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Digital Parametric Emergency Oriented Design — Case Study on City of Mariana, MG, Brazil

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Abstract: The work presented here was conceived considering the need for emergency infrastructural solutions for Mariana's environmental disaster. It is a conceptual prototype of an emergency shelter oriented by biomimetic principles and inspired by the fauna of cerrado that characterizes the Vale do Rio Doce, Brazil. Structural analogies were made with the Dasypus novemcintus specie creating an articulated shelter made of retractable flaps that interpenetrate when it opens and closes. The prototype was developed using a fusion of reflection in action methodology and parametrization, graphic programming and algorithmic computation entirely created in Rhino and Grasshopper generative modeling. The main intention of this work is to develop specific design technology to emergency scenarios such as Mariana's disaster but also to others types of critical events. The project allows many conceptual reflections such as the importance of social responsibility in architectural practice.

Key words: emergency design, parametrization, biomimetics, environmental disaster, social responsibility

1. Introduction

The tragic episode of the rupture of the ore tailings barrier of Fundão in Mariana, MG recently completed a year. The biggest environmental crime in the history of Brazil, committed by mining conglomerate Samarco/Vale/BhP, provoked an unprecedented impact on the ecosystem, compromising directly 660 km of rivers and more than 1.400 ha of vegetation, many of them inserted in areas of permanent preservation. In a broader view, the damage is much more extensive. This is because the concept of ecosystem comprises not only the natural resources, but the whole set of relations of interdependence that are linked to rivers and forests affected by the ore tailings, such as: fishing activity, agriculture, tourism and livestock. All of these activities are responsible for the maintenance of life of local populations. In other words, it is a social body which was also destroyed. This environmental crime broke abruptly many social relations and provoked an ecosystemic tabula rasa in the village of Bento Rodrigues, which was complete vanished from the map (Fig. 1). The president of the *Committee of the Hydrographic Basin of Rio Doce* Leonardo Deptulski said: "from the point of view of the actions of reparation and compensation, we have very little done so far" [1].

The impact of this environmental crime into the academic community was profound. Researchers from several areas were immediately mobilized to help the population. Many teachers reoriented their academic investigations to map the damages, to provide

Fig. 1 Photo from the district of Bento Rodrigues after the rupture of the barrier of Fundão in Mariana, MG[1].

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[1] http://brasil.elpais.com/brasil/2016/01/13/politica/1452723124_212620.html, accessed 25 Feb. 2016.

technical, social, economic and legal assistance in order to minimize the consequences of this brutal event. Despite the multiplicity of their research areas and competencies, it is precisely the synchronicity and coordination between these specificities which shall take effect in the recovery of the territories, populations and biodiversity. In the context of architecture comes into play an important subject: the architecture of emergency or emergency design. It is essential to contemporary architects to understand how to deal with the specificities of emergency design. The complex reality of contemporary world demands architects social engagement and a greater involvement with humanitarian issues.

2. Understanding Emergency Design

The world trajectory passes by countless natural or human-made disaster conditions that demand constant survival efforts. The emergency design emerged from these situations of extreme fragility and vulnerability. The concept of emergency design comprises a methodology dedicated to generate projects, plans and solutions as a response to natural or human-made disasters. Time, economy, urgency and multiple functions are some of the attributes that architects have to consider when designing emergency shelters and equipment. In Brazil, for example, the minimal requirements of spatial quality are regulated by legal codes such as 12.608/2012, but many more design and construction codes can be found around the world.

According to Lopes [2] there are two main situations that require emergency responses: (a) natural disasters and b) human-made disasters, such as wars, territorial conflicts, widespread violence and violation of human rights [2]. In both cases, it is possible to identify a significant number of professionals and organizations connected with emergency design solutions, expanding the availability of information, projects and actions in emergency situations. They represent a growing social engagement movement in contemporary architecture and design and calls attention to a problem presented by Victor Papanek [3] in the early 1970's and exacerbated over the past decades: the lack of social engagement of architects and designers. According to Papanek, the architect should spend more time developing projects in poor countries in order to learn more fundamental needs of living and improve the real meaning of their work [3]. In the same way, Ezio Manzini [4] alerts the architects to the problem of extreme low-quality houses built in underdeveloped countries. The conditions of living in these houses are aggravated by precarious urban conditions, poverty and segregation that configure a major issue in contemporary architecture practice.

It is possible to identify expressive number of architects dedicated to emergency design. One example is the publication Beyond Shelter [5] presented by Marie Jeannine Aquilino, a book that defends the idea that architectural knowledge has huge potential for emergency design in situations such as: prevention and adaptation of houses, mitigation of damages and environmental recovery. Based on the author's reflections it is possible to list four main aspects of architectural knowledge that are essential to emergency situations:

a) the relational knowledge, used to calculate best structural solutions for specific needs, budgets and resources;
b) the polyvalent knowledge, that allows architects to assume different roles such as designer, historian, negotiator, lawyer, helping and orienting the community to act by their own interests. Aquilino [5] highlights the extreme difficulty for the victims to successfully represent their own interests in a moment of weakness;
c) the improvisational knowledge [6], that respond to the ability of architects to develop real-time solutions with all kind of resources and materials available in the site to provide better access to water, sanitation, light and also

creating social spaces to restore proximity among the victims;

d) the visionary knowledge, that permits architects to imagine new possibilities in dead end situations. Calamity situations demand more than the emergency need for a refuge. It demands also the reconstruction of a whole set of living conditions such as the conscience of a new life, new relationships, new expectation for the future of the community;

An important part of this research is the analysis of emergency projects already drawn up by the moment. There is a significant list of design solutions with differentiated levels of complexity forming two major approaches: standardized tents provision or industrialized modulated solutions [7]. The Portuguese researcher Rita Friar alerts that, in some cases, such solutions generate a low level of acceptance from the perspective of the victims due the designer's disregard of the local context that includes habits, needs and cultural values of the affected population. The main limitations identified in these projects are:

a) the high cost of production face the narrow economic efficiency in the country affected;
b) the absence of participation of the victims in the configuration and appropriation of the space;
c) the inadequacy to climatic variations and social configuration;
d) the requirement for specialized knowledge for assembly;
e) the unfamiliarity with norms and principles of specialized humanitarian and local agencies.

These limitations become evident in projects such as *Shelter SES2* designed by Pete Manfield and Tom Corsellis (1998) or *Concrete Canvas* from Peter Brewin and William Crawford (2004). In the critical analysis of Frade (2012), these projects repeat in those simplified morphologies the same principles of the tents whose acceptance by victims are already low. Other solutions, such as *Shelter* designed by Elisa Mansutti and Luca Pavarins (2010) has less concern to the necessity of adaptability to different realities. Another recurrent problem is the requirement for specialized labor for assembly of projects, as occurs in the Red+Housing designed by Obra Architects (2009). It is important to highlight that, methodologically, the visuality in the design process must not overlap functional aspects. The *Hokai* project, designed by Lissa Saruhashi and Antônio de Biase (2017), and created in a workshop of Biodigital Architecture promoted by the BI/OS, reveals this methodological problem: it is a visually Apollonian project with basic problems in its closure system.

The emergency design process demands a correlation between variables and configurations due the complex nature of the problems. Nevertheless, there is still very few approaches that associate the emergency design and prototyping parametric modeling. The parametrization and rapid prototyping may be considered viable alternatives to assist emergency design processes. With the association of these techniques the design process gets more versatility to simulate, remodel, validate and manage the possible solutions through the rapid creation of digital-to-physical models. It makes tangible many problems and makes visible countless possibilities of changes, improvements and optimizations.

3. Metaprocessual Parametric Design

The intention to draw up a proposal for emergency shelter associating parametrization and prototyping is focused on two key issues: a) to add environmental and architectonic quality to shelter solutions in emergency situations and b) to develop and to share specific design intelligence for disaster situations, including directions that may be appropriate for different people and organizations involved with these problems. Emergency projects, as well as many other complex projects in architecture, demand many cycles of reflection during the design process. Complex studies in architecture presented by Schumacher [8] e Fischer & Giaccardi [9] reveal that the remix of all variables involved in complex problems are best understood during the effort to resolve them. In other words, the applied and continuous thinking has considerable potentiality to deal with complexities. The continued experience of design thinking and problem-solving produce, after many cycles, what Speaks [10] calls design intelligence. The design intelligence can be understood as the unique set of techniques, relationships and provisions that can be produced during complex processes of project that does not fit into a broader methodology [10]. Parametric techniques can be used as interfaces to territorialize the design thinking in complex problems situations. Parametric interfaces that uses graphic programming such as the Rhinoceros plugin Grasshopper have shown many positive features to territorialize architect's thinking, helping them to test, adapt and configure the design solutions.

The conceptual proposal presented in this paper derives from a procedural parametric position in order to learn, discover, propose and test how the variables of a emergency design problem may be articulated into a graphic programming interface. The idea is to install many cycles of reflection-in-action, combining parametric design and rapid prototyping, and systematize a parametric design intelligence for emergency shelters. In the first place is important to list the constraints of emergency shelters considering international regulations published by Esfera:

a) minimum space required per person: 3.50 square meters;
b) minimum distance between floor and ceiling at its highest point: 2.0 m;
c) provide internal separations to ensure privacy and safety to the occupants;
d) involve local communities in the implementation of the shelters.

There are complementary urban regulations that specify the recommended number of shelter units in each agglomeration, the organization and disposition of the groups, strategies of supply and the duration recommended until the beginning of reconstruction. The attention to these regulations are not included in the scope of the project presented here because the focus is the design process of each specific units.

The design process was oriented by parametric reflection-in-action methodology. It is guided by the direct involvement between the practical experimentation and the production of knowledge in continuous and recursive cycles. Intermediate solutions were continuously tested and analyzed according its possible arrangements between shapes, materials, performance and aesthetics. The conceptual programming structure of the shelter was developed using Grasshopper software.

In conceptual terms the Grasshopper interface can be understood as a digital and interactive field of investigation composed of many different elements mutually correlated [8]. They permit the creation of a metaprocessual condition required to operationalize the cycles of investigation and resolution of design problems. In practical terms, this metaprocessual condition support a design methodology capable of overcoming the simple repetition of elements to a more complex and gradual differentiation with variability. It also avoids the traditional modern and postmodern collage of isolated elements and the sectorization of functions to explore the communication and interdependence of design elements. Schumacher affirms that the evolution of the design research is necessarily linked to digital simulations of forms open to artificial modulation [8].

In physical terms, rapid prototyping machines were used to simulate and test the resistance, time production and adaptability of design solutions. The prototypes produced since the begging of the design process evolve always connected with concepts and theoretical ideas. This is a fundamental base of parametric reflection-in-action process: machines and thoughts engaged for the production of knowledge. The contribution of digital prototyping over traditional serial production is the custom production. Architects become apt to quickly generate differentiated objects, multiple versions of the same idea, enhancing the exploratory and experimental thinking and action in any design situation.

Rocha [6] argues that the openness condition established by metaprocessual design process introduce to designers and architects a richer evolutionary and exploratory journey with better opportunities for adaptation and evolution of the idea. According to him, it is a journey into the unexpectedness of the creativity process where indeterminate conditions of experimentation are essential to innovation and evolution.

This model of creation based on unexpectedness makes the design process similar to a collective jazz performance. Jazz musicians can perform a theme collectively in open manner for a long period of time, improvising together. It means that they can navigate and explore uncertainty and unpredictability in creative mode based on two basic points: their individual knowledge and the awareness of context [6]. It is a example of a situation where theory and practice are inseparable, flow together and evolve into parity. We can say that metaprocessual parametric modelling has a improvisational condition on it.

The parameterization of many structural elements in the design of the shelter improve cycles of reflection and action and assists the formation of a more integrated and relational view of the project. For example, the width and length ratio could be continuously redefined to accommodate different functional demands. The implications of changing one measure of the shelter could be seen in the overall form instantly and this feature brought a flexible metaprocessual condition to fit the project into different contexts and without compromise international regulations. In the future, the metaprocessual parametric design can be uploaded to the internet and be shared with others researchers and architects in order to be updated, improved and adapted to local realities. The shared condition of the design is an important element to decentralize the conception of artificial structures and upgrade the design intelligence of shelters and small living spaces.

4. Biomimetic Surfaces and Structures

Materiality and 3d printing techniques have a strong connection in contemporary architectural design. The use of 3d printing techniques associated with parametric processes allow architects to explore new relations in the materiality of form. These relations come from the articulation of two main elements: the complex geometry of forms and the new types of organic materials that can be used as filaments in 3d printing machines. A important research field to inspire architects in the journey of new material-geometry relation is biomimetic. Biomimetic is a design approach useful to discover adaptation strategies used in nature that can be used to design forms and architectural elements. The diversity and complexity of organic geometric patterns found in nature have a strong potential in the design of artificial complex surfaces and structures. The rich combination of forms and materials can be simulated and fabricated using parametric modelling and rapid prototyping machines. The improvement in digital fabrication techniques brings a new design intelligence with focus on low environment impact, biodegradable materials, on demand solutions and recycling processes. According to Keating and Oxman [11] the new paradigm of this century manufacture is the coherent, durable, responsible fabrication that will face the challenges of non-polluting materials that helps to conserve natural resources. The paper will explain briefly how biomimetic was used in shelters conception and next discuss the use of new materials in 3d printing fabrication process.

The initial reference for the conception of the temporary shelter was inspired by biomimetic. The criteria used to search biomimetic references were: a) to find organisms configured by equivalent formal elements but with small differentiations between them;

b) to search organic mechanisms that allow structural compression and expansion; c) to identify organisms that belongs to the characteristic biome of the areas where the environmental crime occurred. The *dasypus novemcintus* was the organism that showed more similarity with the demands of the conceptual design. It is an armadillo found in Brazilian *cerrado* and has a shell formed by a series of moveable convex shape plates the fits one with the other and provide mobility, flexibility and protection to the animal. The plate outer structure of the animal has nesting properties that allows its body to become more compact or more expanded. This compression-expansion arrangement is a necessary feature for emergency shelters in order to respond to the demands of transportation and assembly. The beta version of the prototype used a combination of plates with progressive differentiated sizes aiming to produce the nest effect. The dimension and quantity of plates were inserted as parameters into the programming structure and adapted according the demands stablished by regulatory agencies. The result was a semicircle articulated system with compression-expanding properties supported by a rectangular base (Fig. 2).

After the definition of the global form of the shelter the design process engaged with the simulation of complementary subsystems: support, storage, openings, mechanical devices and closures. Using 3d printing it was possible to prototype surfaces with different finishing patterns, sizes and articulations taking into account solar orientation, physical protection and visibility. The first prototype used hexagonal pattern (Fig. 3) to evaluate the possibility to create a perforated surface with membrane properties able to filter sunlight, favor natural ventilation without compromise privacy, and form a light weight board with resistance and durability. The size of the holes and the thickness of the surface were parameterized in Grasshopper software. This version incorporates many conceptual design intentions and was useful to engage the first cycle of reflection. The main idea was to design an adaptive 3d print membrane that could be configured and programmed with different patterns, sizes, openings depending on its position in the shelter's morphology. Adaptability is a major issue in emergency design because each site has its own topography, climate conditions, social relations and economic viability.

The second prototype used Voronoi diagram to investigate the differentiation potential offered by digital fabrication techniques (Fig. 4). The Voronoi diagram is an artificial diagrammatic design that simulates organic patterns and is useful to design non-linear custom geometries using the same amount of time and materials as traditional serial forms. The benefits of using Voronoi patterns rather than hexagonal patterns is the bigger variability of the cells and the better aesthetical relationship with biomimetic concepts [12]. The Voronoi pattern was used as layers both in the structure and covering. The internal layer of the surface was used as structure and the external layer was designed as a covering membrane. The external membrane was responsible to articulate three basic

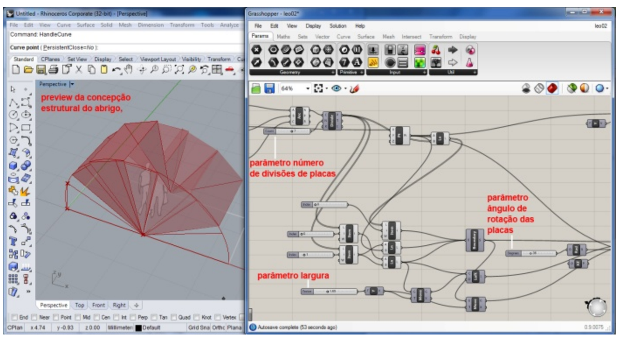

Fig. 2 Graphical interface of software Rhinoceros and Grasshopper used to develop and parametrize the structure of the shelter.

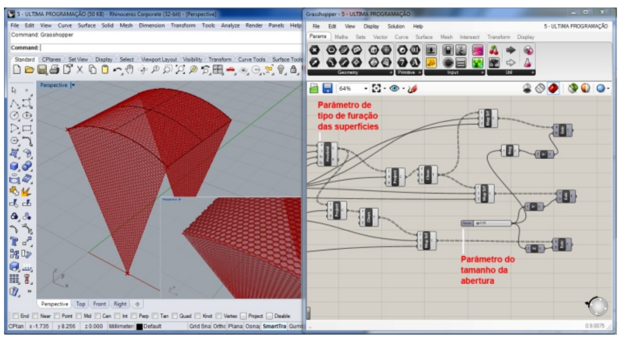

Fig. 3 Image of the plates isolated from the shelter and detail of the drilling surface treatment with parameterized in hexagonal pattern.

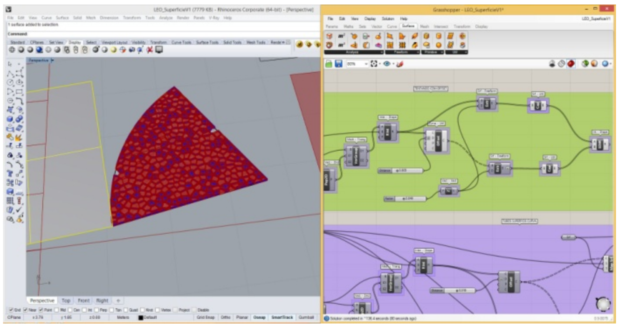

Fig. 4 Voronoi diagram developed in Rhinoceros and Grasshopper.

demands of the shelter: thermic quality, natural ventilation and water tightness. Each nesting element had a combination of inner and outer layers: structural and membrane, respectively.

Each module of the shelter had three surfaces/plates: two in each the side and one in the back. The overall project had three modules that could rotate and produce different configurations. The modules connect to a support subsystem that had specific functions such as: adapt to topography, accommodate water and sewage reservoirs, arrange mechanical devices to control the surfaces and offer storage for personal objects.

5. 3D Printing Materiality

The choice of materials associated to fabrication techniques is a central aspect in the entire spectrum of architecture. In disaster situations this combination of material and fabrication must be able to provide quick, adaptive and effective answers. Oxman, Gramazio and Kohler [13] emphasize the importance of the material as an attribute that should not be subordinated to the form but be able to instigate its primary conception.

There is a new field of investigation in architecture inspired by the growing presence of advanced methods of digital fabrication. This new materiality [14] gives important contributions to amplify the range of new synthetic materials with new methods of fabrication. One of the most relevant contributions is the strengthening of environmental and ecological issues as the use of recyclable and biodegradable materials in architecture.

Computing techniques are key interfaces to explore the potential of this new materiality in architecture and they have leading a significant shift in design thinking. In the context of digital fabrication techniques, the materiality is not only seen as a fixed property or a passive recipient of form but is transformed into an active generator of design and an adaptive agent of the architectural performance. The materialization coexists with the design as an exploratory robotic process.

With current fabrication techniques architects have means to change the basic patterns of materials organization and improve their performance at different levels. According to Oxman [14] biomaterials, mediated and responsive materials and composite materials are relevant examples of the new spectrum of materiality that and have great potential to be incorporated in architectural design.

This is the case of cellulose acetate, an essentially rigid thermoplastic polymer with relative flexibility [15], fully biodegradable under controlled composting conditions and small environmental impacts per kilogram produced [16]. This polymer is one of the most important in the development of biodegradable matrices and has an important role in science as a possibility of reducing the use of raw materials derived from non-renewable sources [15]. In addition, it presents low cost of production [17] and allow complex patterns and wide range of color effects that can be used in art and industry. These qualities give designers possibilities to associate the range of colors with the demands of light absorption/reflection of and solar radiation [16].

The cellulose acetate can play a more complex and decisive role in the design of structural and covering components of the emergency shelter. It is a biomaterial with good resistance and flexibility that can be explored in the generation of various types of patterns printed in 3D. The idea of complex design surfaces using new biomaterials implies the development of different surface attributes: aesthetic, functional and structural [18]. The correct association of these attributes can lead to a happy marriage between structure and coverings in a single solution.

The Voronoi pattern was used in the design of the external membrane of the shelter. The Fig. 4 demonstrate the conceptual shape of the Voronoi pattern forming a perforated surface. Each surface of the shelter should have a suitable performance regarding thermal performance, natural ventilation and illumination, and water tightness. The main design challenge was to conceive a surface that "breeds", in other words, a waterproof surface that at the same time allows the flow of natural light and wind. The first 3d printed prototype was made using ABS filament and the Voronoi pattern, same used in structural design (Fig. 5), as a reference for perforation. The result was not very satisfactory because the surface generated in 3d was not sufficiently water resistant. The morphology of the geometric elements of the surface needed an additional overhang element to ensure water tightness. To solve this problem another cycle of investigation in biomimetic design became necessary in order to inspire a new watertight breeding surface.

The most interesting references identified was placoid scales found on the skin of sharks and the morphology of some types of marine corals. In the first case, the denticles morphology of each scale allows mobility, permeability and resistance to the body of the shark. In the second, the protruding morphology of some species of corals creates a perforated pattern that can be adapted to avoid rain drops but at the same time allow ventilation. The prototype fabrication started with the coral based surfaces. The Fig. 4 illustrates the metadesign of the surface developed in Grasshopper software. The metadesign permits the modification of the size and the position of the holes, what is important to configure the water tightness of surface in different positions and inclinations.

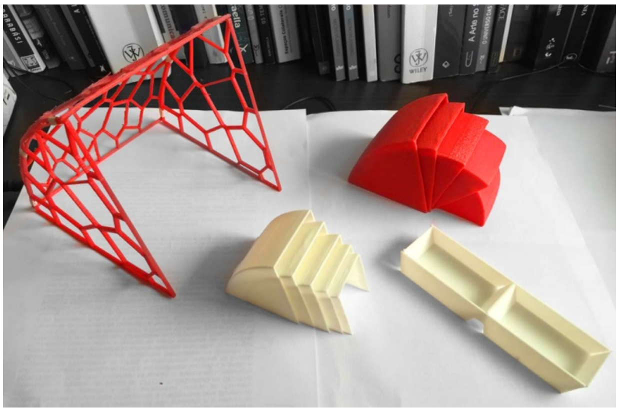

Fig. 5 Compositions of emergency shelter structure made from 3D printing.

The 3d printing test were made using ABS and PLA filaments, but in order to produce architectonic elements in real scale, it is important to accomplish new researches considering high levels of resistance, comfort and durability performances. With the expansion of the use of cellulose acetate in the market, many experiments are being developed to increase the physical resistance, improve thermic qualities, reduce costs and use different material matrices to produce it. The cellulose acetate can be produced from different matrices. For example, studies such as Cerqueira et al. [17] demonstrates how the cellulose acetate can be synthesized from the bagasse from sugar cane. Pinto, Calloni & Silva [19] show that it can also be produced from the bark of rice (*Oryza sativa*). In both studies it is clear that there is a great potential in the reuse of waste of cane and rice by treating them chemically in order to improve their mechanical and physical qualities. Other studies related to bio composites performed by Gutiérrez, Rosa De Paoli & Felisberti [20] show that the cellulose acetate extracted from short fibers of Carauá and treated with supercritical carbon dioxide have a high potential for application mainly as thermal insulators.

It is important to underline that Brazil is a country extremely rich in these three sources of waste and fibers and with great potential in develop applications of cellulose acetate as a material for architectural design.

In addition to all these potentialities mentioned above, there are still reports that indicate its viability in the field of digital fabrication additive technology (3D printing). Despite the difficulty to melt the pulp in the process of 3D printing, researchers at the

Massachusetts Institute of Technology, Pattinson & Hart [21], developed a method in which the powdered cellulose acetate is dissolved in acetone resulting in a viscous fluid.

The extrusion of this fluid is performed using a 3D printer extruder that uses no heat. A pipe connected to the fluid is used to substitute the filament duct. During the disposal of the fluid in the 3d print nozzle the Acetone evaporates allowing a perfect layer by layer fabrication process. To avoid chemical complications between cellulose and acetone molecules the authors indicate a treatment with sodium hydroxide to strengthen the links in the inner structure of the material [21]. This process demands an adaptation in the hardware of the printer replacing the nozzle extruder by another technology. The technique created by Pattinson & Hart showed significant results in terms of resistance compared to traditional PLA and ABS 3D printing materials. In terms of hardness, the cellulose acetate tridimensional printed presented an average of 46% higher than the cellulose acetate produced in the market, exceeding significantly the ABS plastic and the PLA [21].

6. Conclusion and Next Steps

Recent research has identified a type of filament made with wood called Corkfill sold by the company ColorFabb [22]. This filament is composed by a mixture between Cork and PLA. However, the PLA does not present a reasonable thermal performance considering its application in architectural structures. To solve this problem, it is important to invest in new structural morphologies available by parametric design to compensate this weakness.

It is important to explain that the investigations performed and presented in this article occurred in scaled prototypes. However, in the next steps there is a goal to develop applications in human scales, what implies in the development of larger 3D printing machines. Robotic arms have been used in various projects around the world to reach similar results but they are not much common in developing countries and its cost is still high. However, many efforts are being made in free hardware and software movement to produce low cost machines.

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