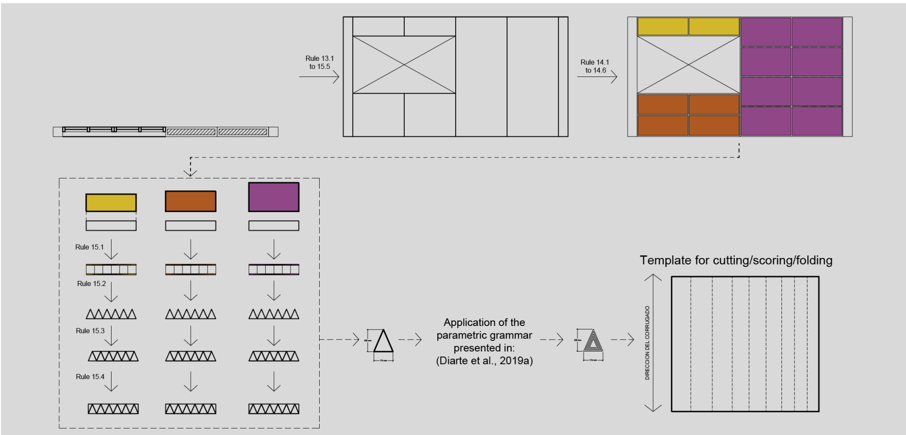

Figure 6. Derivation of rules of the fabrication grammar .

8. Conclusion

The work shown in this paper contributes to ongoing research aimed at developing tools and methods for upcycling waste corrugated cardboard. The outcomes include a grammar-based design tool for configuring modular houses and a set of rules for proving fabrication instructions for making wall panels made with wood and waste corrugated cardboard. Different types of rules were extracted in the proposed two-level grammar: design rules and fabrication rules.

The second section of this paper shows how the *modular grammar* and *fabrication grammar* can be implemented in the design of a house in the proposed typology. The proposed rules can conform to a rule-based generative system. However, further work will focus on testing the applicability of the grammar for different iterations of the typology and improving the fabrication instructions for the waste cardboard and wood-framed panels.

This project aims to contribute to providing methods for increasing the upcycling rate of waste corrugated cardboard in urban areas in low-income countries. We argue that waste corrugated cardboard–in combination with other materials–can be reused as an alternative low-cost and sustainable building material for people who needs housing but cannot afford using only standard building systems. By formalizing a modular housing system with the grammar, we propose a novel way of reusing waste corrugated cardboard, in the form of hybrid wood-cardboard panels.

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