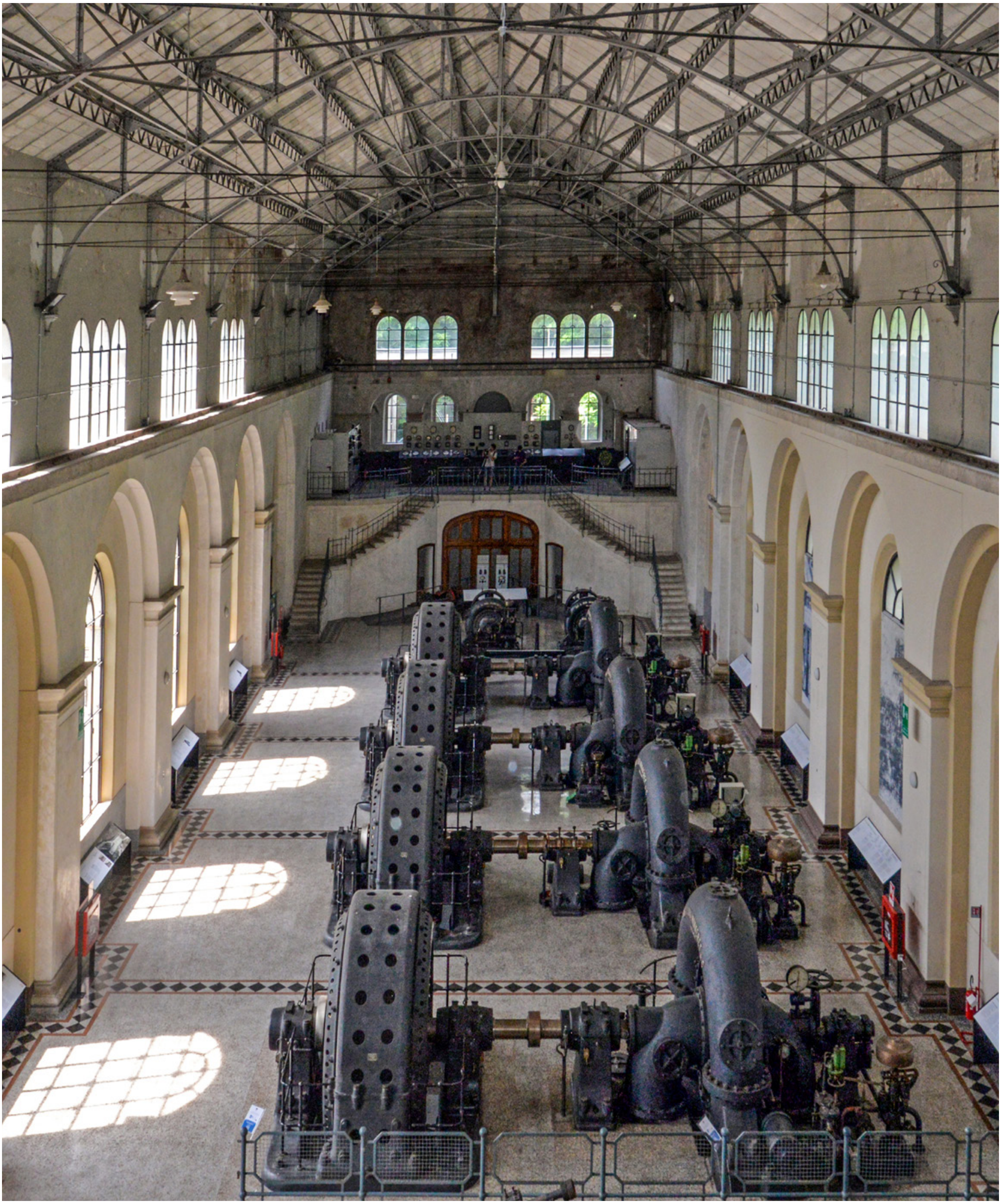

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AN ECO-SUSTAINABLE PARAMETRIC DESIGN PROCESS OF BIO-BASED POLYMERS TEMPORARY STRUCTURES

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Cecilia Mazzoli, Davide Prati, Marta Bonci

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Highlights

Interaction between industrial design and temporary architecture.
Overview of polymeric materials according to the sustainability of their production process and their physical-chemical and performance characteristics.
Temporary structures as a tool for urban and social inclusion.
Definition of design requirements for designing the essential components of the construction system.
Conception and design of an innovative interlocking constructive system to realize self-supporting structures to be dry assembled.

Abstract

The primary common goal of any resource processing intervention is environmental sustainability. It seeks practical collaboration in construction technology and innovation, whether intentionally used to increase eco-friendly energy savings or implicitly used to reduce the impact of construction projects on the global environment. Biopolymers are a promising field for growth because they combine high technological potential with environmental sustainability. A viable alternative to conventional, costly, and complicated construction systems is the employment of technologies that exploit environmental sustainability concepts to create temporary modular structures that maximize manufacturing times and costs.

The paper presents an innovative process for designing temporary structures for social, cultural, and exhibition use. The present paper aims at the following objectives: (i) to illustrate a parametric approach to the design of spaces for such proposes; (ii) to study a prefabricated construction system consisting of interlocking elements to be dry assembled; (iii) to propose the use of new bio-based material. The building system originated based on these research instances targets the requirements of: adaptability, flexibility, and reversibility of spaces; prefabrication, lightness, and speed of installation and assembly; environmental sustainability and recyclability of components employed. In particular, the modules that make up the final product, characterized by vaults, are conceived as small shelters for reading and social activities.

Keywords

Sustainable parametric design approach; Temporary prefabricated architectures; Reversibility and recyclability; Topologically interlocking systems; Bio-based polymers.

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1. INTRODUCTION

The purpose of industrial design has always been to create interactions between humans and their environment. By definition, interactive art cannot ignore the public's involvement in the work's life cycle. The attempt is to overcome the intellectual or contemplative relationship of the artist-spectator duo by activating emotional stimuli that engage the public in a path of participatory experience [1]. When applied to the relationship between man and urban space, the concept of interaction between man and urban-scale construction is now more critical than ever. A recent research trend [2] is examining the life cycle environmental impacts (manufacturing, installation, and service life) of temporary pavilions built with "new materials" and reused materials.

The primary objective of this paper is to show how it is possible to create a temporary spatial structure that respects the environment without sacrificing aesthetics. It entails adopting a new perspective oriented towards recent architectural postulates and the criteria of life cycle eco-compatibility, time design, and zero km materials. Finally, the goal is to propose potential applications for "second-hand" materials, components, and connection systems.

For example, recycling and reusing materials and components at the end of their life cycle to construct a temporary structure demonstrates how this practice can provide tangible benefits in addition to theoretical benefits [3]. In other words, feasible concrete strategies with genuine green accounting benefits through avoided impact can be developed. Recycled and reused materials have a high potential that extends beyond the scope of any single project. There is a substantial amount of available waste and secondary products that would otherwise be discarded.

The Delft University of Technology created a research project that promotes the use of reclaimed plastic material in the construction of temporary structures [4]. Rather than new resources, the project is supported by using digital techniques and reversing design processes. As a result, temporary structures appear to be the most suitable buildings for developing and prototyping innovative construction systems based on yet-unexplored materials and components.

As defined by the Ellen MacArthur Foundation, the circular economy "is a generic term for an economy designed to be able to regenerate itself. In a circular economy, material flows are of two types: biological ones, capable of being reintegrated into the biosphere, and technical ones, intended to be reutilized without entering the biosphere. Thus, the circular economy is an economic system planned to reuse materials in subsequent production cycles, reducing waste as much as possible" [5]. The circular economy is a model of production and consumption that involves sharing, lending, reusing, repairing, reconditioning, and recycling existing materials and products for as long as possible. This extends the life cycle of products, helping to minimize waste.

The topic of eco-sustainability is a source of conflicting views. Plastic consumption has grown dramatically in recent years, but plastic waste recycling is also on the rise. The global production of plastic has increased, and the disposal of plastic waste is an increasingly pressing issue.

Even the issue of "biodegradability" is complex and unknown, so that the average individual still tends to confuse what is biodegradable and what is only bio-based. Still, by calling it "*bio*", they are convinced they are not harming the planet. Indeed, the topic of bio-based polymers is proving increasingly interesting and compelling. While the world's major powers seek agreements to address the recycling problem, scientists from all over the planet find viable alternatives to single-use plastics. From this brief depiction of the clash that exists between the supporters of recycling and those of nature, the road narrows, and there is only one choice to make: the countless raw materials that nature offers us and the interesting discoveries being made by chemistry departments are the basis of a new viable and specific alternative to the problem of environmental pollution: the bio-based polymer [6].

2. STATE OF THE ART

The present research intends to promote an innovative design process to build eco-sustainable temporary structures by combining different innovative products and systems. Indeed, the original character of the study does not concern the innovation of a specific product – i.e., bio-based material block – that has already been studied and patented, but rather the process innovation, based on the combination of different design criteria and requirements. In order to define the guidelines for achieving a final design solution that is coherent and compatible with the objectives of the project, it is necessary to carry out a state-of-the-art study mainly concerning the following topics: prefabricated and dry assembled construction systems; bio-based polymers; temporary structures.

2.1. PREFABRICATED AND DRY ASSEMBLED CONSTRUCTION SYSTEMS

One of the requirements at the base of the eco-sustainability of the building systems concerns the realization process reversibility, thanks to the adoption of techniques based on dry assembly, which provides for the union of components through mechanical joints, without the use of glues and sealants. In fact, the prefabricated components, which may concern portions of the building, or its entire structure, are assembled and connected in place and, once disassembled, can be recycled or reused. Moreover, damaged or degraded components can be easily and quickly repaired and replaced in such building systems. Therefore, this technique is an excellent solution to reduce construction time after a careful previous phase of design and production and achieve a high level of flexibility of use for the building. Even if the assembly is commonly considered a specific industrialized construction technique, it should be noted that, nowadays, it strongly interacts with the creative and methodological aspects of the construction sector, thus being considered a real design technique.

Among the pioneers of prefabrication, Gino Zani, an engineer who graduated in Bologna in 1908, is considered one of the pioneers of reinforced concrete and aseismic structures. The tools and methods he used are described by Saverio Liconti in his 1986 essay entitled “A Testimony” [7]. Gino Zani also studied and experimented for the first time with prefabricated slabs and the use of blocks in pumice from Lipari in construction to produce perforated blocks of cement on the outside pumice on the inside, suitable to have the strength and thermal insulation together. Zani’s aseismic house is a noticeable example of how prefabrication, with on-site design, can be a valid solution for the fast and functional construction of structures that can be assembled and disassembled (Fig. 1).

Other fascinating examples inherent to the theme of prefabrication and dry assembly can be found in stereotomy construction, particularly in the realization of flat vaults (in French *voûte plate*), consisting of interlocking ashlars. The most famous flat vault is the one designed by the French engineer Joseph Abeille, at the end of the seventeenth century. “The modular components of the vault are polyhedra of equal dimensions, having a square base, an upper rectangular surface, and four sloped surfaces on the sides, which are used to support the elements. Abeille’s structure is conceived as a dry masonry

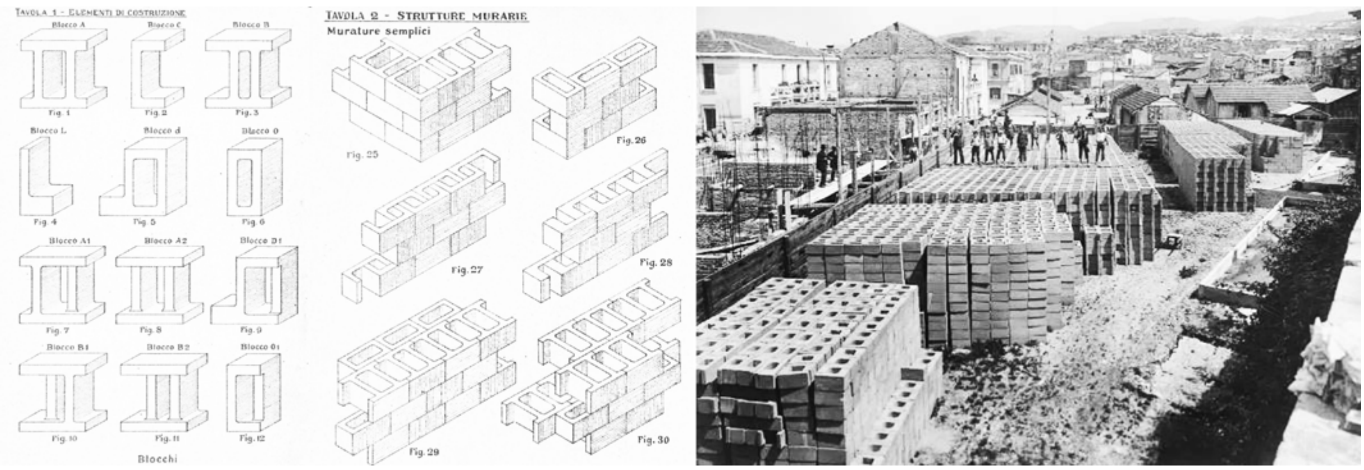

Fig. 1. *(left) overview of prefabricated building blocks designed by Gino Zani in the 1920s and different configurations of simple masonry structures and (right) Construction site for realization of blocks © Fondazione Gino Zani www.ginozani.org.*

system: the stone modules are arranged alternatingly so that each stone piece is supported by two adjacent pieces, without the use of any type of joinery or mortar. The resulting vault is able to redirect the vertical load horizontally towards the walls on the perimeter and features a checkerboard pattern on its intrados and pyramidal voids on its extrados" [8]. Until the eighteenth century, numerous theorists, including Truchet and Frézier, developed different configurations of ashlars that would allow the construction of such vaulted systems. Still today, thanks to the development of digital technology, several research experiments are carried out to elaborate parametric algorithms for exploring new morphologies of flat or curved vaulted systems constituted by topologically interlocking components. Among these experiments, the study conducted by the Laboratoire GSA (École Nationale Supérieure d'Architecture de Paris-Malaquais) is significant. Through mechanical and geometrical analysis and construction experiments, it has come to define different stone vaults and domes based on the Abeille parameter (Fig. 2) [9].

All the above-mentioned systems are classifiable as heavy systems, made of stone materials of mineral origin. Therefore, although they permit the realization of dismountable and versatile structures, they require specialized technical operators and often the use of machinery to lift the blocks. The present research intends to explore new prefabricated design solutions based on prefabricated components that are light and hence easily assembled through a self-construction process.

2.2. BIO-BASED POLYMERS

The collection of plastics in the oceans is a very sensitive and problematic issue. Talking about the reuse of polluting plastics becomes meaningless when used to make objects even more challenging to dispose of. When people hear about bioplastics, not everyone knows they can be divided into three major and, sometimes, distinct categories. "Biopolymers represent an area with great potential for development because they combine high technical potential with the factor of eco-sustainability. The causes of the growing interest in biopolymers derive from issues related to waste recovery, the possible significant increase in prices of petroleum products, and their use favored or made mandatory by law. There are mainly three ways in which biomass can be processed: using natural polymers that can be modified but remain essentially unchanged (e.g., polymers from starch); producing by fermentation bio monomers that are subsequently polymerized (e.g., PLA or polylactic acid, Polypropylene, Polyethylene); or producing biopolymers directly from microorganisms (e.g., PHA)" [10].

The advantage is that bio monomers can replace similar traditional materials already on the market. Therefore, biopolymers can be of three types: polymers derived from renewable sources but not necessarily biodegradable, called "bio-based", others derived from petroleum but biodegradable, and those both bio-based and biodegradable. The first fundamental difference between bio-based and biodegradable polymers lies in their life

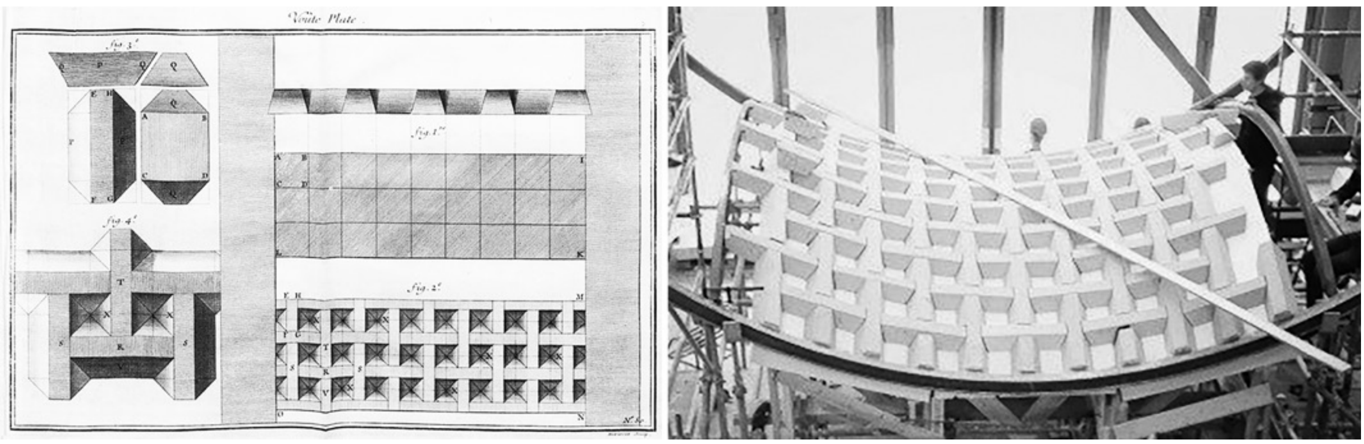

Fig. 2. *(left) Joseph Abeille's voûte plate: drawings of polyhedral stone modules and assembled system of a flat vault, invented in 1699. (Image source: Gallon 1735). (right) Prototype of the stone vault based on the Abeille module, realized by the Laboratoire GSA, coordinated by Brocato M and Mondardini L in 2013 © Cecilia Mazzoli, 2013.*

Fig. 3. *The molecular structures representation of PE (polyethylene), HDPE (high-density polyethylene), and LDPE (low-density polyethylene) © Thorsten Graunke, Katrin Schmitt, Jürgen Wöllenstein, 2016.*

cycle. Biodegradables derived from organic sources, used in packaging and food, have an extremely short life span. These include common cornstarch bags, for example, that are sold at the supermarket to package fruits and vegetables or the beeswax films that have recently found use in food packaging. Non-biodegradable polymers, on the other hand, but derived from biological sources and therefore recyclable, are long-lasting and are used in the automotive, appliance, footwear, and construction sectors. In general, bio-based plastics refer to all plastic materials containing a certain percentage of a renewable source. When we note the term bio-based, the material is partially or entirely derived from biomass (plants) such as corn, sugar cane, beeswax, beet, cellulose, vegetable oils, and castor oil. They are part of the wide range of renewable sources used in the production of polymers, for example, polyols in which the "starters" are precisely the biomasses. "Castor oil, chemically modified, can be processed for the production of polyester polyols. Soybean oil is also easily usable: by inserting OH groups into the chain, double bond reactions are created that lead to the creation of the polymer" [11].

During the research phase, however, the main requirement was to use non-biodegradable bio-polymers. Biodegradable ones are poorly equipped from a mechanical and energy point of view, and most of the polymers derived from biomass are extremely sensitive to weathering when exposed outside. Of course, this must not be allowed while designing a safe outdoor structure dedicated to the shelter of things and people. The material used must highly perform in all its aspects, and therefore the focus has shifted to non-bio-based products. The genuinely innovative issue is that green polyethylene maintains the same properties, performance, and versatility of application as fossil-derived polyethylene, facilitating its immediate use in the plastics production chain. For the same reason, it can also be recycled within the same recycling chain as traditional polyethylene.

The following PE families are currently available: high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). HDPE green has a bio-based content of more than 90% and can be processed by blow molding, injection molding, and film extrusion, as well as LDPE green (Fig. 3).

The research focuses on the HDPE for its chemical-physical properties (i.e., lightness, ductility, impermeability, and resistance to the weathering agents) and its eco-sustainable features in terms of the high percentage of bio-based content and hence low environmental impact.

2.3. TEMPORARY STRUCTURES

The effects of the global crisis on the city are manifold, both socio-economic and ecological-environmental. Still, they can be synthetically traced back to an increased demand for quality, services, and functions that are not adequately addressed. The city is a dynamic organism, taking shape in step with human life evolution by its very nature. Therefore, its continuous variation is a prerequisite for the coexistence of the built form of the environment and collective living structure [12]. A change in the system of values has been brought about by the need to meet increasingly complex and mixed needs originated by new individual and collective behaviors [13]. In the transition towards a renewed urban comfort, urban planning must be synchronized over time. It must propose solutions that consider both the needs of the city and people trying to reconnect the social and spatial fragmentation, according to an inescapable ecological key concerning climate change also [14].

In recent years, the temporary use of urban public space has consolidated as a system of being together in the open air. Today, living in a small metropolitan outdoor area is an international trend. Custom-made products can be installed in the space between the sidewalk and the street to perform a noble practice for man: meeting and sharing a place. In the United States, this kind of architecture has become a regular practice for recovering non-places in the community over the last decade. The goal is to "steal" as much as possible portions of asphalt and space dedicated to vehicles and give it to people, giving shape to small areas to stop, sit, and rest. New social needs dictate the decision to adopt this type of design to slow down the increasingly frenetic pace of living in a large metropolis. San Francisco was the first city to experience this new way of stopping along city streets [15].

Since 2012 the city has been filled with temporary installations. They contribute to welcoming people and enhancing the landscape while sharing a social and ecological responsibility. They become a resting place surrounded by vegetation and often used to display art to create pleasant and comfortable spaces in portions of the city previously anonymous and without identity. These temporary installations establish themselves as eco-sustainable small-scale interconnected products to activate new social practices, share readings and information, and strengthen the civic fabric. Structures "scattered" throughout the urban space to bring people together and reactivate the economy and vitality of areas that had died out over time.

Whether it is a project commissioned by public authorities or an initiative from a private client, temporary installations represent the interconnections and interdependencies that arise between society and territory. They enhance the respect for the space in which we live and, consequently, the behaviors we assume. Morphologically similar places differ in atmosphere, care, vitality, and the number of involved people. As stated by Mariateresa Aprile of the University of Rome La Sapienza: "Why are some spaces preferred to others? First, it should be considered an aesthetic question, but the morphology is not a consciously considered element in the choice of places, and it is not enough to explain how space becomes a place. Instead, the functional aspect has a greater incidence. Vital spaces, crowded with people on the move and intent on doing many different activities and preferred by citizens, are those that are most able to adapt to many activities that take place there even simultaneously; they are flexible spaces for different uses" [16].

The world is seeing an increase in architectural experiences based on the design of interventions aimed to fulfill new and growing needs for populations – in more or less critical situations – which not only respect the environment but place it at the center of the project through the adoption of sustainable criteria, constructive systems, and materials.

In general, bio-based materials can be used in architecture to create structural components with a load-bearing function and cladding and infill components. In the literature, there are many examples of laboratory construction experiments in the scientific-academic field and building experiences in a real environment for the design and construction of temporary structures.

The present research focuses on case studies involving bio-based materials to create load-bearing structures. Among them, we find the "Observe/Reverse Pavilion" developed by the Department of Architecture and Visual Arts of the Faculty of Architecture of Wroclaw, University of Science and Technology, in collaboration with the Super Architektura Michał Święciak. The structure consisted of five frames in cardboard honeycomb panels, strengthened by lamination with layers of timber-based OSB. The frames were connected to each other through OSB floor plates, wooden battens in the longitudinal direction, and planks diagonally fixed to the battens. The roof is supported by a structure made of paper tubes and is covered by a membrane in Cordura, a polyester textile impregnated with a PVC layer [17]. This experience is inspired by the projects designed and promoted by the Japanese architect Shigeru Ban, who was the first one who used the paper tubes as structural elements in temporary architecture in the 1980s [18]. The paper could certainly be included within the bio-based materials since it is a material of entirely natural origin – whose main component is a cellulose fiber, the most common natural polymer – and its resources are inexhaustible [19]. After the Hanshin-Awaji earthquake in 1995, Ban used paper tubes for the walls' main structural elements to build temporary shelters and a church for disaster victims. The project was further adapted and used in 2001 for relief homes in Ahmadabad (India) and 2010 for post-earthquake shelters in Haiti. While suitable for permanent applications, paper tubes have become popular for temporary structures, especially for their potential inventiveness and minimal environmental impact [20]. For instance, Shigeru Ban designed the "Japan Expo Pavilion" for Expo 2000, whose structure was realized with pressed paper tubes (12 cm diameter and 40 m long) and an impregnated textile and paper fabric over a paper membrane for the roof covering. Other examples of pavilions with structure composed of bio-based materials are: the "HY-FI Pavilion", designed by David Benjamin in 2014 in the framework of the MoMA's Young Architects Program, and based on the assembly of mycelium blocks, derived from a combination of discarded corn stalks and specially-developed living root-like structures from mushrooms; the entirely timber-made "Wood and Shadow Pavilion" designed by Opolska OIA RP in 2016; the "BijenPavilijoen" designed by Frank Marcus in 2016, whit a structure composed of pinewood pillars and beams and a façade realized with plywood; the "Flotsam & Jetsam Pavilion" by SHoP Architects in 2017, made of a bamboo composition (20% bamboo and 80% PLA composite by weight).

A relevant project is the "De Vogelvlucht Pavilion" (Fig. 4), designed by Owais Arman, Laura Eshuis, Rog-

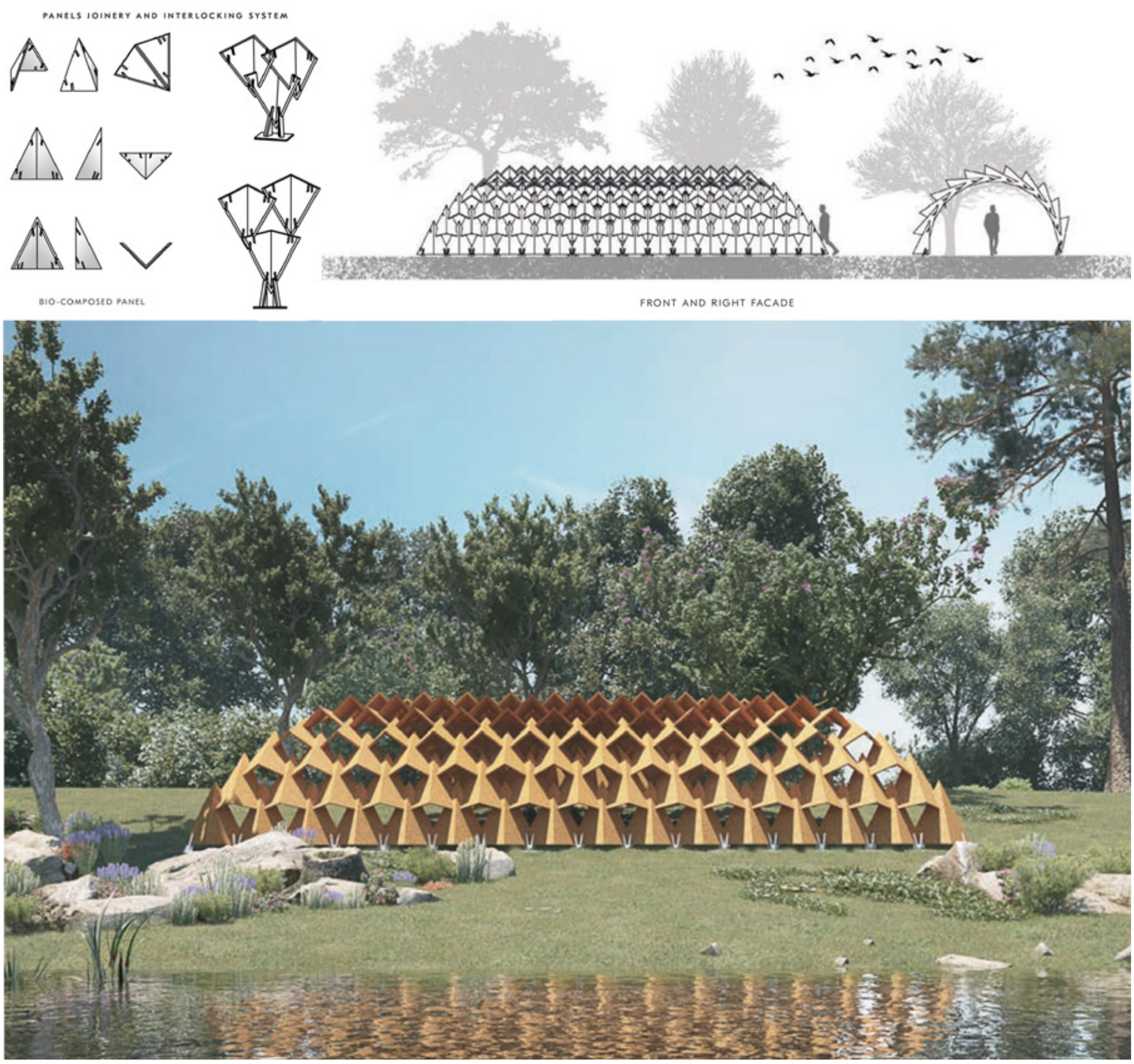

Fig. 4. *The "De Vogelvlucht Pavilion": detail of the tridimensional angular panels in bio-based material, scheme of the dry-assembly system, front and right façades, and rendering representation © Oswais Arman, Laura Eshuis, Roger Ruber, and Anne Holthaus, 2019.*

er Ruber, and Anne Holthaus from the Eindhoven University of Technology and published in 2019 [21]. This project, which has reached the stage of prototyping in scale, shows the potential of the bio-based materials used in architecture for realizing self-supporting temporary structures constituted of prefabricated components. The particular design of the three-dimensional angular panels – from which the name of the pavilion derives, dedicated to the flight of the birds – that are parametrically designed, entails that the pieces are connected to each other through a dry-assembly system that excludes the use of non-bio-based connectors. All panels are identical, so only one mold is required for their fabrication. Thanks to the topological self-locking system, the pavilion's construction is simple, quick, and sustainable. The material selected to make the components to be dry assembled is a bio-composite made from natural raw materials, namely hemp fibers, which are then bound by a polyethylene resin, which harden together to form a resistant material. Hemp fibers, as well as flax, jute, wood, and wood fibers – often used in construction – can be derived from recycling processes of used textiles or wastepaper, thus further reducing the environmental impact of the project.

The latter represents a sound synthesis of the design requirements pursued in the current research project: prefabrication, dry assembly, reversibility and ease of assembly/disassembly, topologically interlocking system, parametric design, bio-based materials.

3. "C'ERA UNA VOLTA" PROJECT

"C'era una volta" is the name of the project created and submitted to the "Portable Reading Rooms" design competition held by Bee Breeders [22]. The project, which was shortlisted, also showed potential for future developments, such as to make it adaptable for use as temporary architecture. From the outset, the aim was to create a modular and versatile structure that would be an alternative to the traditional, expensive, and complex construction systems used today to build temporary structures. In general, the project combines several issues: eco-sustainability, modularity, user experience, the relationship between form and function, the design process of assembly systems with low environmental impact, the study of safety and waterproofing, production processes associated with biopolymer materials, a parametric reversible and adaptable construction system, and finally recyclability [23].

3.1. PROJECT STRATEGIES

The product development phase is aimed at solving some problems that emerged during the design phase. Initially, the structures were made up of many different brick blocks (about 21 standard blocks and many more "unique" blocks). In the first phase, some shapes were simplified, and then a parametric method was studied to justify the redundancy of different ashlars. This method proved to be suitable for the feasibility and stability of the male-female joint system based on the bio-based material identified. Moreover, it allowed solving natural ventilation needs creating alternated slots into completely closed walls. The roofs have been realized by studying special closed brick ashlars to solve water drainage and waterproofing. The innovation of this project lies mainly in the parametric process adopted for elaborating the proposed prefabricated system, suitable for the realization of temporary installations in different contexts, with different dimensions, with various materials, according to the changing needs of the users. The parametric design gives the structure the characters of: pre-fabricability, modularity, flexibility, reversibility, adaptability, customizability, disassembly, and sustainability. Following the decision to design modules that would use the technique of dry assembly with mechanical joints without adhesives or sealants, it was necessary to define a method to be adopted to realize the vaults. This parametric process has been obtained by algorithmic construction. But what exactly is an algorithm? Several definitions have been proposed, but an algorithm is generally a procedure (a recipe). In fact, it is a sequence of coded steps to achieve a result. This definition allows saying that it is not necessary to use software to implement an algorithm; the algorithms are the theoretical part at the basis of a possible software implementation [24]. At the moment, the research is limited to defining the procedure to be followed.

The geometry of the blocks to be prefabricated is defined on the basis of the "vault span" (the distance be-

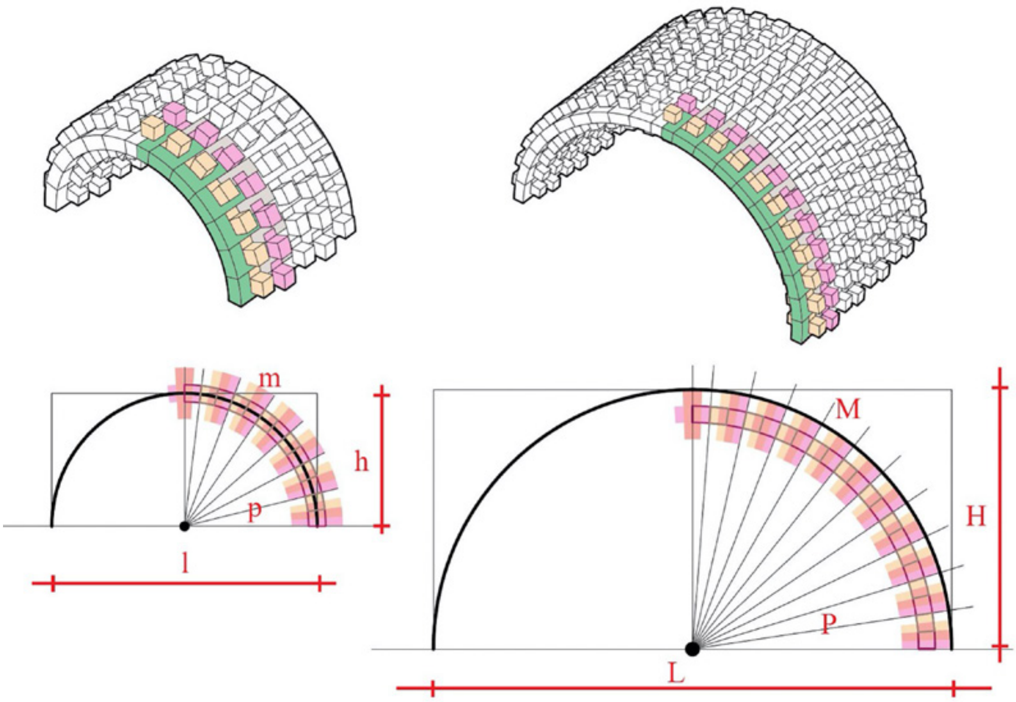

Fig. 5. *Algorithmic construction process for the vault – axonometric views of the two different vault spans realized by interlocking ashlars. Construction schemes highlighting the parametrization used to obtain the proper dimensions of the ashlars © Marta Bonci, 2019.*

tween two pillars), which in turn determines the length of the vault's arch. Indeed, the geometry of the ashlars is obtained from the vaulted arch subdivision according to the span (l), the desired brick size (m), and the pitch (p) to be kept between one brick and the other. In the case under consideration, two different vault spans were determined (l and L), consisting of specially designed brick segments (Fig. 5). The front arch, for example, is obtained by assembling two different types of bricks (green and yellow), placed orthogonally to each other. The second arch is made by two other types of interlocking ashlars (pink and grey), lightly scattered from the one of the front arch but always placed orthogonally to each other. The process is repeated identical until reaching the desired depth of the vault.

The ashlars, which may appear identical for both vault's spans, are different in size and inclination of their faces. From this parametrization system and algorithmic construction derives the geometrical uniqueness of the blocks, and therefore of the final configuration of the sequence of arches (always vaulted arches), that depends only on the starting vault span. Although the two vaults may seem made with the same bricks, being, in fact, at first glance, only differently scaled, it is not possible to create different spans starting from the same ashlar. An obvious confirmation can be gathered by trying to build an arch with a greater span with an ashlar not explicitly designed for that particular span. The interlocking system will not be precise, inevitably obtaining tolerance problems for the intrados and extrados of the arch and a technical impossibility of hooking ashlars and dowels.

Once confirmed the possibility of quickly obtaining an abacus of different ashlars in bio-based material through injection molding, it was necessary to identify the least expensive and most quickly customizable solution for the prefabrication phase of the blocks to significantly optimize production time and costs.

The light and hollow ashlars have a thickness of only 3 mm and may not support the loads. A first improvement was made by introducing internal stiffening supports of the same thickness to ensure higher stability of the entire structure under loads and avoid torsion phenomena. These elements could already be included in the design phase in correspondence with the joint area, which is the most stressed area. Moreover, the male-female anchorage joints between the bricks, having to resist shear stresses

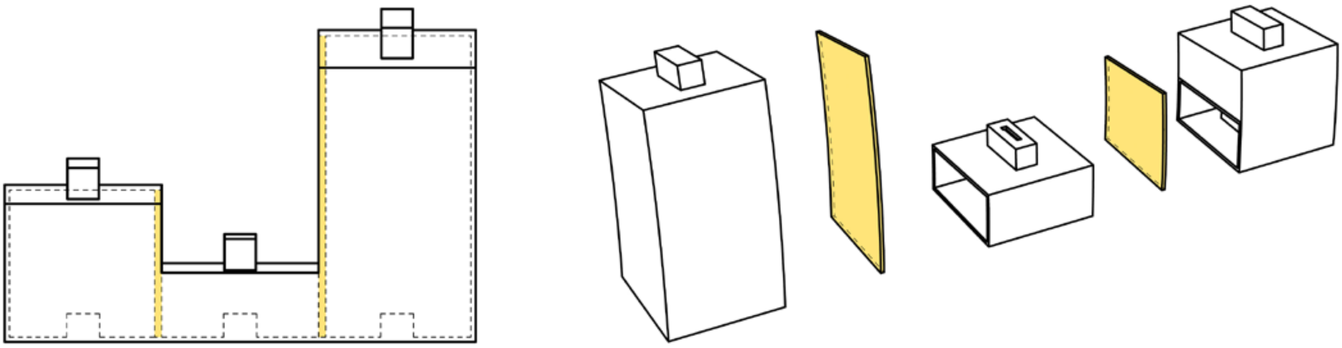

Fig. 6. *Ashlar for the vault – views and axonometric section with internal stiffeners highlighted © Marta Bonci, 2019.*

(more than compression stresses), have an adequate size to support the weight and ensure an excellent interlocking system made of 2x5x2 cm parallelepipeds (Fig. 6).

3.2. PROJECT CONCEPT

The structure is composed of three distinct modules and occupies an area of 20 m². Each module has been designed as a unicum, keeping in mind space optimization according to its function. The ashlars are also used for internal furnishings: shelving, seats, and bike racks are incorporated and adapted to the module to optimize the limited surface available and, at the same time, create a stiffening of the structure. The modules are entirely closed to prevent rainwater leakage from the top, while the walls grant internal ventilation thanks to the tiny holes created by the geometry of the special bricks.

The reading room consists of a 4 m² shelter module that can host two to three people, including a wheelchair for the disabled. Light enters thanks to the opening on one side and the fanlight on the other. The "book box" module measures 3 m² and is organized into 4 shelves that serve as book supports and as a structural component alternating with the standard bricks. The last module is the bike rack which measures 6 m² and may accommodate 4 bikes that can be parked using the internal protruding bricks as racks. The bike rack is an open structure so that readers can deposit their bikes and pass through the complex to reach the other two modules (Fig. 7).

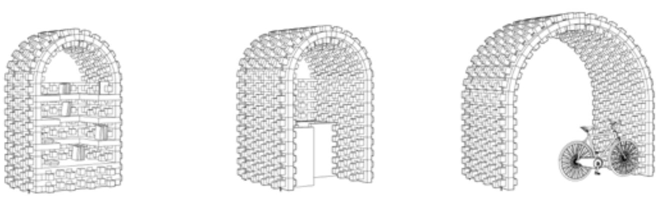

Fig. 7. *"C'era una volta" modules © Marta Bonci, 2019.*

The blocks are made of bio-based, 100% recyclable HDPE with gas-assisted injection molding that makes them lightweight, ductile, waterproof, and full-green. Two rubber tie-rods (natural rubber), placed at the ends of each module, anchor the structure to the prefabricated wooden base, which defines the area of intervention. The tie-rods improve the compression between the vault segments, thus contributing to the roofing system's water tightness performance. The rubber bands used to contrast the wind loads are fully compatible with other bio-based materials, thus obtaining a good level of mechanical safety while using a limited number of blocks (30 different types). Moreover, it is possible to leave the primary brick row unchanged and exhibit the "tensioning" system (Fig. 8).

The basement also is helpful to protect the modules from ground moisture and prevent blocks' direct contact with the terrain, allowing a longer duration without degradation. This sort of "slab" is prefabricated in wood and can be assembled in situ, assuring proper insulation to protect the base itself from rising damp from the ground. For this project, it was decided to use a mix of lime and hemp, both ecological and environmentally sustainable, with high performance. The mix is used to fill up the base grid made of wooden beams nailed to the ground. An upper wooden panel finishes the basement surface, while a slight side slope allows the ascent and descent of wheelchairs/bicycles (Fig. 8).

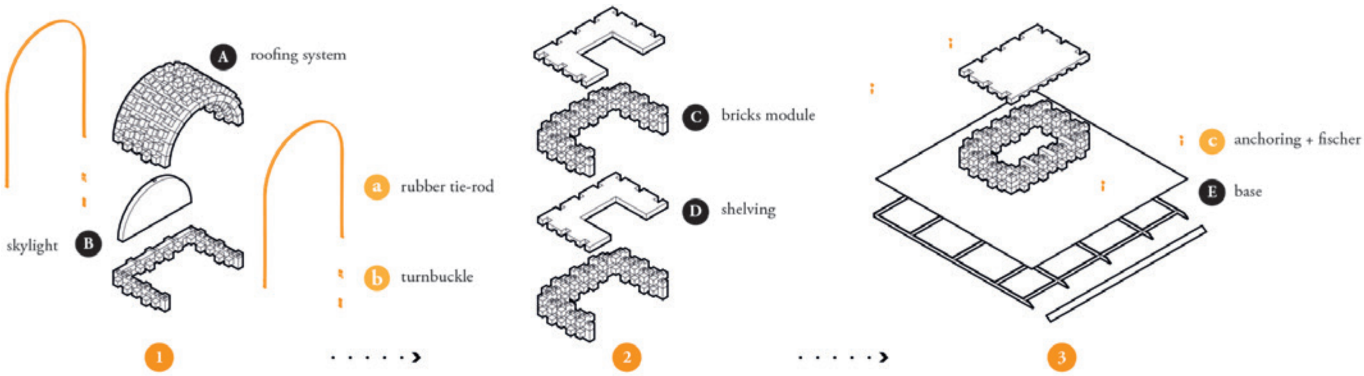

Fig. 8. *"C'era una volta" module assembly phases of prefabricated, modular, and interlocking bricks © Marta Bonci, 2019.*

	Fluidity Index (190 °C/2,16 kg)	Density (190 °C/2,16 kg)	*Yield Point*	*Fracture Point*	*Flexural Strength*	*Hardness*	*Injection-molding*
Units	[g/10 min]	[g/cm³]	[MPa]	[MPa]	[MPa]	[-]	[-]
HDPE SGE7252	2.0	0.952	26	30	1,100	62	YES

Tab. 1. *Some of the main physical properties of Green PE.*

Table 1 shows the characteristics of the chosen HDPE. Since there are as many as thirty different grades of Green HDPE, the one selected for the project meets the requirements of eco-sustainability and weather resistance. Moreover, it is as easily injection-molded as a normal thermoplastic, allowing to obtain hollow bricks while ensuring sufficient thickness (3 mm) to avoid torsion problems. HDPE SGE7252XP is 96% bio-based and 100% recyclable (in accordance with ASTMD6866). It is produced from ethanol obtained from the alcoholic fermentation of sugar cane. The ethanol is converted into ethylene monomer by dehydration, and then by standard catalyzed polymerization addition, the ethylene is transformed into polyethylene. The material is completely waterproof and suitable for outdoor applications due to its polyolefin nature (Tab. 1).

Despite costing about 50% more than conventional HDPE (1€/Kg), the material is not particularly expensive. The only disadvantage is its low creep resistance, which can be overcome with a 3 mm brick thickness. The HDPE density is about 0.9 g/cm^3, and the standard brick dimensions are: height 15.6 cm, width 30 cm, and depth 10 cm. Given an approximate volume of 4,680 cm^3, the final weight of the hollow brick obtained by gas-assisted injection molding is about 555 gr. The thickness has been determined by calculating the stresses that will weigh on the bricks and keeping in mind that HDPE has about 30 MPa yield strength and about 25-30 MPa breaking strength.

Unlike "normal" molding (Fig. 9), the process to be used involves gas addition during the production cycle. The gas added is usually nitrogen, making it possible to produce empty inside and high-precision items. In practice, this technology consists of pure nitrogen's co-injection inside the plastic material and allows emptying the piece, realizing extremely resistant and light products. The pellet and nitrogen insertion process takes place in the same mold and simultaneously, without post-production steps. The technology reduces the typical surface problems caused by the cooling of the part (suction) by decreasing the processing time compared to products with equivalent apparent thickness. This high-pressure gas-assisted injection molding solution is used for many components/products. It brings significant advantages, including material savings, the possibility of obtaining incomparable lightness to the piece, and the reduction of cycle times with high energy-saving (about 20-30% for each cycle). It also avoids any shrinkage and reduces the injection pressure and tonnage of the machine. Furthermore, the process al-

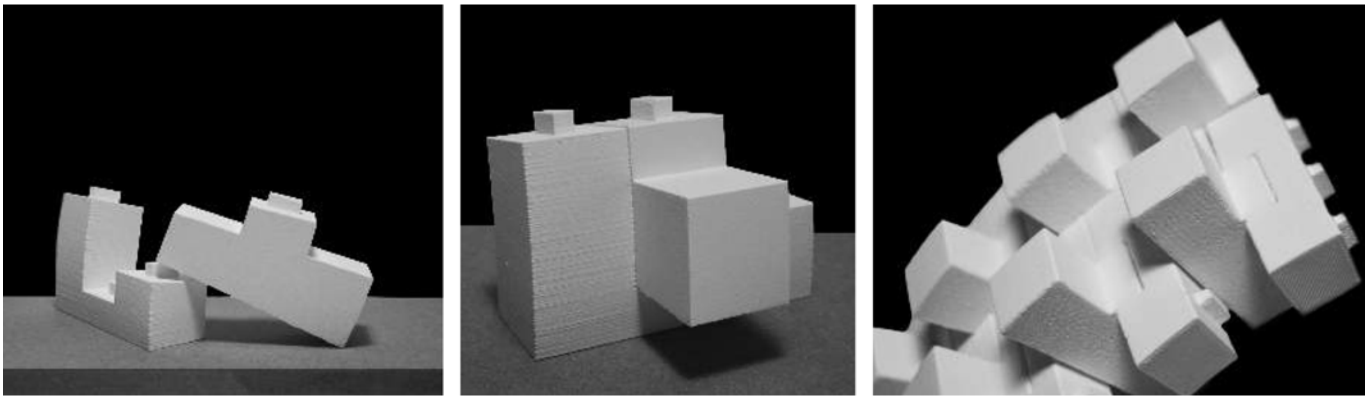

Fig. 9. *PLA brick prototypes made with 3D printing in 1:2 scale © Marta Bonci, 2019.*

lows great freedom in design and the combination of different thickness external shells. We can consider injection molding as a process suitable for mass production, given the large number of pieces to be produced in a short time (for three modules of this project, the total number of bricks amounts to 1,757 pieces).

A rough estimate of the total cost of brick mass production can be made using known data about the cost of the material [€/Kg] and the weight of the individual bricks [Kg]. Bio-based HDPE costs 1.50 €/Kg (50% more than conventional PE), and an average size brick weighs 0.55 kg and, therefore, costs 0.80 €. The total cost of the production of the three modules in bricks only can be estimated as about 1,405.60 € (excluding production costs, the cost of tie-rods, and the cost of labor for assembly in situ) (Fig. 10).

4. CONCLUSIONS AND FUTURE RESEARCH DEVELOPMENTS

The project research is placed in the interdisciplinary field related to the design of products and services for

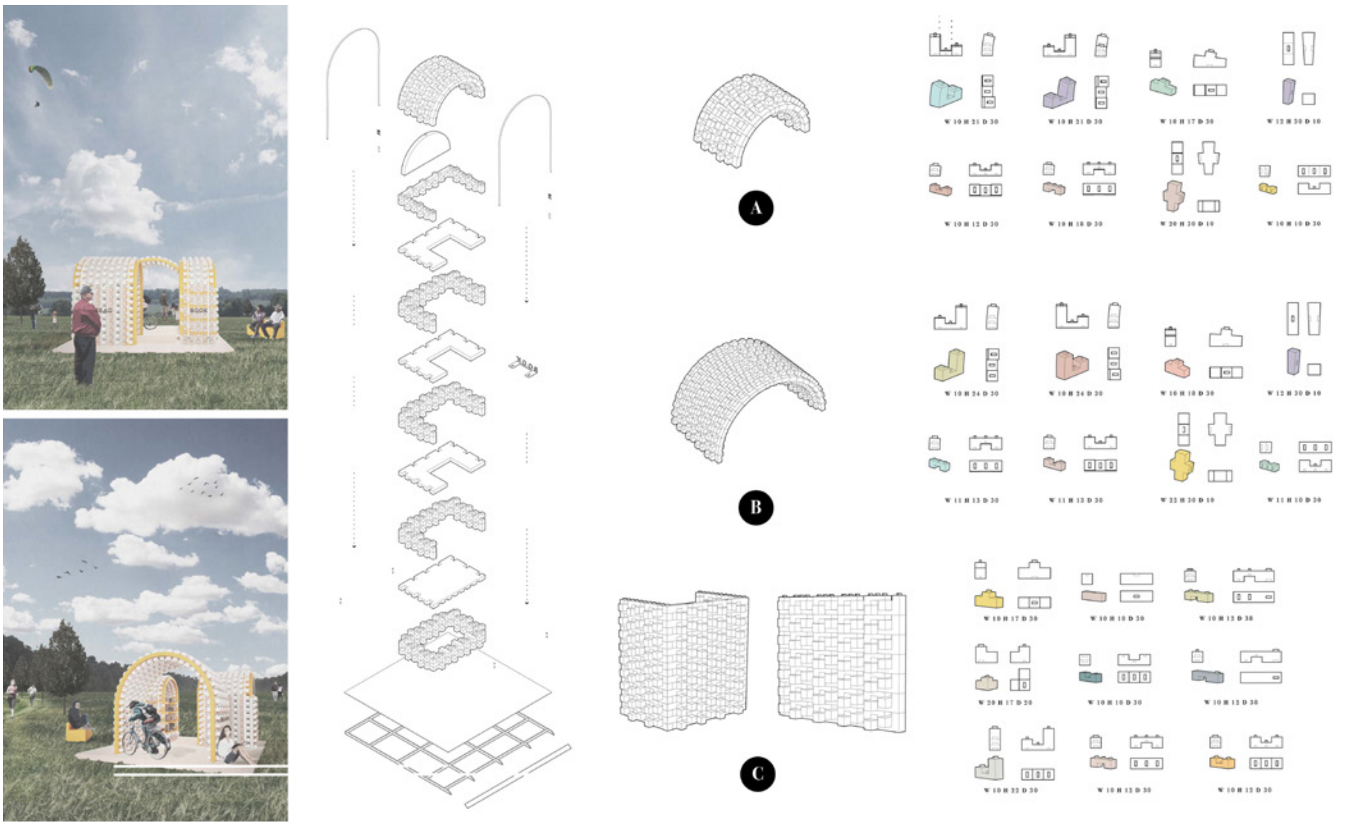

Fig. 10. *"C'era una volta": parametric process for temporary bio-based structures © Marta Bonci, 2019.*

social interaction, technical architecture, and chemistry of materials. Concerning the predetermined objectives, the proposed building system intercepts different requirements according to specific logics:

(i) One of the primary requirements of the construction system is the parametric design of the prefabricated modules, thanks to which it is possible to obtain different configurations based on the users' needs and the social purposes for which the temporary structure is built. In this regard, George Mead, an American sociologist, and psychologist argued that human behavior is not simply a set of passive reactions to physical rewards and punishments but based on attraction. The design has the critical task of surprising, in a positive sense, and pushing the user to get in touch with it. Creativity allows the designer to imagine how society should interact with objects, and the challenge is nothing more than to facilitate and enable the relationship between man and technology. It is essential to convey the infinite interactive combinations that the project allows and communicate them to the user. Where the structure becomes reversible and adaptable to multiple contexts, it is possible to create different experiences continuously [25].

(ii) The proposed construction system belongs to the interlocking prefabricated systems. This kind of system is generated from the segmentation and assembly of modular elements, similar or identical to each other: they constitute a compact and unitary system without additional connecting elements, exploiting only the intrinsic topological properties of the assembled solids. Within such systems, each ashlar transfers its weight force to the blocks immediately below, on which it rests [26]. Proceeding by successive rows, from the bottom to the top – as in any system working by gravity – and successive arches, it is possible to realize a self-supporting structure. Once completed, it is endowed with great stability and resistance, thanks to every single ashlar's weight and the interlocking system given by the intrinsic geometric properties, which confers entirety and strength to the whole [27]. However, to guarantee the stability of the system and the anchorage to the basement, despite the hollow and extremely light ashlars, it is necessary to introduce two rubber tie-rods, placed at the ends of each module acting as thrust containment and make the aggregate system compact. Thanks to these rubber rods, it is also possible to limit rainwater leakage inside the modules. The inducted compression stresses squeeze the joints between the blocks, and the feasible insertion of joints in elastic and waterproofing material would solve the problem.

(iii) Finally, the project intends to promote recent discoveries in the field of Materials Chemistry, illustrating one of the possible ways to implement interventions that are both environmentally sustainable and technically performing. The problem of environmental pollution due to plastics is addressed and contrasted by introducing biopolymers derived from plant raw materials in buildings. In particular, the material identified is the bio-based HDPE (High-Density Polyethylene), derived from sugar cane processing, which has high eco-sustainability properties, recyclability, and reusability.

By matching the starting objectives of the research with the achieved results, it is clear that an innovative design process for the realization of eco-sustainable temporary structures could be achieved only by combining different innovative products and systems, adopting an algorithmic approach. As already stated, the original character of the research lies mainly in the innovation of process, based on the combination of different design criteria and requirements. The "C'era una volta" project can be considered a promising starting point for future developments.

For example, the research could spawn other structures with multiple shapes and combinations thanks to the parametric approach adopted. The blocks themselves could be designed with an unlimited number of different geometries, depending on the intended type of construction. For example, the vertical wall system can be revised by providing its integration with furniture and other equipment such as displaying photographs or works of art. Else, it can be transposed horizontally to realize slabs or flat roofs after introducing an adequate system of perimeter confinement of the ashlars to ensure the system's correct assembly and load-bearing capacity. Similarly, vault modeling can offer many creative ideas to give life, for example, to a small arena. In the case of a social or cultural event, a circular, open structure would lend itself very well as a gathering center for visitors. The algorithmic construction process could be implemented into modeling software opening multiple ways of exploiting its potentialities.

The research, therefore, offers significant insights into further future developments of the project in terms of customization and variability of prefabricated components, materials used, and geometries originated from the parametric process. Thanks to the adopted approach, it is possible to create multiple envelope solutions in line with the research paradigms while respecting many sustainability principles: modularity, prefabrication, rapid production, on-site assembly, reversibility, customization, and material recycling.

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