3D-Printed Biodigital Clay Bricks

Subjects: Architecture And Design
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An optimized formal design of Bricks to achieve sustainability in the use of materials and were achieved by using a bottom-up methodology of biolearning to extract the formal grammar of the bricks that is suitable for their various applications in the built environment as building units, thereby realizing the concept of formal physiology, as well as employing the concept of fractality or pixilation by using 3D printing to create the bricks as building units on an architectural scale. This enables the adoption of this method as an alternative construction procedure instead of conventional clay brick and full-scale 3D printing of architecture on a wider and more democratic scale, avoiding the high costs of 3D printing machines and lengthy processes of the one-step, 3D-printed, full-scale architecture, while also guaranteeing minimum material consumption and maximum forma–function coherency. The “Biodigital Barcelona Clay Bricks” were developed using Rhinoceros 3D and Grasshopper 3D + Plugins (Anemone and Kangaroo) and were 3D printed in clay.

Keywords: clay bricks ; 3D-printed bricks ; 3D printed architecture ; fractal dimension ; form finding ; biolearning ; biodigital ; reaction diffusion ; shortest path ; sustainability ; material consumption

1. Clay Bricks in Architecture

The defining mechanical properties of clay are its plasticity when wet and its ability to harden when dried or fired. Clays show a broad range of water contents within which they are highly plastic, from a minimum water content (called the plasticity limit) where the clay is just moist enough to mold, to a maximum water content (called the liquid limit) where the molded clay is just dry enough to hold its shape [1]. High-quality clay is also tough, as measured by the amount of mechanical work required to roll a sample of clay flat. Its toughness reflects a high degree of internal cohesion [1].

Clay has a high content of clay minerals that give it its plasticity. Clay minerals are hydrous aluminum phyllosilicate minerals composed of aluminum and silicon ions bonded into tiny, thin plates by interconnecting oxygen and hydroxyl ions. These plates are tough but flexible, and in moist clay, they adhere to each other. The resulting aggregates give clay the cohesion that makes it plastic [2]. When the clay is dried, most of the water molecules are removed, and the plates’ hydrogen binds directly to each other so that the dried clay is rigid but still fragile. When the clay is fired to the earthenware stage, a dehydration reaction removes additional water from the clay, causing the clay plates to irreversibly adhere to each other via stronger covalent bonding, which strengthens the material.

The tiny size and plate form of clay particles give clay minerals a high surface area. In some clay minerals, the plates carry a negative electrical charge that is balanced by a surrounding layer of positive ions (cations), such as sodium, potassium, or calcium. If the clay is mixed with a solution containing other cations, these can swap places with the cations in the layer around the clay particles, which gives clays a high capacity for ion exchange [2]. The chemistry of clay minerals, including their capacity to retain nutrient cations such as potassium and ammonium, is important for soil fertility.

On the other hand, composing a bio-based material requires concrete knowledge of what the base should be and what the filament should be and, in between them, what can enhance their coherence and total physical, chemical, and mechanical properties. Based on the mentioned properties of clay, it is the most prominent candidate for serving as a base material due to its high surface area as well as being the most widely available mineral possessing unique crystal structures, cation exchange capabilities, plastic behavior when wet, and catalytic abilities. Moreover, clay is a bio-receptive material that boosts the growth of living organisms such as plants and algae. This bio-receptive capacity of clay bricks has even been discussed in association with conventional construction systems using bricks and mortar [3], where the high moisture content of both bricks and mortar has been described as a pivotal criterion in boosting the bio-receptivity of these materials. An example of bio-receptive clay building units is the precedent in Richard Beckett’s “Bio-receptive Tile Bricks”. Another example was communicated in [4] work, proposing biomimetic place-based design (BPD) as an approach for integrating biological strategies developed by ‘champion adapters’ within the ecosystems via translating their logics into design principles for built environment design and engineering. This approach supports a design that is locally

attuned, adaptable, and resilient to local operating conditions and challenges [4][5]. These properties enable greater application in many industries and clay-based materials. Thus, building with clay has always been a sustainable, cost-effective method due to its very low environmental impact, easy excavation, and simple processing and production methods. However, building with clay according to common methods is not easy, nor is it standardized for applications on a large and rapid scale. For example, the Mousgoum building technique in Africa [6] is an example of sustainable clay buildings having a very solid construction, as they have thicker walls at the base and thinner walls at the top, which enhances the structure's strength while being highly textured to allow individualization of the surface, offering a drainage function, natural thermal insulation, and passive cooling due to clay's hydrophilic nature. However, these Mousgoum structures require frequent maintenance of the coating, and they are unsuitable for use in rainy climates. Another example of sustainable clay architecture is exhibited in Hassan Fathy's earthen architecture in Egypt. Fathy's Nubian clay domes and the unique architectural programming nourished and influenced by the Islamic architectural passive cooling elements have enabled the design and construction of a vernacular clay architecture that is environmentally friendly and sufficiently sustainable [7]. **Figure 1** exhibits the vernacular clay architecture in Africa, showing simple building technologies that are mainly based on hand labor.

Figure 1. Vernacular clay architecture in Africa with simple building technologies: (**a**) shows Mousgoum houses built with clay by manual methods, while (**b**) exhibits the ruins of some of these Mousgoum houses due to cracking or poor rain resistance due to the hydrophilic nature of clay materials, and (**c**) exhibits earthen architecture by Hassan Fathy in New Gourna village in South Egypt, exploiting the passive cooling nature of clay materials through employing it in the design and construction of passive cooling Islamic architectural elements [8] (Photos: Institute of Nomadic Architecture. http://artsection.org/mousgoum.html).

However, these vernacular clay architecture examples are the results of their time and the technology available for material synthesis and construction techniques. Not to mention their insufficiency in material consumption control, or the lengthy time they require for building a single housing unit. In our current biodigital age where rapid advancement is occurring equally and in parallel in both in biotechnology and digitalization, the synthesis of clay materials and adequate physiological design forms are informed by digital data. These digital tools have enabled the direct insertion and realization of biological physiological forms that are biolearned from nature [9], thereby solving the relevance of the physiological form of a material structure from the micro to the macro level through topology, mechanical simulation, and formal optimization, accordingly. Few recent design projects have tackled this relation between 3D printed Brick's formal design and sustainability. For example, the Twisted Tower developed by the Plasma Studio, that used robotic printing arms to 3D print 2000 3D-printed terracotta bricks [10]. Another experimentation on formal design optimization to achieve structural efficiency is evident in "Building Bytes 3D printed Bricks" by Brayan peters that has adapted a desktop 3D printer to produce ceramic bricks for building architectural structures. Predicting that 3D printers will become portable, inexpensive brick factories for large-scale construction, with the implementation of several 3D printers that could work simultaneously on site using pre-made or locally manufactured material [11]. Despite these previous trials to optimize the formal design of a brick to achieve structural efficiency, they lacked the biolearning reference of formal physiology. As the majority of the reached bricks' forms resulting from these studies, did not follow biological logics that are related to the typical design case. Furthermore, 3D printing in Clay is still in need for further experimentation, as it undergoes significant alteration before, during and after 3D printing. Material properties of clay as viscosity, color, and texture, as well as printing sittings and tools (i.e., 3D printer, extrusion nozzle, tool paths, etc.) are among the variables that have major effects on the form resolution of the final outcome. This way, 3D printing with clay still requires formal customization to attain maximum resolution with minimum material deposition [12].

2. Form Physiology of the Biodigital Clay Brick (Reaction Diffusion and Shortest Path)

From a biolearning point of view, physiology is the scientific study of functions and mechanisms in a living system. Physiology focuses on how organisms, organ systems, individual organs, cells, and biomolecules carry out their chemical and physical functions in a living system [13], whereas histology is the microscopic anatomy or microanatomy of biological tissues. Looking deeply into these two concepts, a strong bond always exists to relate the shape or form to its function. Human beings have always been subconsciously aware of this interdependent form–physiology relation, and they have applied it in designing their lives, from the simplest utilities to the largest shelters. Of course, the maturity, scale, and level of processing and integrating this concept in the design process has always been dependent on the level of invasion and magnification of visualization and analysis of the natural source of inspiration. This multi-scale biolearning started by the mere imitation of successful bio examples that applied the concept of formal physiology on a “macro” scale, for example, Gaudi’s Casa Batllo Bony Facade. Moving forward in time and in technological advancement, the level of invasion and magnification of these sources of inspiration has matured the biolearning process and enabled deep understanding and integration of the concept of formal physiology, from design to production. Complying with this concept, the Biodigital Barcelona Bricks presented in this work applied formal physiology in their formal design to achieve sustainability through minimum material usage and form-function adequacy. In the current study, a digital simulation was applied to perform a two-step simulation of the reaction–diffusion behavior based on clay’s hydrophilic properties and water content diffusion through its particles, as well as tuning the structural coherency of the resulting forms by applying the shortest path algorithm to minimize the distance between every two bearing points in the brick’s design, resulting in a distributed load effect. As implied from the structural function of the bricks, the function can be broken down into its physical and mechanical requirements [14]. The first of these requirements is the load distribution avoiding stress being concentrated over specific points. The second is achieving maximum coherency and strength with the minimum amount of material. **Figure 2**. Exhibits the followed methods to design and fabricate the proposed biodigital bricks.

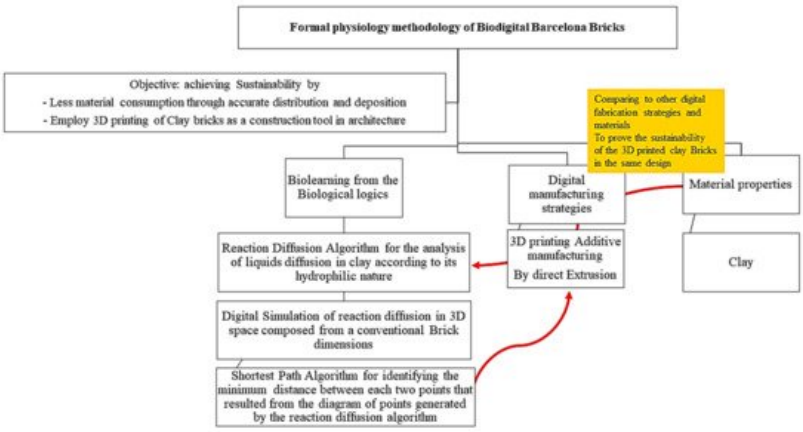

Figure 2. Methodology of achieving Formal Physiology of the 3D printed Biodigital Barcelona Clay Bricks.

2.1. Form Physiology: Biodigital Form-Finding, Simulation, and Optimization

Recently, achieving sustainability in the built environment takes the track of material customization and control. This is focused on developing the formal design of clay-based materials that open both the possibilities of integrating biodigital generative forms of digital DNA that is the algorithms or digital codes that are responsible for specific formal phenotypes that are extracted from the shape grammars of the original biological reference, or via hosting natural organisms or parts of them (as bacteria, fungi, algae, cells, genes, etc.) in an autonomous way to attain generative behavioral materials. These materials also facilitate the shape-changing of architectural elements, enabling the design process to include real-time morphogenesis by integrating an organism that grows and interacts with a consortium of materials, that compos its microenvironment. This aspect opens infinite applications of self-healing, clay-based materials and morphogenetic architecture in real performance, which are still a novel multidisciplinary field that requires further contributions.

Clay bricks in our biodigital age and by biodigital means, aims to achieve formal physiological sufficiency using a biolearning method while maintaining ease of implementation, mass production, and standardization. These were applied in the design and fabrication of the Biodigital Barcelona Bricks that were generatively designed using a form-finding process utilizing branching and reaction–diffusion algorithms to simulate the physical reaction of aqueous diffusion in clay. Reaction–diffusion systems are mathematical models which correspond to several physical phenomena. The most common of these is the change in space and time of the concentration of one or more chemical substances due to local chemical reactions and diffusion, which causes the substances to spread out over a surface in space. Reaction–diffusion

systems are naturally applied in chemistry, biology, geology, and physics. Physically, the reaction–diffusion model describes the emergence of periodic patterns such as spots, stripes, and mazes through chemical interaction among cells [15]. In the current work, this was applied as a first step of form finding a simulation. Through this simulation, the latest regions to absorb water (in clay) in the diffusion reaction were then connected through a branching algorithm of the shortest path, which, at the same time, describes a behavioral growth pattern found in nature. The shortest path, or Dijkstra's algorithm, is an algorithm for finding the shortest paths between nodes in a graph, which may represent, for example, road networks. [16], and as the name of the algorithm suggests, the "Shortest Path" was developed congruently with the structural function of these bricks, shortening the span between each bearing's solid point in order to create a distributed load effect. In structural mechanics, the distributed load is a load that is distributed continuously over a given area or along a given line. A continuous load may be uniformly distributed, having a constant intensity, or vary according to some specific patterns [17]. Thus, this shortest path algorithm applied in the current brick's form finding is congruent with achieving the distributed load by minimizing the distance between each two points in the population of points composing the 3D space of this brick. These form-finding simulations were performed in Rhinoceros 3D [18][19] (Anemone, and Kangaroo and fabricated by 3D printing by Noumena in Barcelona from November 2020 to March 2021, with the measurements of the traditional Catalan manual ceramic brick (4.5 × 14.5 × 29.5 cm).

As an initial step, the reaction–diffusion algorithm was employed to generate a diagram of the latest points to absorb water or liquids based on the clay hydrophilic nature. Given these maps that specify where the latest points to absorb liquids are, a shortest path algorithm in Anemone was used to connect these points. **Figure 3** shows the diagram of the shortest path algorithm connecting the reaction–diffusion's latest points to absorb water.

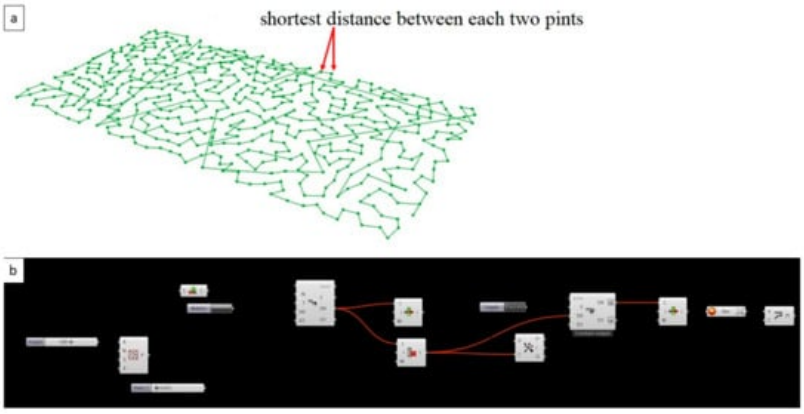

Figure 3. The shortest path algorithm in Grasshopper Anemone that was employed to connect the resultant latest points in the reaction–diffusion system based on the hydrophilic nature of clay. This proves the structural coherence of the bricks' design by minimizing the span between every two points while also minimizing the material consumption due to the accurate distributed material deposition where needed. (**a**) the resultant shortest path diagram of the connected points that were the last to absorb water in the volume of a conventional Catalan brick, and were resulting from the first step simulation of reaction diffusion, (**b**) the grasshopper algorithm of the shortest path logic that was applied to connect the result points from the first step simulation, in order to find the shortest distance between these points to minimize the span between them to achieve distributed load and minimum material deposition as well. Images by the author.

The third step was to examine these resulting shortest paths forms for the final brick resistance to cracking by applying a standard load simulation in Kangaroo, resulting in different design iterations: V1, V2, and V3. The optimum design iterations for structural behavior were selected to be further tested for various material densities, varying the density of each brick in a bulk brick model from 25%, to 55%, 75%, and 95%, and a linear or hollow brick model starting from the thickness of 0.25 cm, 0.55 cm, 0.75 cm, and 0.95 cm for each iteration (V1, V2, and V3), as shown in **Figure 4**, **Figure 5** and **Figure6**.

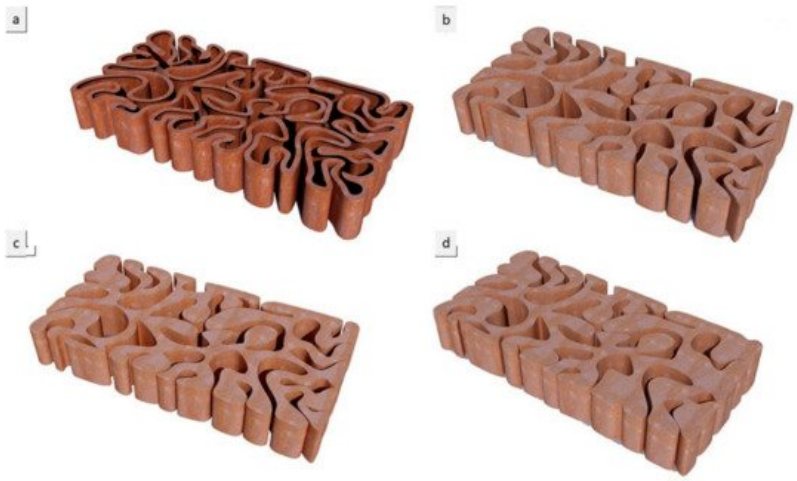

Figure 4. Alberto T. Estévez (Yomna K. Abdallah, computational designer), Biodigital Barcelona Bricks (3D-printed clay), GENARQ/iBAG, UIC Barcelona. V1 design iteration of the Biodigital Barcelona Bricks showing the bricks' varied material density from a linear model of 0.5 cm thickness to a bulk model (**a**–**d**), with the densities of the brick varying from 25% to 55% and 75%, to experiment structurally different densities of the 3D-printed bricks. Images by the author.

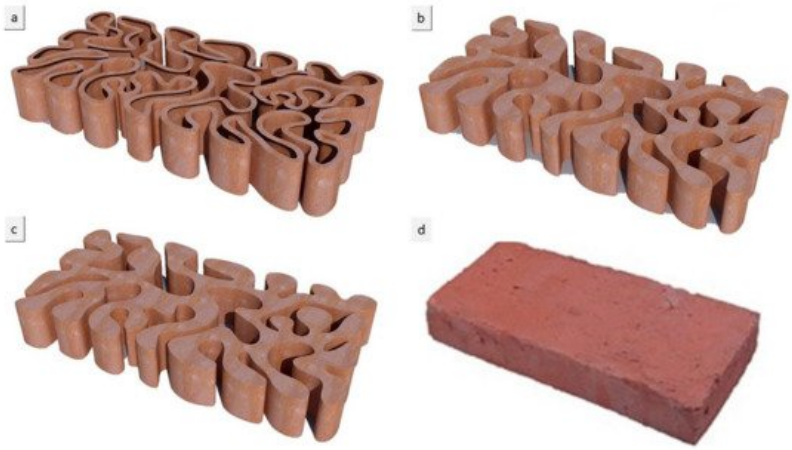

Figure 5. Alberto T. Estévez (Yomna K. Abdallah, computational designer), Biodigital Barcelona Bricks (3D-printed clay), GENARQ/iBAG, UIC Barcelona. V2 design iteration of the Biodigital Barcelona Bricks showing the bricks' varied material density from a linear model of 0.5 cm thickness in (**a**) to a bulk model, with densities of the brick varying from (**b**) 25% material deposition density to (**c**) 55% material deposition density, (**d**) exhibits the original Catalan brick form and unified density in comparison to the optimized proposed Biodigital Barcelona Bricks. Images by the author.

Figure 6. Alberto T. Estévez (Yomna K. Abdallah, computational designer), Biodigital Barcelona Bricks (3D-printed clay), GENARQ/iBAG, UIC Barcelona. V3 design iteration of the Biodigital Barcelona Bricks showing the bricks' varied material density from a linear model of 0.5 cm thickness to a bulk model (**a**–**d**), with the density of the bricks varying from 25% to 55% and 75%. Images by the author.

This density variation in the biodigital bricks' iterations enabled the actual study of the used material amount in these physical models, as well as their resistance to cracking. A following research paper will exhibit in detail further mechanical

tests to prove the structural efficiency of the proposed forms of the biodigital bricks. This 3D printed material examination customization was also reinforced by comparing to other digital fabrication strategies that will be exhibited in the following section, to prove the competence of 3D printing to achieve sustainability in material usage and production processes

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