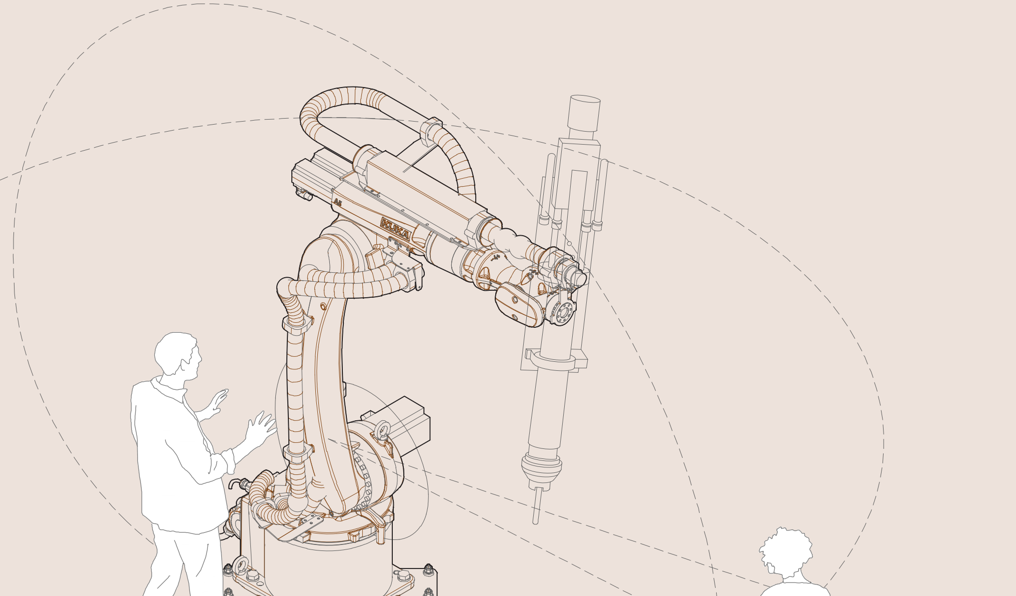
REPHRASING CONSTRUCTION

The emergence of 3D Printed Clay Building



I would like to express my sincere gratitude to my tutors, Relja and Carles, for their guidance and support throughout the writing of this paper. I am also thankful to all those who have helped me with their valuable feedback and encouragement. And those whose unwavering support and belief in me have been a constant source of motivation throughout my academic journey.

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ABSTRACT

With an increasing concern for the future of the built environment, sustainability and efficiency have become popular terms in many industries, including architecture. Through the development of computational technologies and 3D printers, many studies show the potential to revolutionize traditional design and construction methods. This essay explores the potential of clay 3D printing and materials, focusing on the uniqueness of clay as a construction material, including its sustainability and versatility. The essay delves into the difference between printing a large-scale continuous print versus printing individual elements, highlighting the benefits and drawbacks of each approach. Two case studies, Digital Adobe and TECLA, are analyzed in depth, showcasing the real-world application of continuous and discrete clay 3D printing processes. Subsequently, the discussion is shifted onto such a technology's future viability and potential. With the ultimate goal of providing insights into how this technology can be integrated into the traditional construction process to achieve better outcomes for the environment and the building industry as a whole.

Keywords:
Clay 3D printing
Computational design
Innovativion
Efficiency
Sustainable construction

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MOTIVATION

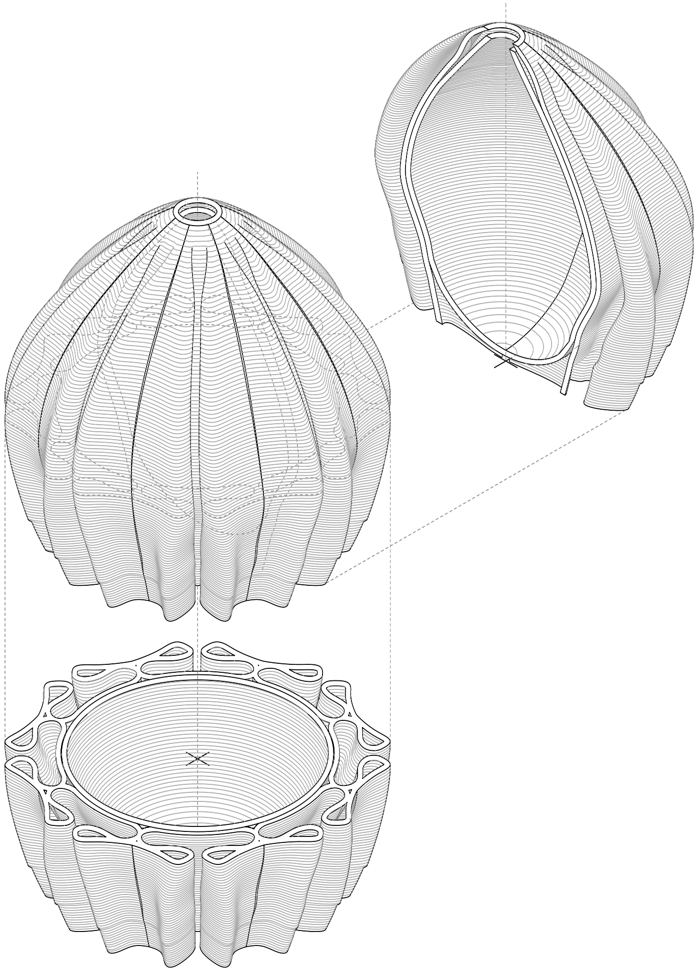
Throughout the many years of university we have been taught to face new problems with different design solutions. Courses such as projects and urbanism have given us the creative freedom to imagine whole buildings and environments off of a concept. While others such as construction and structures gave us the tools to understand the stability and feasability of our designs. Many students have fought to find their own style throughout these years, and I am no different.

My interest in sustainability and the usage of materials in unconventional arised from the very start of these formative years. However, it wasn't until third and fourth year that I started to implement it in my designs.

Fourth year Projects was my first dive into recycled materials, creating a temporary pavilion soley from recylced materials found nearby. Since the setting given by our mentors was close to the construction of a large new railway station on the west side of Barcelona, this gave me plenty of material to catalogue and use.

Moving on from that, in fifth year I was given the oportunity to experiment with different materials and techniques in the course of Taller Tematic LAC (Laboratory of Computational Architecture). Given the creative freedom of the course we were able to investigate areas and ideas that broke the boundaries of the more traditional concept of architecture.

Once having dived into sustainability methods, novelty techniques and materials thoughout university, my interest in these areas increased, leading me into taking part of a workshop based off of ceramic 3D printing in relation with wine making, lead by the AA architecutre school. The workshop called 75cl lasted a week, giving us just enough time to test out and execute the design of a multilayered vase, expected to hold wine during its fermentation process. Seeing how many ideas and designs failed due to the physical and chemical properties of clay gave me the first insight into this thesis paper. Eventually leading me into a path of questioning how ceramic 3D printing could be involved in the future of architecture and how current projects solve the issues that arrise.



Drawing generated during the 75cl workshop

OBJECTIVES

This research has as an objective reflecting on the necessity of change and readaptation of traditional methods of construction through the use of modern technology such as 3D printing. In particular, this essay aims to explore the potential of 3D printing, specifically clay 3D printing, within the architecture and construction sector. By investigating the unique properties of clay as a construction material, it will evaluate its suitability and limitations within the 3D printing technology, identifying the benefits and challenges for large-scale architectural projects. In addition, by discussing two case studies, the essay will evaluate their strategies and discuss their successful implementation of clay printing in architectural design and construction. Finally, the essay will identify the current limitations of clay printing technology and argue its impact on construction, material, and cost efficiency. Further discussing the potential of clay 3D printing to revolutionize the construction industry by offering creative freedom while promoting sustainable and efficient building processes.

METHODOLOGY

A systematic methodology for the literature review is adopted in this paper which includes three main stages: Research, case study selection, and analysis. These stages involved identifying and reading academic articles, research papers, and other relevant sources to understand the topic thoroughly. The investigation involved the search for keywords related to 3D printing in architecture, as well as the properties of clay as a construction material. Secondly, two case studies will be selected based on their relevance and significance. The selected case studies will have a clear connection to the application of clay in 3D printing architecture while simultaneously having two different approaches. The essay will then analyze and compare the two cases, focusing on the use of the material and technique. The essay will analyze and compare the two, identifying their similarities and differences while examining factors such as the design process, construction methodology, and material process.

INTRODUCTION

With the development of technology and design, we have seen a proliferation of new forms and construction processes. Nevertheless, it has not been until a few years ago that we started to see a market flooded with the ideas and experiments of 3D printing. In the mid-1980s, Charles Hull developed the first commercial 3D printer. However, it was in the 1990s that the first large-scale printer was developed, enabling the possibility of involving it in the construction sector. Since then, we have seen a new generation of ideas based on the automation in architecture and its ability to push architecture into an unexpected new domain of previously unachievable complexity, detail, and materiality[1]. As stated by Dries Verbruggen in the book Printing Architecture: Innovative Recipes from 3D printing when talking about the influence of architecture on design: "We witness a flood of algorithmic designs straight from the future that exploit this freedom as if the objects were unbound by the laws of physics, the limits of real-world materials, or the age-old traditions and heritage of making things."[2]

Not only does it respond to flexibility, detail, and personalization, but it also becomes an alternative to inefficient and wasteful production chains. As established, materials and their manufacturing process are highly related to their carbon footprint. Through performance analysis and simulations of materials and designs, digital fabrication becomes the perfect asset for answering the demand for energy, cost, and material-efficient construction.[3]

By analyzing the current market of materials used in 3D printing, we can establish a clear dominance in concrete-based construction. However, there is a recent surge in research using locally available, inexpensive, sustainable sources of materials, such as clay, due to its sustainability, performance, and thermodynamic properties.

Clay has been used to make objects and architecture for centuries. Its abundance in nature and the ease with which clay can be extracted and processed by adding water and other additives, such as straw and sand, to change its shape and strength, respectively, meant it would become one of the most popular building techniques to this day. It is evident that there is a clear evolution in the composition, shape, and manufacturing processes from their very simplistic origins. Knowledge of the composition and properties of clay products has given us a broader range of possibilities and, most importantly, allowed us to exploit its strength, stability, and durability. Combined with digital fabrication, we can achieve results that overcome the deficiencies and waste that arise from traditional-based construction methods.

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[1] Žujović, Maša, et al. "3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review." Buildings, vol. 12, no. 9, 2022, p. 1319., https://doi.org/10.3390/buildings12091319.

[2] Rael, Ronald, and Virginia San Fratello. "Clay Bodies: Crafting the Future with 3D Printing." Architectural Design, vol. 87, no. 6, 2017, pp. 92–97., https://doi.org/10.1002/ad.2243.

[3] Dubor, Alexandre, et al. "Energy Efficient Design for 3D Printed Earth Architecture." Humanizing Digital Reality, 2017, pp. 383–393., https://doi.org/10.1007/978-981-10-6611-5_33.

[4] Moretti, Francesca, et al. WASP, WASP World's Advanced Saving Project, 8 Nov. 2021, https://www.3dwasp.com/en/.

> "Earth is available everywhere in the world; it is cheap and easily malleable. Combined with other "zero-mile" local materials, clay can create printed buildings that last in time, that adapt to the territory and that do not leave ruins behind once no longer used" (Moretti, Francesca)[4]

3D PRINTING

METHODS AND PROCESSES

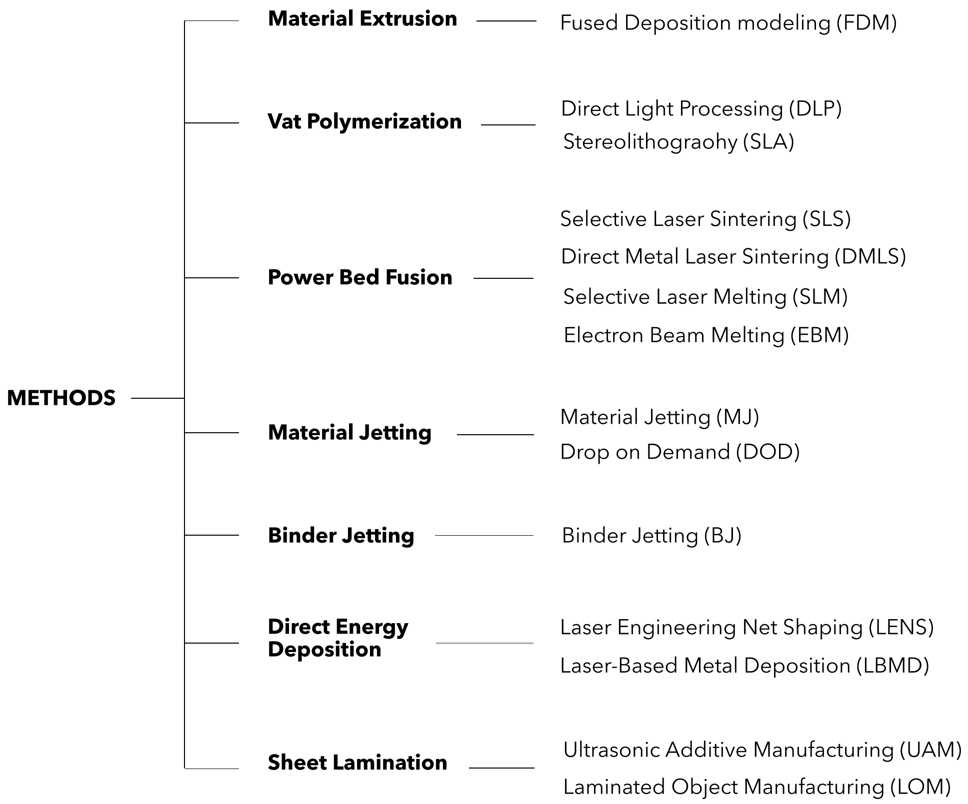


Diagram made by author

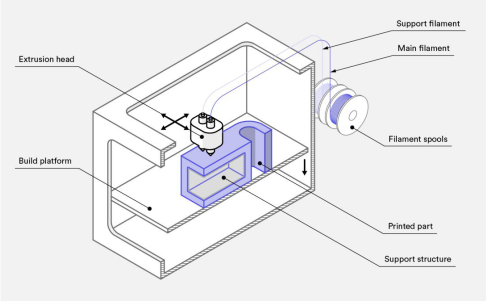
OVERVIEW OF 3D PRINTING

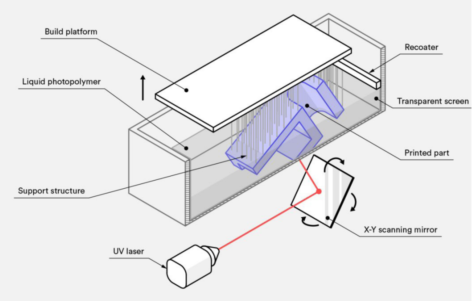
To preface, 3D printing encompasses a set of processes and technologies that carry out production through a layer-by-layer additive process. Since the creation of the first 3D printer, new printers, and printing types have been exponentially developed. In the past decade, there has been a flood of different 3D printers, with alternate applications emerging almost daily. Although initially limited to industrial applications, it has become more accessible to a broader range of users. It can now be applied to numerous fields, from medicine to construction or fashion. According to the 3D printing guide published by the 3D printing industry, the reasoning behind this insurgence and growing popularity is the ability to overcome many of the limitations of traditional manufacturing. For many applications, such as those mentioned above, traditional design and production processes impose several constraints and can result in up to 90% of the original block of material being wasted.[5] Therefore, the need to counteract these constraints has led to the exponential emergence of new processes, summed below.

To further talk about the different methods and applications of 3D printing, we will often reference a book that has become well-known for anyone intending to venture into the world of 3D printing due to its simplicity and understandability. The book mentioned is The 3D Printing Handbook by Ben Redwood, Filemon Schöffer, and Brian Garret.

The 3D printing technology that will be focused on in this paper is Fused Deposition Modeling (FDM) due to the nature of the material used. Having said that, we can currently find seven different methods of 3D printing, standardized with the ISO/ASTM 52900 according to the 3D Printing Handbook.[6] The seven methods and their respective technologies are represented in the previous diagram.

It is important to note that some of the limitations of 3D printing are that there is no "one solution fits all" and, therefore, many of the technologies currently used can overlap in terms of materials and applications. Despite that, in general, the most popular technologies and their applications at this moment are:





FUSED DEPOSITION MODELING:

Fused Deposition Modeling (FDM), also known as fused filament fabrication (FFF), is a process that builds models layer by layer by selectively depositing melted material on a path. It is currently the most popular process and has the most extensive base of 3D printers worldwide. It works through the deposition of thermoplastic filament and is ideal for creating prototypes, models, and functional parts such as prosthetics and architectural models.

STEREOLITHOGRAPHY:

Stereolithography (SLA), widely recognized as the first 3D printing process, and Digital Light Processing (DLP) are resin-based printing that produces high-resolution parts with a smooth surface, used in jewelry, dental models, and figurines. According to the 3D printing guide, they are generally accepted as being one of the most accurate 3D printing processes but have limiting factors, including post-processing steps and materials' stability over time.

Diagrams courtesy of HUBS[7]

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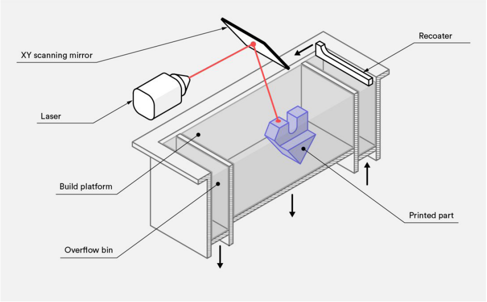
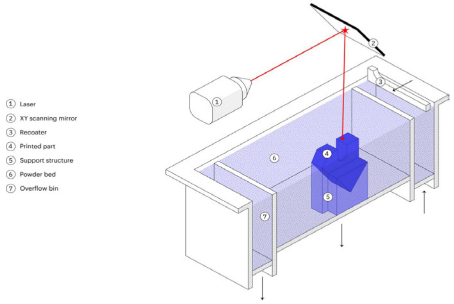
[5] Beginner's Guide to 3D Printing. 3D Printing Industry, https://3dprintingindustry.com/, https://3dprintingindustry.com/wp-content/uploads/2014/07/3D-Printing-Guide.pdf.
[6] Redwood, Ben, et al. The 3D Printing Handbook: Technologies, Design and Applications. 3D Hubs B.V., 2020.
[7] "On-Demand Manufacturing: Quotes in Seconds, Parts in Days." Hubs, https://www.hubs.com/.



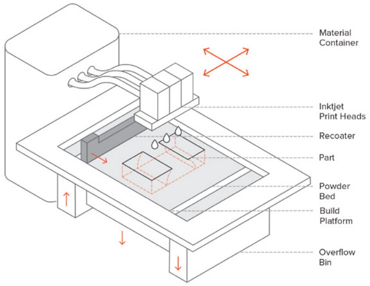
SELECTIVE LASER SINTERING:

Selective Laser Sintering (SLS) is a process that uses lasers to sinter or melt powder together from a variety of materials, including nylon and metal, to form the final object–commonly used for more complex geometries such as aerospace components, medical implants, and automotive parts.



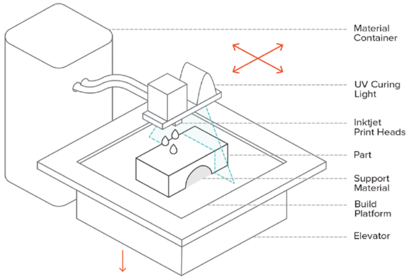
DIRECT METAL LASER SINTERING:

Direct Metal Laser Sintering (DMLS) is a method of SLS that uses explicitly metal powder to create high-strength, intricate parts that can be practically impossible to make through other conventional methods.



BINDER JETTING:

Binder Jetting is a process that consists of a binder selectively deposited onto a powder bed to bond together parts of the material one layer at a time. Typical applications are full-color prototypes, large sand casts and molds, and architectural models.



MATERIAL JETTING:

Material Jetting, unlike other processes, the material is solidified through photopolymerization in a line-wise fashion. Multiple inkjet printheads deposit material on the whole print surface in a single pass, allowing the heads to dispense different materials. Multi-material and multi-color printing can be found in prototypes, educational medical models, or jewelry.

Diagrams courtesy of HUBS[7]

3D printing has come a long way since its inception and continues to revolutionize various industries today. Each method of 3D printing has its unique advantages and disadvantages, and the choice of method depends on the project's specific needs. Each method has its strengths regarding materials used, accuracy, and speed. As the technology continues to evolve, we can expect even more advancements in 3D printing methods and materials, pushing the boundaries of what is possible in the world of additive manufacturing and beyond.

3D PRINTING

MATERIALS AND PROCESSES

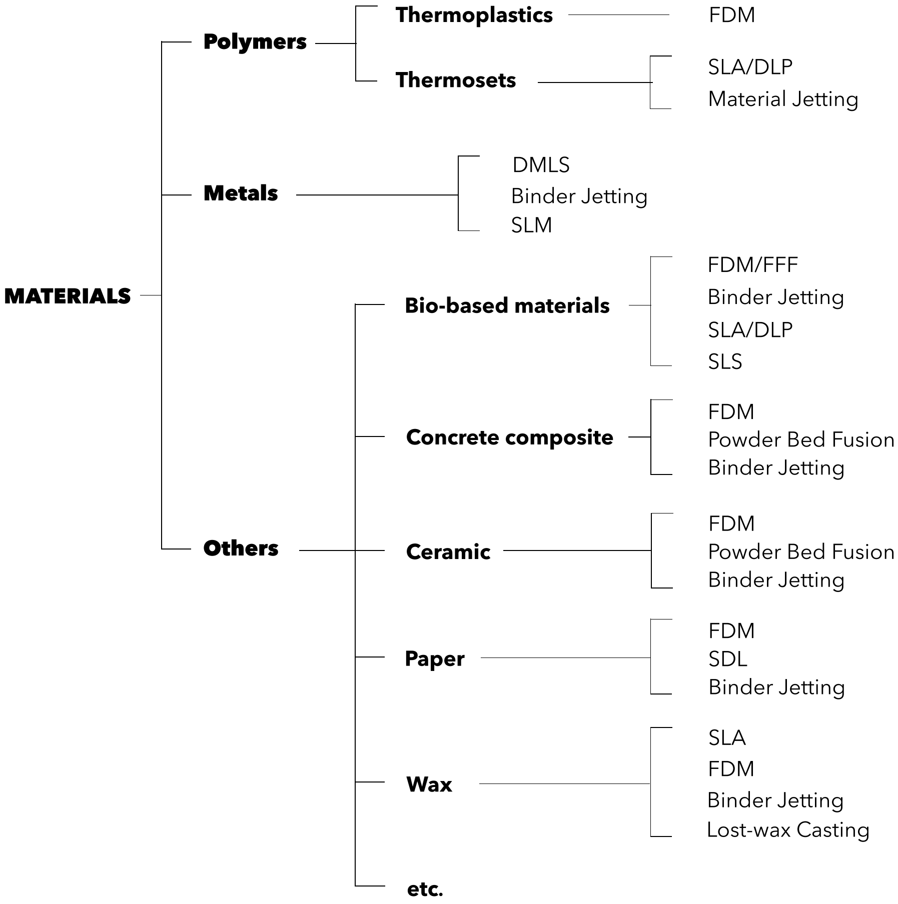


Diagram created by author

3D PRINTING MATERIALS

Alongside the evolution and development of the new technologies mentioned in the previous section, there has been a continuous appearance of new materials for use in 3D printing, driven in part by the efforts of "material designers," according to Alessia Romani. The designers' experimentation with various materials and formulations provides us with the variety that can be found in the market.[8] While the typical 3D printing materials are still widely used today, we now have a more expanded range of options. The 3D printing Handbook categorizes the materials commonly used into three areas, though the rapid evolution in the last couple of years leads to the belief that it has become obsolete. While we can still categorize them as plastics, metal, and other,[9] the other has grown far beyond those mentioned in the book.


image courtesy of Formlabs

POLYMERS:
FDM, SLA/DLP, Material Jetting
Polymers, or plastics, are either **thermoplastics** or **thermosets**. The first can be melted and solidified repeatedly, used mainly through FDM processes. In contrast, the second does not melt and usually starts as a viscous fluid that is cured to become solid through processes like SLA/DLP or Material Jetting. Some examples of thermoplastics are PLA, ABS, PETG, nylon, and TPU. Common thermosets include epoxies, resins, or photopolymers. These are some of the most readily-available and inexpensive materials in small-scale printers, making them trendy choices in the industry.[10]
Despite their popularity, their high carbon footprint and the current social and environmental context have caused a push into academic research and practice of waste-based thermoplastics, according to Alessia Romani. We can now see early applications of waste-based thermoplastics with material extrusion processes flood the market.

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8. Romani, Alessia, et al. "Design, Materials, and Extrusion-Based Additive Manufacturing in Circular Economy Contexts: From Waste to New Products." Sustainability, vol. 13, no. 13, 2021, p. 7269., https://doi.org/10.3390/su13137269.
9. Redwood, Ben, et al. The 3D Printing Handbook: Technologies, Design and Applications. 3D Hubs B.V., 2020.
10. Beginner's Guide to 3D Printing. 3D Printing Industry, https://3dprintingindustry.com/, https://3dprintingindustry.com/wp-content/uploads/2014/07/3D-Printing-Guide.pdf.
11. "Metal Filament 3D Printing – the Ultimate Guide." All3DP Pro, 10 Apr. 2023, https://all3dp.com/2/3d-printer-metal-filament-for-real-metal-parts/.


image courtesy of ALL3DP.pro

METALS:
DMLS, Binder Jetting, SLM
In most additive manufacturing processes that involve metal, such as DMLS or Binder jetting, it is used exclusively in powder form. Typical metals include stainless steel, titanium, aluminum, or cobalt derivatives.[9] Due to the incredible high-quality, functionality, and mechanical properties, but at the same time higher cost of these materials destines them to more industrial rather than hobbyist uses. In the last couple of years, gold and silver have also been incorporated into the list of metals used, making a significant advance in the jewelry sector.[11]

OTHERS:
The term others is an extensive classification of the materials that have been emerging in recent years. Nevertheless, since many are still in experimental phases and have just a few practical applications, it is hard to classify which materials will be successful in the long run. Romani's article analyzes the emerging trends in design and materials in extrusion-based additive manufacturing from 2015 onward, where we can observe an exponential increase in academic research and practice on the subject. Some of the materials that are mentioned are:


image courtesy of 3Dnatives

-Bio-based materials:
FDM, Binder Jetting, SLA/DLP, SLS
This could be any material derived from plant-based sources, such as crops, trees, and other vegetation. Many of these are often biodegradable, compostable, and have a lower environmental impact, making them favorable over petroleum-based plastics. Some examples of bio-based materials used in 3D printing include cellulose, Starch-based materials, or hemp-based materials.

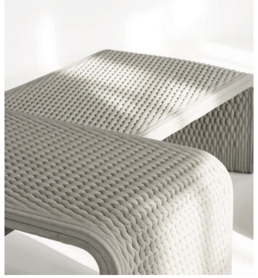
image courtesy of Dezeen

-Concrete composite:
FDM, Powder Bed Fusion, Binder Jetting
Very similar to the traditional mixture of concrete, including cement, water, and other additives such as polymers or fibers, many of the applications of the concrete are construction-based. With a growing trend in rapidly printed houses, this has become one of the most popular materials used in large-scale printing.

image courtesy of Emerging Objects

-Ceramic:

FDM, Powder Bed Fusion, Binder Jetting

Curiously enough, ceramic materials can be found in more than one printing process through the use of powder, liquid form, or filaments with ceramic composites. They have been implemented not only in large-scale and small-scale art and architectural projects, but also in medical and dental settings. The use of ceramics improves mechanical properties, thermal stability, and electrical insulation. With the added benefit of being a relatively easy recyclable material, we can establish a closed circular life cycle.[12]

image courtesy of 3Dnatives

-Paper:

FDM, SDL, Binder Jetting

Paper is a relatively innovative material and can be found in some of the emerging processes. Due to the properties of paper, the current applications can mostly be found in prototypes and architectural models. The main advantages to using paper are and the recyclability and biodegradability of the material, as well as the drastic price difference, specifically 5% the cost per volume of other filaments as stated in 3D Sources.[13]

image courtesy of Formlabs

-Wax:

FDM, SLA, Binder Jetting, Lost-wax Casting

In contrast to many of the materials mentioned above, it tends to be used as formwork when used in its pure form. As stated in ALL3DP.pro, this is one of the few materials used almost exclusively in two industries, the jewelry and dentistry sector. As research continues, some exceptions arise, expanding the possibilities of wax in small-scale and industrial-sized projects, such as the construction formwork researched by IAAC.[14]

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12. Romani, Alessia, et al. "Design, Materials, and Extrusion-Based Additive Manufacturing in Circular Economy Contexts: From Waste to New Products." Sustainability, vol. 13, no. 13, 2021, p. 7269., https://doi.org/10.3390/su13137269.
13. Shepheard, Sam. "Paper 3D Printing: The Complete Guide." 3DSourced, 19 Mar. 2021, https://www.3dsourced.com/guides/paper-3d-printing/.)
14. Behram, Yigitalp. "Wax 3D Printing." IAAC Blog, 21 June 2020, https://www.iaacblog.com/programs/formwax/.

CLAY

PROPERTIES AS A CONSTRUCTION MATERIAL

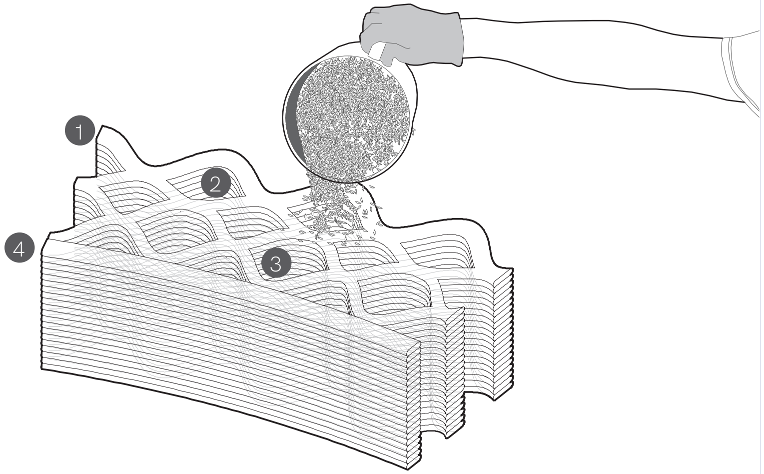
THERMAL PROPERTIES

Although the thermal characteristics of a material can vary largely on its mass, water content, and porosity, it is known that as a material, adobe has a low thermal resistance (R-value). Since there are too many factors that affect the thermal resistance of clay, for the purpose of this research and to understand the properties of clay, we will take into account the values recorded by the New Mexico energy conservation code.[15] They establish a certain set of parameters of common construction materials where we can find that Adobe has an R-value of 0,11 per cm while a common brick has an R-value of about 0,08 per cm,[16] meaning that for a thickness of 25cm of either adobe or a common brick we could have a value of 2,75 or 1,97 respectively.

When comparing it to other building materials we see that concrete has a similar thermal resistance with about 0,04-0,08 per cm while wood has a much higher resistance around 0,5. Therefore to achieve a good thermal resistance there is an inherent importance placed on mass and insulation methods within the adobe walls.

On the other hand, we can observe that Adobe is a capacitor which means it has the ability to store heat and moisture really well. With this storage comes a slow release, making it ideal in climates with a large fluctuation in temperatures and/or other extremes. High-mass walls and correct orientation of the buildings will favor this characteristic. Consequently, acknowledging both its deficiencies and advantages in its thermal characteristics help us adapt the structure and design of the building to favor the local climate.

In the drawing adjescent, we can observe an example of a project, created by WASP called GAIA, that took into consideration the clays' thermal characteristics and used it to an advantage when designing. In this case they used a thicker outer layer, giving it more inertia, and therefore storing more heat in the colder seasons. But also kept a ventilated chamber before the insulated layers in order to allow the flow of air to cool down the exterior layer in warmer months. In order to counteract the lack of insulation that the clay provided, the interior layers were filled up with rice husks, a byproduct of rice production which happens to be very insulating. The succession of layers is finished with a thick inner lining in order to control the humidity in the interior of the home.



1 Thick outer layer for heat gain in colder months

2 Ventilated layer to release heat in warmer months

3 Rice husked filled layers to provide insulation

4 Thick inner layer to regulate humidity

Drawing created by author

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15. Dondi, Michele, et al. "Thermal Conductivity of Clay Bricks." Journal of Materials in Civil ENgineering, vol. 16, no. 1, 2004.
16. Oti, J.E., et al. "Design Thermal Values for Unfired Clay Bricks." Materials & Design, vol. 31, no. 1, 2010, pp. 104–112., https://doi.org/10.1016/j.matdes.2009.07.011.

DURABILITY AND STRENGTH

Much like its thermal properties, its durability depends on the composition of the adobe. Since we have very limited information on the characteristics of the compressive strength of 3D printed clay we have to extrapolate information gathered from other clay, specifically adobe based construction techniques.

Although there is a limited amount of research, and a large part of it depends on the manufacturing technique and permissiveness of deformations in construction, results vary throughout. However, looking at a few studies that did in depth research on the mechanical properties of adobe bricks, we can establish that it has a compressive strength of about 0,5 to 3,2 MPa when you assume a maximum of 5% deformation in the element[17]. This is backed up by the International Building Code 2021 which establishes that the most adobe units (meaning adobe bricks) have an average compressive strength of 300 psi (2,06MPa).

In the case of extruded adobe, it is yet too innovative to have established a universal required compressive strength. But due to the similarity in execution and composition, for the sake of this study we will establish it to have a compressive strength similar to that of an adobe brick.

Having a compressive strength of around 2 MPa signifies that the adobe construction will need a significantly higher mass in order to withstand vertical loads, and even then it might be insufficient. It also suggests that compared to other construction materials, its durability is limited, especially when you consider freezing and thawing cycles. Due to its high water composition, when in extreme cold weather the freezing and thawing damages its interior structure, producing cracks and diminishing its final compressive strength.

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[17] Illampas, R., *et al. "A Study of the Mechanical Behaviour of Adobe Masonry." WIT Transactions on The Built Environment, 2011*, https://doi.org/10.2495/str110401.

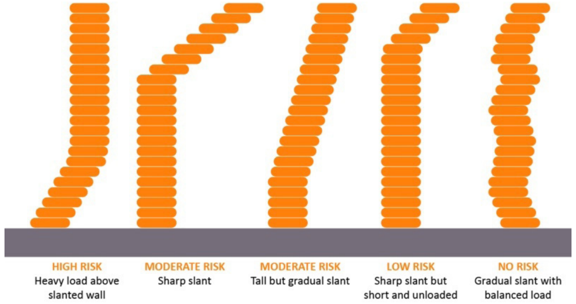
DESIGN RESTRICTIONS OF 3D PRINTING

Previously we have talked about the characteristics of the material and how these can alter the design and construction of the piece. Yet we have not considered the restrictions due to the combination of such material and additive manufacturing.

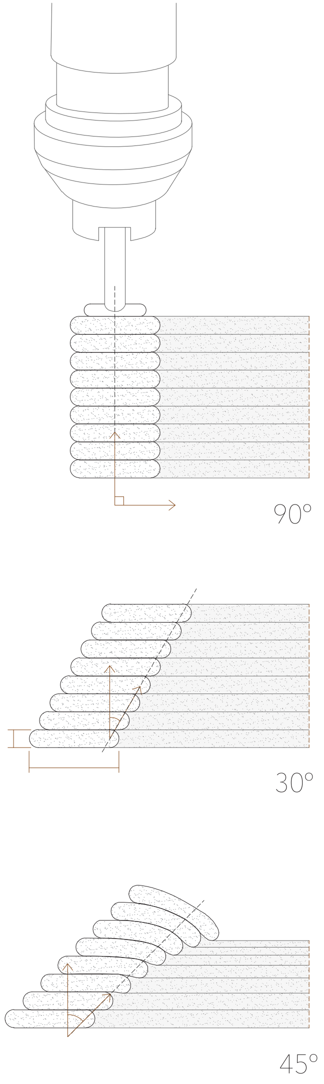
Throughout this paper, we have mentioned 3D printing many times, but to be specific, we are referencing 3D printing via material extrusion additive manufacturing. This encompasses a form of printing based on material extrusion through a nozzle to create a three-dimensional object layer-by-layer. Since all materials are poured and extruded in liquid form, there will always be restrictions to the angle and curvature that the design may have. Albeit, combined with the type of material, the toolpath and threshold of the geometric requirements will vary. Since clay does not have the structural stability of many other common materials and, at the same time, tends to shrink and slump, the angle of the surfaces being generated relative to the perpendicular to the plate or base needs to stay under a certain threshold.

Many guides to 3D printing recommend a maximum overhang of 45 degrees. Notwithstanding, this usually applies to plastic printing and considers the possibility of creating supports. Nevertheless, the support offered by slicing software is often too flimsy to be built in soft clay. [18] Therefore, as a general rule of thumb, as stated by Jonathan Keep, an artist whose last years have been dedicated to the experimentation with clay 3D printing, as well as other experienced users through forums dedicated to Ceramic 3D printing and various IAAC studies, the safer option is to stay under 30 degrees.

In contrast to other materials used in 3D printing, this rule becomes much more restrictive when it comes to the design, as it is important to be much more conscious and add other elements if the goal is to achieve greater angles. This will be touched upon when we analyze the design process of the architectural projects in the two case studies chosen.



Taking into account the risk of overhangs at high degrees and the lengthy time it takes clay to harden, the figure above, posted by the University of Yale, shows a series of wall sections, rated according to how likely they are to succeed or fail during printing. [19]



Drawing created by author

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[18] Keep, Jonathan. "A Guide to Clay 3D Printing." 10 Jan. 2020.

[19] "Example Sections through Toolpath." Clay 3D Printing Design Guide, Yale Architecture, 28 July 2020, https://www.architecture.yale.edu/advanced-technology/tutorials/32-clay-3-d-printing-design-guide.

DISCRETE VS CONTINUOUS PRINTING

This paper analyzes two different construction methods through 3D printing with a clay-based material. We have looked at clay's properties and how they can be used to their advantage. Now we must understand the advantages and disadvantages of the technique used to achieve the finished product. Purposefully, the two projects chosen were Digital Adobe by the IAAC and TECLA by WASP, which have two very distinct approaches to 3D printing. One through discrete elements and the other with one continuous piece.

The discrete element-based method allows for printing individual elements that can vary in shape and size depending on the project's necessity. If the project is relatively simple, printing individual, repetitive elements become rather fast and mechanical, making it a prefabricated solution that achieves time-process sustainability.

The use of digital design for these bricks can generate many more functional elements and possess formal adequacy for the necessities of the construction at hand. While simultaneously permitting the adoption of fluid, complex shape geometries and guaranteeing minimum material consumption and maximum forma-function coherency. Therefore, being a tremendous alternative construction procedure to conventional clay brick production.

Even though it avoids the high cost of much larger 3D printing machines and lengthy processes of the one-step, full-scale architecture, we have to consider that a component-based method has an added labor cost that comes with the construction on site. [20]

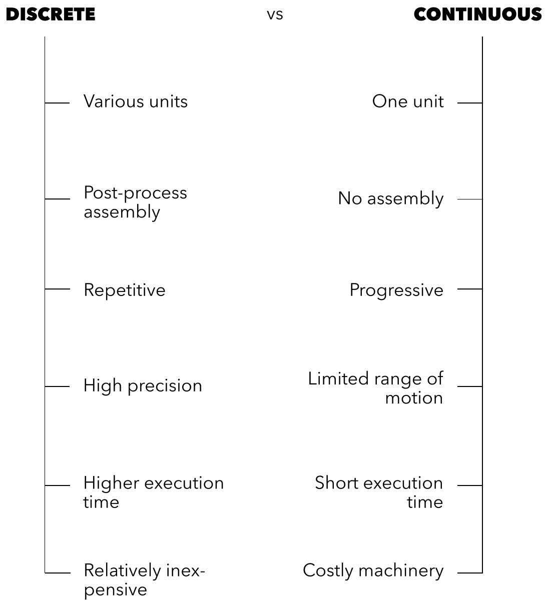
Let us look at the continuous printing method, also known as large-scale additive manufacturing. in comparison to the method mentioned above, it has been more extensively researched. It requires the development of much larger 3D printers, thus also requiring a much larger surface area to print, usually the project's area plus the area required by the 3D printing machinery. These printers have the negative attribute that they have limited mobility and need to be assembled and disassembled at each construction site. Therefore also decreasing economic efficiency due to additional costs for transportation and assembly of individual elements.

Similarly to the previous method, there is little to no waste in material due to the precision and effectiveness of digital production. With the added benefit that, in this case, it is possible to use a thicker grain and can include thick recycled aggregates from previous projects.

Much harder to control the end product when upsizing a project from model to full-scale house.

Nevertheless, one of the most significant advantages is that using one continuous print reduces the active labor required and construction time. It now only becomes necessary to have a few qualified specialists develop and print the project. Compared to component-based manufacturing, the time needed to complete the entire building can be drastically lower. Due to the lack of physical labor and aggregation of different components, building floors of about 130m2 can be built in up to one day.[21] Making this the ideal process for building homes in short periods.

To understand how the properties of such printers were taken advantage of, in combination with the properties of clay, in the following pages, there will be a detailed comparison of the aforementioned projects. For the reader's sake, it is essential to mention that the pages on the right will be dedicated to the project of Digital Adobe. Whereas those on the left will be dedicated to TECLA, in order to achieve a simultaneous comparison.



DISCRETE	vs	**CONTINUOUS**
Various units		One unit
Post-process assembly		No assembly
Repetitive		Progressive
High precision		Limited range of motion
Higher execution time		Short execution time
Relatively inexpensive		Costly machinery

Diagram created by author

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[20] Abdallah, Yomna K., and Alberto T. Estévez. "3D-Printed Biodigital Clay Bricks." Biomimetics, vol. 6, no. 4, 2021, p. 59., https://doi.org/10.3390/biomimetics6040059.

[21] Puzatova, Anastasia, et al. "Large-Scale 3D Printing for Construction Application by Means of Robotic Arm and Gantry 3D Printer: A Review." Buildings, vol. 12, no. 11, 2022, p. 2023., https://doi.org/10.3390/buildings12112023.

TECLA

CONTINUOUS PRINT

DIGITAL ADOBE

DISCRETE ELEMENTS

BEHIND TECLA

Founded in 2012 by Massimo Moretti, WASP (World's Advanced Saving Project) is a company dedicated to designing, producing, and selling 3D printers in Italy. The company was built on a vision to use 3D printing to address global housing shortages and provide sustainable solutions for building constructions. Therefore, in addition to selling 3D printing technology, they offer training and educational programs worldwide to incentivize sustainable construction practices and the use of local materials. As stated in their manifesto: by making their projects accessible to the general public, they create a new production chain with ground-zero materials, less material waste, and adaptability to the users' needs.[22]

Their sales revenue is then re-invested in the research and development of their projects. Many are based on the use of clay and other environmentally friendly materials such as bio-plastics, silicone, and biocompatible materials. Presented as a long-term program in 2019 as "3D printing for Sustainable Living", they have curated their vision into creating "zero-mile" homes for the past few years, TECLA being one of these projects. In order to achieve their goals, they rely on the collaboration of institutions, companies, architects, and engineers to achieve high construction performance with low environmental impact.

With the help and development of some of the world's largest and most innovative 3D printers, they have been able to present projects that break boundaries in terms of cost and time efficiency. Some of the recent projects include GAIA, a housing project which combined raw soil with natural waste materials that came from the rice production chain; TOVA, a project in collaboration with IAAC with zero waste and nearly zero carbon emissions; and the House of Dust, a collaboration with TinyBE to bring to life a visionary sculpture developed in 1968 through artificial intelligence.

TOVA

Location: Barcelona
Printer: Single Crane
Year: 2022

THE HOUSE OF DUST

Location: Wiesbaden
Printer: Single Crane
Year: 2021

GAIA

Location: Wiesbaden
Printer: Single Crane
Year: 2018

Images courtesy of WASP's press releases: https://www.3dwasp.com/en/3d-printing-architecture/

22. Moretti, Francesca, et al. WASP, WASP World's Advanced Saving Project, 8 Nov. 2021, https://www.3dwasp.com/en/.

BEHIND DIGITAL ADOBE

IAAC stands for Institute for Advanced Architecture of Catalonia. It is an international center for education, research, and development in architecture, urbanism, and technology-based in Barcelona, Spain. As they claim, their mission is to position themselves as a worldwide reference for education and research, as well as for self-sufficiency and digital fabrication through the consolidation and expansion of research projects and academic programs. Similarly to WASP, most of their current research is related to green architecture, sustainability, and renewable energies, highlighting the use of innovation and technology to achieve their primary goal: imagine the future habitat of our society and build it in the present. Their multiple pioneering master programs approach their mission through different paths, one of them through the development of 3D printing technology in combination with clay (origin of the Digital Adobe project).

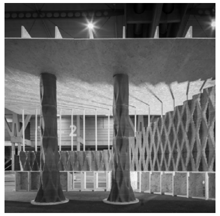
IAAC has conducted research projects in different parts of the world, including Brazil, Taiwan, Croatia, and Romania. As a curious fact, the Institute is responsible for designing the first 3D printed bridge in the world in collaboration with Acciona (a Spanish multinational conglomerate dedicated to developing and managing infrastructure and renewable energy), which was built in Alcobendas, Spain, in 2016.

Beyond its educational and pro-research project work, it is also seen as an interdisciplinary and multicultural stable community that seeks permanent contact and cooperation among hundreds of teachers, researchers, institutions, and companies from over 40 countries, enabling a platform for the exchange of knowledge in order to provide solutions to the significant challenges of humanity.

3D PRINTED BRIDGE

Location: Madrid
Year: 2016

Bridge printed with discrete elements and assembled on site



BCN CONSTRUMAT INSTALATION

Location: Barcelona
Year: 2017

On site 3D printing robotics instalation

DIGITAL MATTER STUDIO

Location: Barcelona

Master dedicated to material research for the built environment

Images courtesy of the IAAC webpage: https://iaac.net/

23. "About IAAC - Institute for Advanced Architecture of Catalonia." IAAC, 30 Nov. 2022, https://iaac.net/iaac/about/.

DESCRIPTION OF TECLA

Date: April 2021

Location: Massa Lombarda, Italy

Time: 200h

Toolpath length: 150km

Max. height: 4,2m

Printer configurations:

2 collaborative Cranes

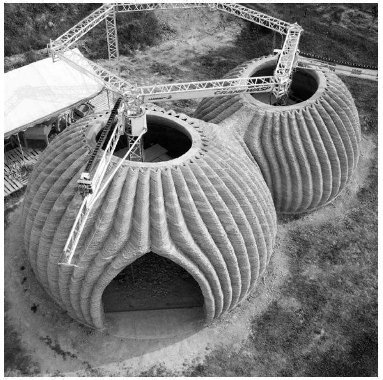


Image provided through WASP's press release

TECLA is a zero-emission housing prototype located in Massa Lombarda, designed by MCA (Mario Cucinella Architects) in collaboration with WASP, one of the largest companies dedicated to 3D printing with eco-friendly, sustainable and functional materials. TECLA, unlike other projects developed by WASP, had the peculiarity of being a construction dependant solely on one material: clay. The entirety of it's structure was made out of a Km 0 material, raw earth found in the vicinity of it's production. The final installation showcased two domes, with a total of 60 square meters and 4,20m tall, connected with a shared opening, with three space, a kitchen, a living spaces and a sleeping area. The top of the domes, were topped off with a skylight and its entrance by a glazed door within an arch.[25]

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24. Moretti, Francesca, et al. WASP, WASP World's Advanced Saving Project, 8 Nov. 2021, https://www.3dwasp.com/en/3d-printed-house-tecla/

25. Parkes, James. "Mario Cucinella Architects and WASP Creates 3D-Printed Sustainable Housing Prototype." Dezeen, 23 Apr. 2021, https://www.dezeen.com/2021/04/23/mario-cucinella-architects-wasp-3d-printed-housing/.

DESCRIPTION OF DIGITAL ADOBE

Date: March 2018

Location: Barcelona, Spain

Time: aprox. 10 days

Toolpath length: 26,25km

Max. height: 5m

Printer configurations:

KUKA robotic arm

Image provided through IAAC's blog

Digital Adobe is an innovative research project that took part in a more extensive post-graduate program called Open Thesis Fabrication on Adobe 3D printing for the performative habitat. The intention was to provide architectural solutions using readily available materials, such as clay, in addition to additive manufacturing. The goal was to enable the customization of the building form on multiple scales, creating a final piece with highly performative structural and passive climatic behavior. [26]

Starting with a series of small-scale prototypes that would help evolve and study the behavior of the final piece, a 1:1 scale prototype of a small section of the whole building was later constructed. This resulted in a 2-meter wide and 5-meter high printed clay wall with varying thicknesses facing south. Its intrinsical infill patterns varied as height increased, incorporating the design of a structural support for four wooden beams and a wooden platform that would simulate a building's first floor.

The final design resulted in 26.254 meters of 3D printing path, divided into 99 individual elements assembled in IAAC's Valldaura Self-Sufficient Lab campus in March 2018.[27]

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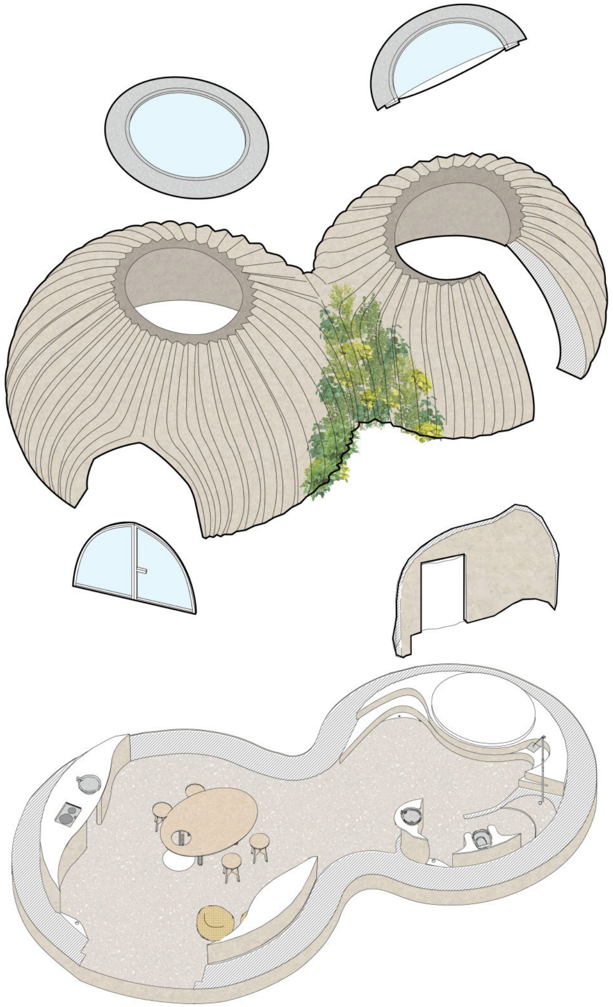
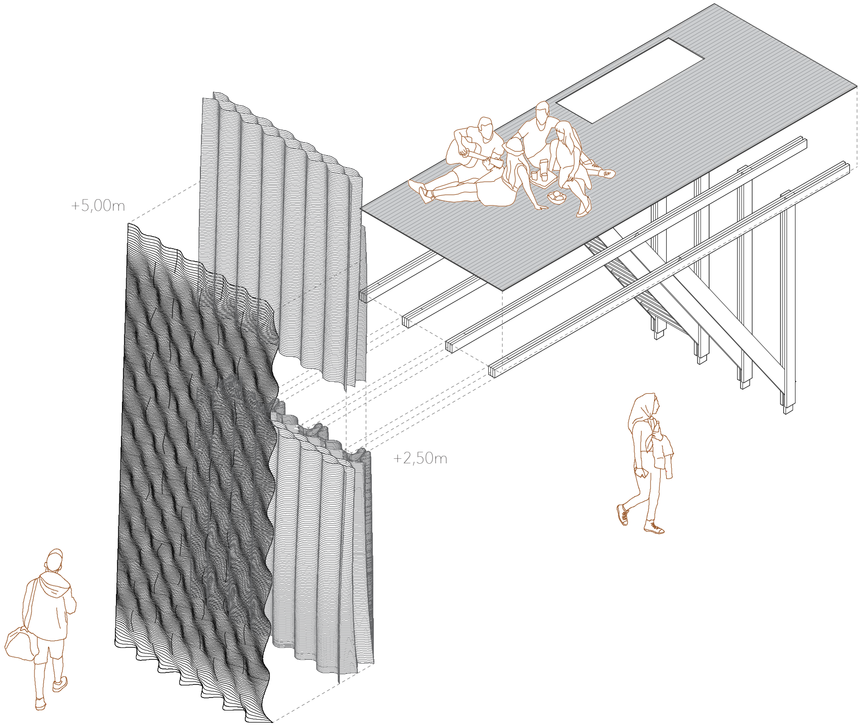
26. Chang, Yachieh. "Digital Adobe - Additive Manufacturing with Adobe towards Passive Habitats." IAAC Blog, 11 Aug. 2018, https://www.iaacblog.com/programs/digital-adobe-additive-manufacturing-adobe-towards-passive-habitats/.

27. "Digital Adobe." IAAC, Institut d'Arquitectura Avançada De Catalunya, 30 Apr. 2019, https://iaac.net/project/digital-adobe/.

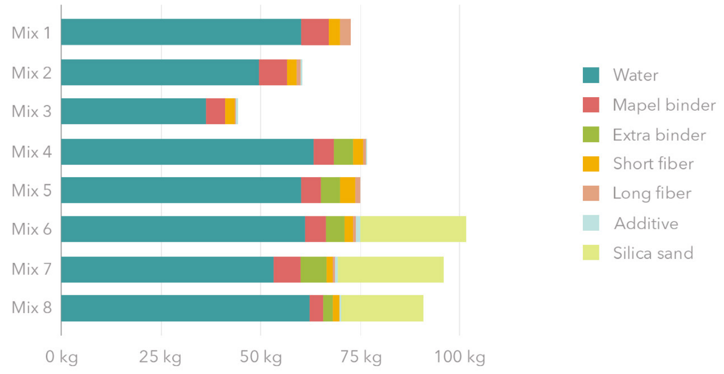


Images courtesy of Mario Cucinella Architects



Drawing created by author

Mixture composition utilized throughout TECLA (per 100kg of local soil)

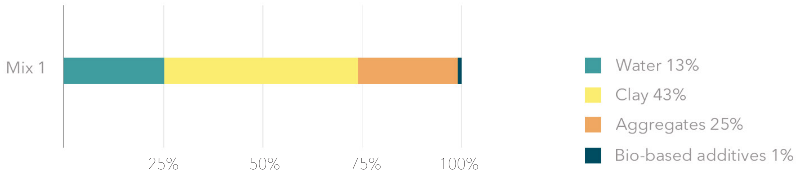


TECLA

MATERIAL COMPOSITION

Diagram created by author based on a diagram provided by WASP

Mixture composition utilized throughout Digital Adobe



DIGITAL ADOBE

MATERIAL COMPOSITION

Diagram created by author

CLAY COMPOSITION IN TECLA

Part of the success of such a sizeable continuous print comes down to the knowledge and use of material properties throughout the mix. Therefore, there was a need to alter the mixtures being poured through the nozzle as the conditions of height, section, and environment changed. There was a total of 8 mixtures created, all of which were different. Even though there was a similar percentage of additives used throughout, we can observe more considerable variations in water content and the addition of sand in the final layers of the print. This differs from the project of Digital Adobe, mainly due to the fabrication method. Having discrete elements printed in a controlled environment and with similar dimensions allows for using one consistent mixture, as seen previously.

CLAY:

51-58% of extruded material

The clay used for the print was based on local soil, extracted and processed close to the building site. As established previously, one of the benefits of large gantry 3D printers is that they can use a much thicker grain than small scaled robotic arm printers. This was used to their advantage since soil tends to have a mixture of different grains and, therefore, need less processing. By simply filtering and discarding the larger grains, the soil was then ready for mixing.

WATER:

28-35% of extruded material

As established, water is essential in any clay mixture, but the moisture content can vary depending on the environment and its additives. According to a study by Shareen S.L. Chan, which tested out the printability of architecture components with varying moisture levels, a moister level of about 34-55% produces pastes with the highest levels of printability without the use of additives[28]; however, the typical water content of 3D printed clay in other executed projects can be found to be around 20-30%, most likely due to a difference in clay and additives. In this particular case, we can observe a varying water content depending on the mix extruded and the quantity of additive incorporated.

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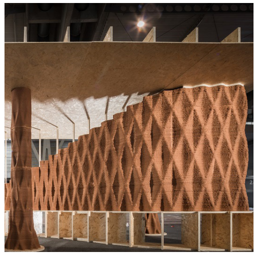
[28] Chan, Shareen S.L., et al. "3D Printing of Clay for Decorative Architectural Applications: Effect of Solids Volume Fraction on Rheology and Printability." Additive Manufacturing, vol. 35, 2020, p. 101335., https://doi.org/10.1016/j.addma.2020.101335.

CLAY COMPOSITION IN DIGITAL ADOBE

Regarding the material used throughout the project of Digital Adobe, we can find a combination of recycled clay, water, aggregates, and bio-based additives.



CLAY:

43% of the extruded material

Unlike other 3D printed clay projects, in this one, we can find the peculiarity of the employment of recycled material in the mix. Before the project of Digital Adobe, IAAC had organized and built a temporary installation for the Barcelona Building Construmat on campus. Once broken down, this provided 2 tons of dry clay that would be mechanically ground and filtered through a 2mm mesh. Once made into a fine powder, it would provide the base for the final clay mixture.[29]

WATER:

13% of the extruded material

In all clay-based products, water is the essential component to bond everything together. As discussed before, the amount of water determines the final piece's porosity, durability, and physical properties. A 13% of water means that the clay mixture had a relatively low water content, giving it less porosity but, at the same time, less shrinkage when the water evaporated. This is a dramatic difference compared to TECLA with its 28-35% moisture levels. Be that as it may, it could be attributed to two main factors: the clay and the environment. A study published in the Journal of materials in civil engineering suggests that using recycled clay components that have gone through a curing process in new construction and production can impact the water absorption of the new material.[30] Since most of the clay used for the project was from a previously cured installation, this could explain lower than average water content. The second vital aspect to take into

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[29] "Digital Adobe." IAAC, Institut d'Arquitectura Avançada De Catalunya, 30 Apr. 2019, https://iaac.net/project/digital-adobe/.

[30] Silva, J., et al. "Recycled Red-Clay Ceramic Construction and Demolition Waste for Mortars Production." Journal of Materials in Civil Engineering, vol. 22, no. 3, 2010, pp. 236-244., https://doi.org/10.1061/(ASCE)0899-1561(2010)22:3(236).

AGGREGATES:

1% of extruded material

Rice husks: Although TECLA also implemented the use of sand to enhance the mechanical properties of the mix, it opted to add rice husks rather than sawdust to augment the tensile strength and flexibility of the mixture. The choice of aggregate shows a clear difference between the needs and performance of each project. Due to the continuous nature of TECLA, the clay had to withstand the constant shrinkage and deformation of the lower layers as the mixture dried and was compressed throughout the duration of the print. In order to perform well, there was a more urgent need to increase flexibility rather than density. Since rice husks are also considered waste from rice production, it generates a negative carbon footprint when implemented in the project.

12% of extruded material

Silica sand: One of the most significant differences we can observe in TECLA is the addition of sand to only the last three mixes of clay. Since sand helps with the material's density and strength, the importance shifted as the external layers of the project closed in, and the angle increased.

OTHER ADDITIVES:

1% of extruded material

Mapei mix: Throughout the design process, WASP consulted with a material supplier, Mapei. As they stated: they developed a specific mix design to obtain a mix with rheological properties suitable for the printing phase and with mechanical properties suitable for the type of use.[31] In other words, it optimized the performance of the raw earth in order to make it printable and livable. According to the press statement, the following additives were used:

- **MAPESOIL 100**, a powdered stabilizing agent used to consolidate soil, which enables the raw earth and water-based mix to be progressively broken up, promoting the durability and resistance to leaching of the mix once it has been extruded.

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31. "Mapei Research and Technology for Tecla." MAPEI, 4 Nov. 2019, https://www.mapei.com/it/en/news-and-events/event-detail/2019/11/04/mapei-research-and-technology-for-tecla

account is that of the environment. The bricks for Digital Adobe were produced and dried in an interior-controlled environment, where humidity and temperature stayed the same throughout. While on the other hand, TECLA had to consider the temperature fluctuations throughout the day, sun exposure, and humidity changes throughout the 200h of print.

AGGREGATES

25% of the extruded material

Sand and sawdust: Using sand and sawdust as an aggregate improved the mechanical properties and reduced the shrinkage of the material. Sand is an inert material that can fill the voids between clay particles, increasing the material's density and strength. While sawdust, similar to other fibers such as straw or bamboo, is added to improve its tensile strength and flexibility. Thus reducing shrinkage and warping of the clay during its drying process.

Bio-based additives:

1% of the extruded material

Gelatin: Gelatin is a bio-based additive that provides several benefits to the 3D printing of clay. Since it is a biodegradable and renewable material, it becomes a more sustainable option than other synthetic additives used in traditional construction techniques. Furthermore, it can improve the strength and ductility of the clay material, making it less brittle and more resistant to cracking or deformation.

- DYNAMON SR4 super-plasticizing admixture which helps the mix maintain its workability and pumpability for up to two hours after preparation.

- PLANICRETE synthetic latex rubber used when mixing slurry to help it bond more firmly to surfaces that have already set.

- PLANISEAL WR 100 ready-mixed water-repellent applied with a spray bottle on dry-facing walls, highly effective in waterproofing structures after just 12 hours.

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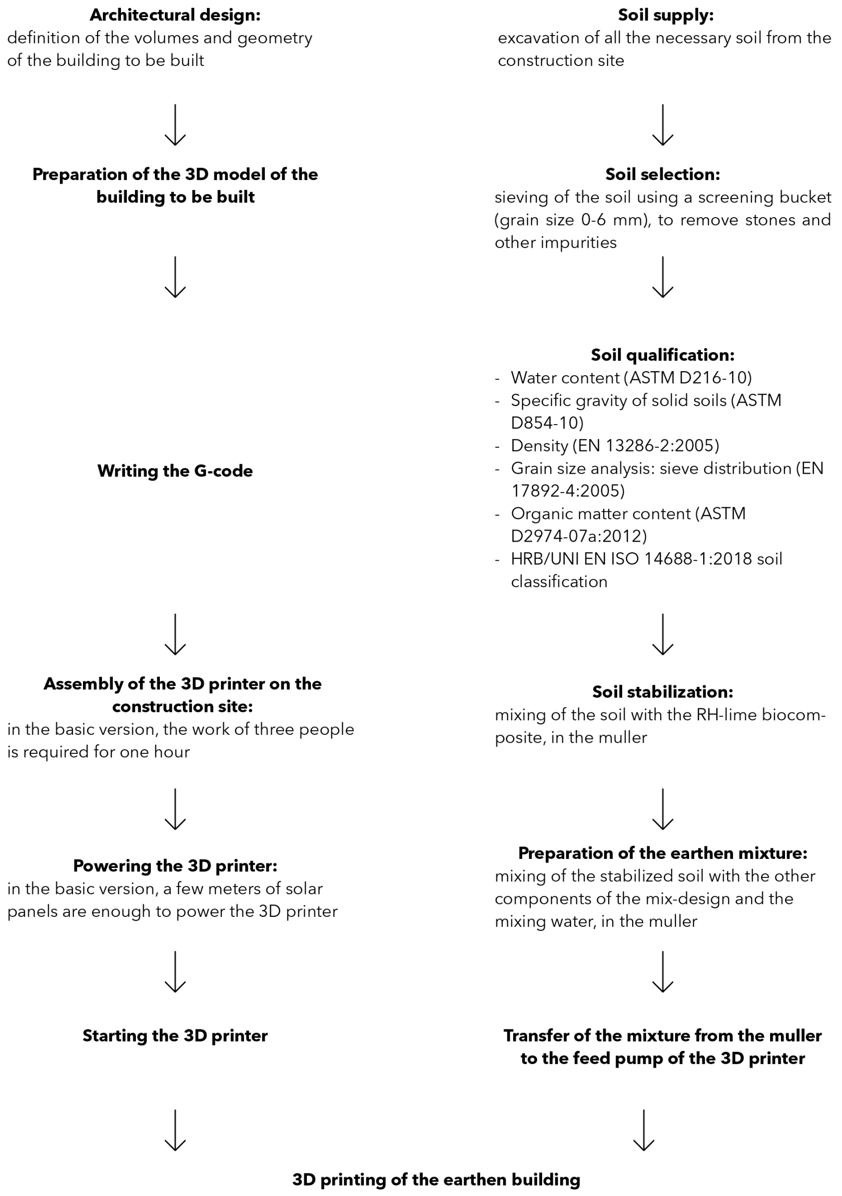
31. "Mapei Research and Technology for Tecla." MAPEI, 4 Nov. 2019, https://www.mapei.com/it/en/news-and-events/event-detail/2019/11/04/mapei-research-and-technology-for-tecla

TECLA

DESIGN PROCESS AND EXECUTION

DIGITAL ADOBE

DESIGN PROCESS AND EXECUTION



Architectural design:
definition of the volumes and geometry of the building to be built

Preparation of the 3D model of the building to be built

Writing the G-code

Assembly of the 3D printer on the construction site:
in the basic version, the work of three people is required for one hour

Powering the 3D printer:
in the basic version, a few meters of solar panels are enough to power the 3D printer

Starting the 3D printer

Soil supply:
excavation of all the necessary soil from the construction site

Soil selection:
sieving of the soil using a screening bucket (grain size 0-6 mm), to remove stones and other impurities

Soil qualification:
- Water content (ASTM D216-10)
- Specific gravity of solid soils (ASTM D854-10)
- Density (EN 13286-2:2005)
- Grain size analysis: sieve distribution (EN 17892-4:2005)
- Organic matter content (ASTM D2974-07a:2012)
- HRB/UNI EN ISO 14688-1:2018 soil classification

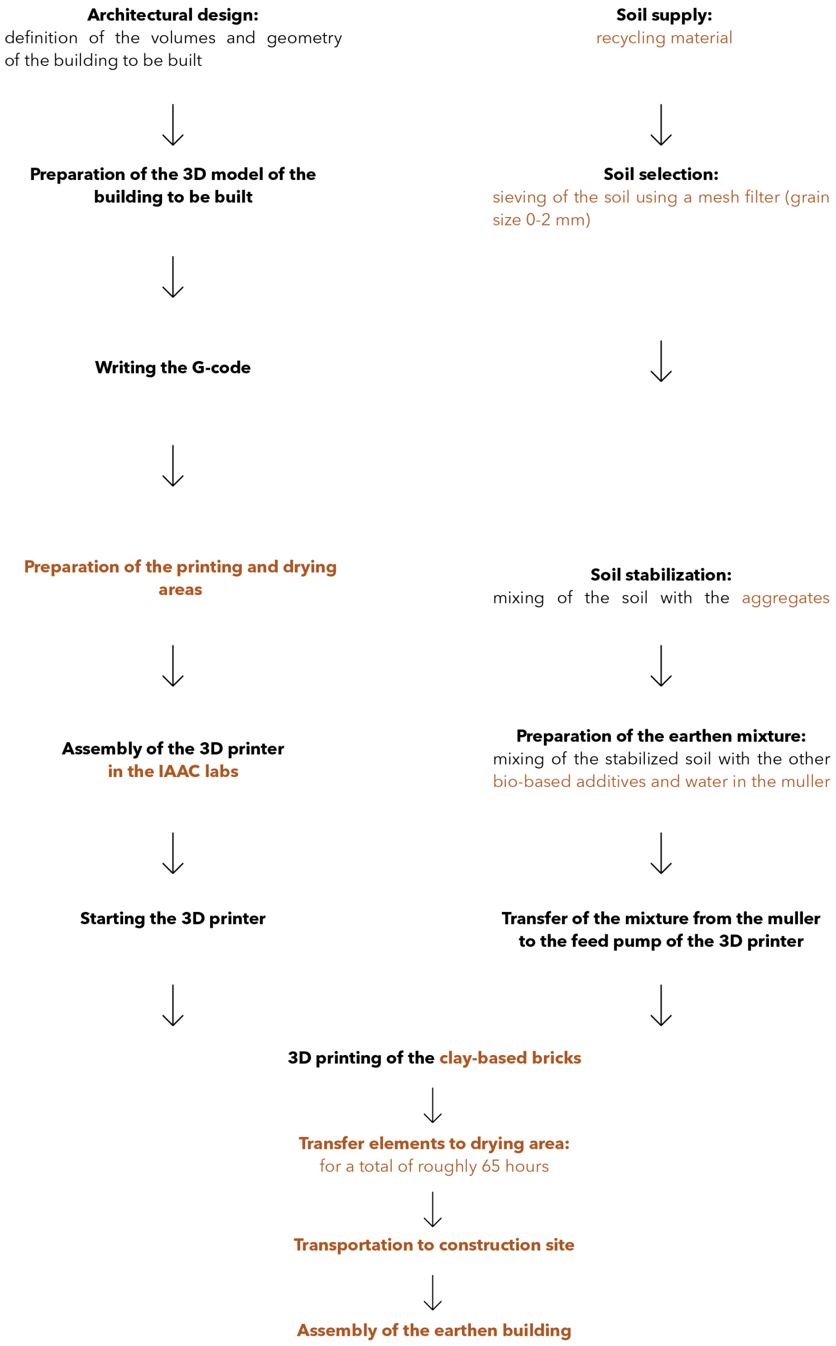
Soil stabilization:
mixing of the soil with the RH-lime biocomposite, in the muller

Preparation of the earthen mixture:
mixing of the stabilized soil with the other components of the mix-design and the mixing water, in the muller

Transfer of the mixture from the muller to the feed pump of the 3D printer

3D printing of the earthen building

Diagram courtesy of: Ferretti, Elena, et al. "Mechanical Properties of a 3D-Printed Wall Segment Made with an Earthen Mixture."



Architectural design:
definition of the volumes and geometry of the building to be built

Preparation of the 3D model of the building to be built

Writing the G-code

Preparation of the printing and drying areas

Assembly of the 3D printer in the IAAC labs

Starting the 3D printer

Soil supply:
recycling material

Soil selection:
sieving of the soil using a mesh filter (grain size 0-2 mm)

Soil stabilization:
mixing of the soil with the aggregates

Preparation of the earthen mixture:
mixing of the stabilized soil with the other bio-based additives and water in the muller

Transfer of the mixture from the muller to the feed pump of the 3D printer

3D printing of the clay-based bricks

Transfer elements to drying area:
for a total of roughly 65 hours

Transportation to construction site

Assembly of the earthen building

Self-generated diagram that highlights the differences in Digital Adobe's design and execution process in comparison to TECLA's

DESIGN PROCESS OF TECLA

TECLA was produced by some of the most prominent names in the 3D printing and sustainability industry. The joint research and knowledge of WASP, Mario Cucinella, and other engineers and providers such as Mapei created the perfect base to achieve peak performance in any project.

When researching the project, a fundamental aspect seems to define it: its climatic properties, fast and efficient production, and the combination of structural and aesthetic necessities. As stated various times by Mario Cucinella in interviews, their final design stemmed from research into a self-supporting structure that would solve all requirements within one construction process.

Even though the research and design process must have been lengthy, most of it has yet to be published, and therefore, some assumptions will be made about the reasoning behind some design features. What is known is that two fundamental characteristics limited and molded the final product: the properties of clay as a material and its method of execution, 3D printing.

The focus on climatic and structural efficiency shaped the entirety of the envelope but did so in an alternative way to Digital Adobe. Unlike in Digital Adobe, where infill patterns were developed to achieve maximum insulation, TECLA's project thickness, fill, and pattern suggest an infill design catered more toward the structural necessities.[33] In contrast with Digital Adobe, 55% of the infill layers are filled with rice husk, further suggesting that the thermal insulation depended more on other methods than the 3D printed structure. Even though the infill patterns do not show the intricacy that could come with developing an ideal climatic performance, a clear priority is placed on developing an exterior layer that benefits it.

To further understand how the design was thought through, in Fig. 2, we can observe the solution adopted by TECLA. In order to hold up the weight and mass of the dome, the exterior wall of the dome required a series of sine patterns, as explained before, and, most importantly, a large surface area at the bottom. The large surface area eventually reduces, as evident through the three

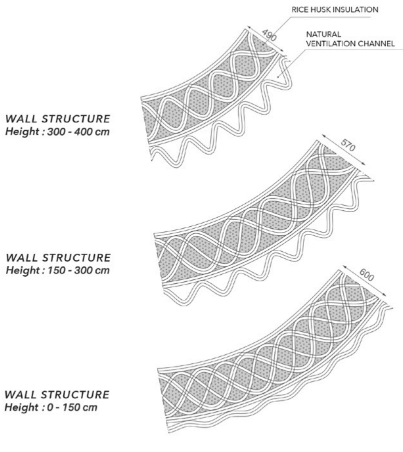


Fig 2: TECLA's varying wall sections throughout various heights

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[32] Parkes, James. "Mario Cucinella Architects and WASP Creates 3D-Printed Sustainable Housing Prototype." Dezeen, 23 Apr. 2021, https://www.dezeen.com/2021/04/23/mario-cucinella-architects-wasp-3d-printed-housing/

[33] Ferretti, Elena, et al. "Mechanical Properties of a 3D-Printed Wall Segment Made with an Earthen Mixture." Materials, vol. 15, no. 2, 2022, p. 438., https://doi.org/10.3390/ma15020438..

DESIGN PROCESS OF DIGITAL ADOBE

Digital Adobe is a project that stems from an extensive line of research aided by years of student and faculty projects. Over the years, IAAC has tested not only the performance of different clays and additives but also different techniques and forms of 3D printing. Consequently, the architectural design process has a solid background to evolve from.

Similarly to TECLA, two fundamental aspects limited and molded the final product. One is the material's very properties, and the second is the method of execution. Through their design process, there is a clear predominance of clay's limitations as a material.

Research conducted by Iason Giraud demonstrated that clay's thermal properties, specifically high conductivity ,was a definig factor on infill patterns.[34] We can observe in Fig. 3 a small extent of the fundamental research and how it was later translated into the project of Digital Adobe. The research proclaimed that the longer the path and more bifurcations it had, the more efficient it became in managing conductivity. Therefore, walls with wider sections and more intrinsically infill patterns are favored over simpler, air-filled sections.

Due to a primary focus on the climatic and structural performance of the final design, we can observe the influence of the parameters above in the sections of the 1:1 wall prototype. As seen in Fig. 4, there is an apparent use of all the concepts above in 3 main layers, the first for energy exchange, the second for energy transmission, and lastly, one for structure. Combining the three leads to a changing section design that decreases width with height.

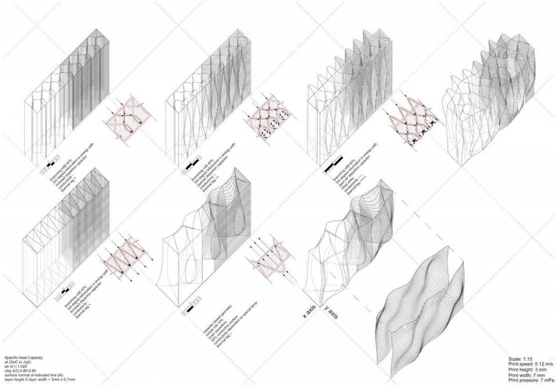

Fig 3: infill pattern research to achieve maximum thermal insulation

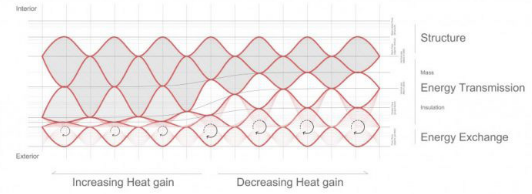

Fig 4: Generative design shows a change in the infill pattern to garantee thermal insulation and ventilation throughout the entirety of its section

To achieve peak climatic performance, this project innovated, in comparison to both past projects and TECLA, with the implementation of a ventilated layer through operable top/bottom openings to either reduce heat gain in summer or retain heat in the

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[34] Giraud, Iason. "Incorporating Thermal Performance in Clay 3D Printing." IAAC Programmes, IAAC, 16 Apr. 2017, https://www.iaacblog.com/programs/incorporating-thermal-performance-clay-3d-printing/.

different sections, in order to hold less mass as height increases.

According to a paper written by Elena Derreti, which analyzes the mechanical properties of a 3D-printed wall segment made with an earthen mixture, WASP adopts a similar geometric configuration within all their projects. Derreti explains that the geometry includes two thicker perimeter shells that confine the infill stratigraphy, an accurate description of the solution adopted by TECLA. Furthermore, this contour-crafting technique derives from construction with concrete.

Although this strategy evidently works, it seems the material was not selected due to its potential mechanical and thermal properties. Instead, its selection was most likely due to the potential life cycle and sustainability aspect, as referenced in an interview about WASP's current projects.

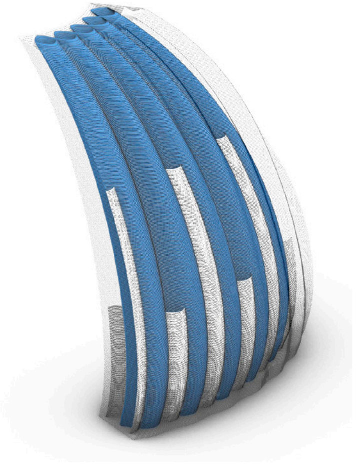
Fig 5: TECLA's internal structure showing a decrease in sine waves at given heights

Due to both load barring capacity of the wall structure and the maximum permitted filling ratio of around 50-60%, the number of sine waves that occupy the infill decreases as height increases, as seen in Fig.5. This leads to the progressive decrease in section width and finishes with an overlap of the two dome surfaces to achieve structural stability.

In comparison, Digital Adobe uses the same strategy of material reduction; however, with a starting section size of about 70cm, relatively smaller than TECLA's 60cm. This could be surprising due to the nature of the print, which requires the structure to hold the entirety of the building's mass before thoroughly drying. Nonetheless, the difference in thickness and widths of each layer on account of the type of printer used can explain the necessity for an overall broader section in Digital Adobe's case.

As mentioned, the physical properties of the material alter the final design. Since the material is poured in liquid form, there will always be restrictions to the angle and curvature that the design may have. As many studies have shown, a reasonable overhang angle for clay 3D printing is 30 degrees.[36] For the most part, the entirety of TECLA's print seems to stay in line with that rule. However, a few exceptions can be attributed to the smart use of infill, various layers, and shrinkage of the final piece. The section shows a more significant angle change in the exterior layer than the interior lay-

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35. Ferretti, Elena, et al. "Mechanical Properties of a 3D-Printed Wall Segment Made with an Earthen Mixture." Materials, vol. 15, no. 2, 2022, p. 438., https://doi.org/10.3390/ma15020438..

36. Clay 3D Printing Design Guide, Yale Architecture, 28 July 2020, https://www.architecture.yale.edu/advanced-technology/tutorials/32-clay-3-d-printing-design-guide

winter. The design of this outer layer was, in theory, optimized for solar radiation. However, even though they stated its purpose was to provide self-shading during summer, the angles permitted through the printability of the material could be its defining factor. On a smaller scale than in TECLA, the angles of the entirety of the project had to be confined to an angle of fewer than 30 degrees, as they mention in their Open thesis fabrication pamflet. Hence the geometry and angles of the surface of bumps.

Before printing 1:1 scale prototypes of the wall, their design process proceeded with developing and verifying smaller-scaled prototypes that would perform well structurally and climatically. With the help of software such as RHINO CFD, Ladybug, and Karamba and simulations of wind and sun, they could critically analyze the behavior of each piece within the context of the final project, as can be observed in Fig 6.[37] The ability to cater individual elements of a project to specific needs depending on location and sun exposure exhibits another advantage of 3D printing over traditional methods of construction, even if we have started to implement other digital-based programs that help us develop structurally and thermally adequate buildings.

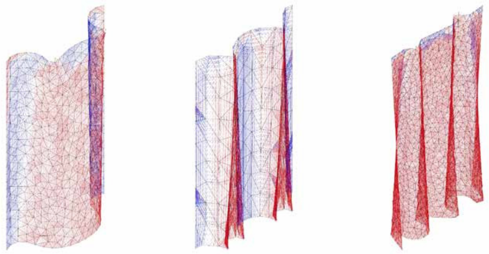
Fig 6: Use of Karamba to calculate and evaluate structural stability of the wall shape, drawings courtesy of IAAC


Fig 7: Trial and error of smaller-scaled prototypes throughout the design process

Mainly due to the fact that this was just a research project, and was therefore not explored fully as a complete building, part of the facade elements are not optimized to their total capacity. As we saw in TECLA, the orientation of each facade meant a change in its surface design, protruding more or less depending on the need for self-shading. If we were to be scrupulous, the design for Digital Adobe would have to alter depending on its orientation. Moreover, since its surface bumps, although very aesthetically pleasing, are designed

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36. Chang, Yachieh. "Digital Adobe - Additive Manufacturing with Adobe towards Passive Habitats." IAAC Blog, 11 Aug. 2018, https://www.iaacblog.com/programs/digital-adobe-additive-manufacturing-adobe-towards-passive-habitats/.

37. Raaghav, Chenthur. "Structural Principles for 3D Printing Unfired Clay." IAAC Blog, https://www.iaacblog.com/programs/structural-principles-3d-printing-unfired-clay/.

er, meaning that the increased overhang can be attributed to its infill and interior layers' supports.

At the same time, there is an essential element that we do not take into account as much in the Digital Adobe pieces, which is shrinkage. According to the Yale University study: A clay body that is equal parts clay/water by volume (a good ratio for smooth flow) will shrink by as much as 15% in any dimension as it dries to the humidity of the studio air.[36] This shrinkage could cause an even more exaggerated angle and a generally compressed look. When mentioning that shrinkage is more significant in TECLA than in Digital Adobe, it is a consequence of the nature of the print. Even though in the research for Digital Adobe there is a mention of taking into account shrinkage in the final print, the use of different discrete elements means that each component has a smaller percentage of shrinkage in accordance to its volume, which is less. While TECLA's continuous nature means the volume shrunk will be approximately 15 percent of the entire project.

in this particular way due to printing constraints, this could be an issue when needing to provide more self-shading. Nonetheless, the efficiency and novelty of the air-flowing exterior cavities could easily compete with many traditional brick facade systems.

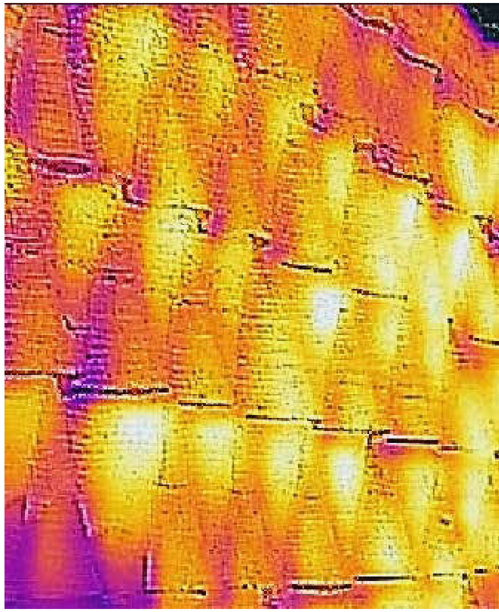

Fig 8: Thermal analysis of a wall segment using heat sensors to analyze the thermal propreties of the wall, image courtesy of IAAC

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[36] Clay 3D Printing Design Guide, Yale Architecture, 28 July 2020, https://www.architecture.yale.edu/advanced-technology/tutorials/32-clay-3-d-printing-design-guide

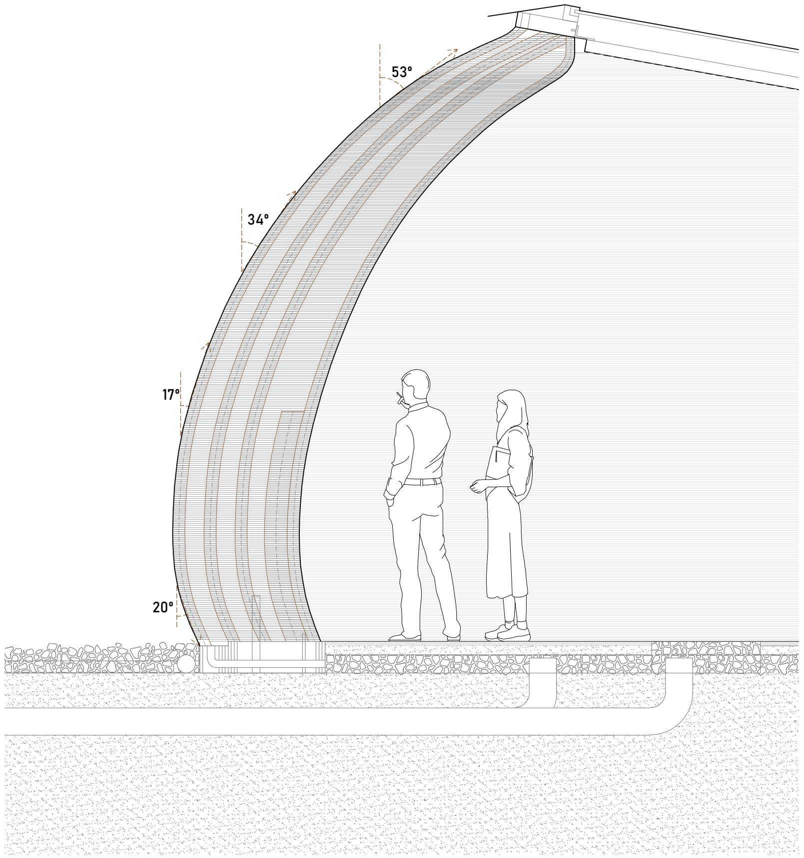

Diagram generated by author showing the change in angle of the exterior layer

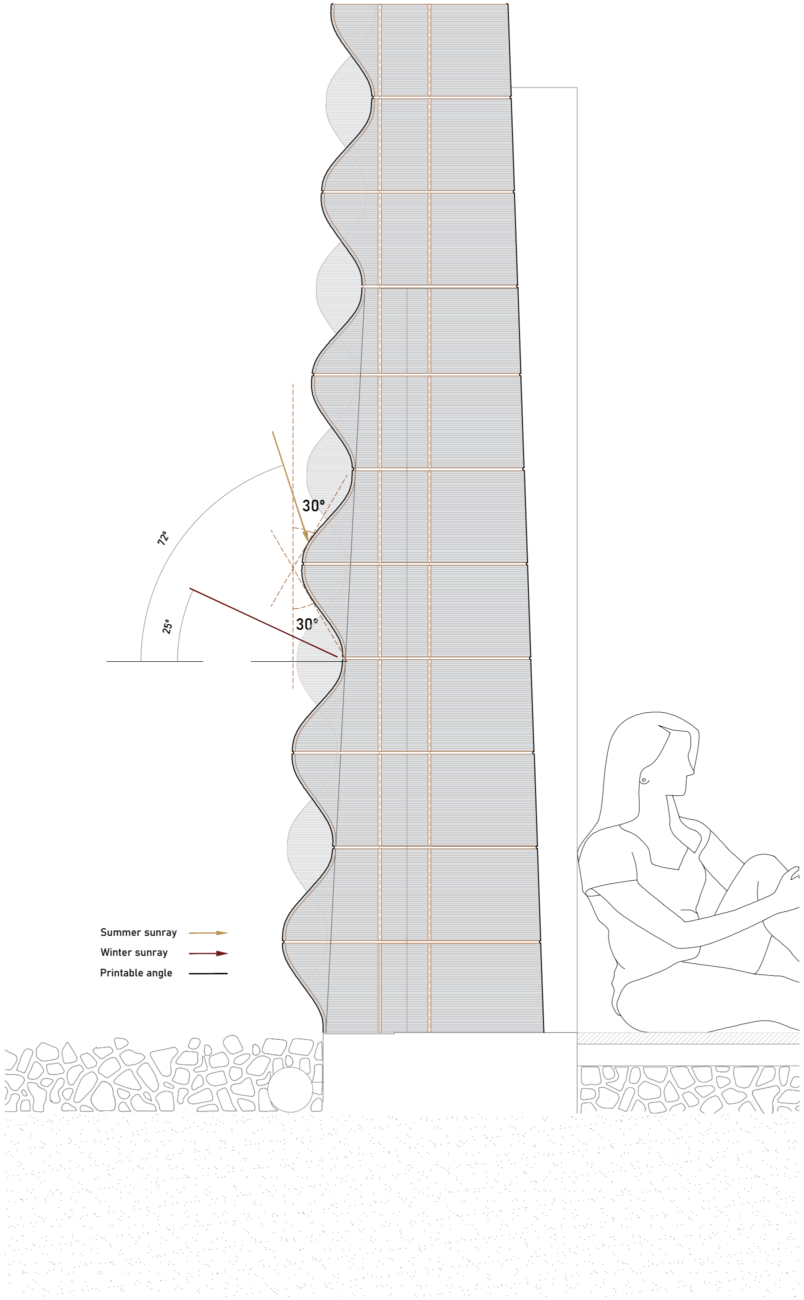

Diagram generated by author showing the angular restrictions that the surface texture had to adhere to

The successful execution of TECLA was led by the use of WASP's innovative printing system. In contrast to many gantry printers on the market, WASP's BigDelta 3D printer was designed to be modular and adaptable, meaning it could be used for various construction projects. Because of the different possibilities in configurations, the crane printer offered a degree of flexibility lacking in some of the more famous gantry printers. The modular printer consists of a metal frame that can potentially change its configuration by attaching several modules. As stated in their press release, the WASP printers could print on an infinite area when working together. In this particular case, the configuration used was that of two simultaneous cranes that shared one structure, printed in collaboration, and occupied an area of about $100m^2$.

The reason for this configuration and the selection of their gantry printers rather than the company's smaller ceramic printers was due to research purposes. Their previous projects, such as Gaia,[37] already implemented the use of one individual crane and were able to show the potential in insight construction. But further experimentation into the potential of gantry printers led them to push the limits and employ two simultaneous printers.[38]

Since the printer was already thought to use locally sourced and environmentally friendly materials such as clay, straw, and rice husk, the project's material selection combined with the printer did not become a defining factor. However, the final house's dimensions and shape clearly indicate the production method. The size of one module is 5,53m in radius and 4,65m in height with a nozzle hole that could range from 18 to 30mm. Even by maximizing the print area, we can observe a maximum range of 8,20m in diameter and around 4m in height. Since the execution process combined two modules, the final design had a maximum width of 7,2m, a length of around 12,5m, and a height of 4m. Through the image below, we can further attest to the circular nature of the printer and its limitations.

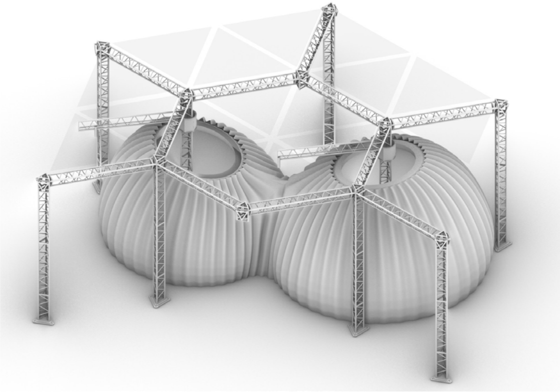

Fig 10: Fig. 9 3D model of TECLA with its designated printers, image courtesy of WASP

Compared to the freedom of form that was available through the use of a robotic arm, the crane system shows a clear disadvantage. Albeit, the execution process of these crane printers can be

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[37] Moretti, Francesca, et al. WASP, WASP World's Advanced Saving Project,, https://www.3dwasp.com/en/3d-printing-for-sustainable-living/

[38] Moretti, Francesca, et al. WASP, WASP World's Advanced Saving Project, 8 Nov. 2021, https://www.3dwasp.com/en/3d-printed-house-tecla/

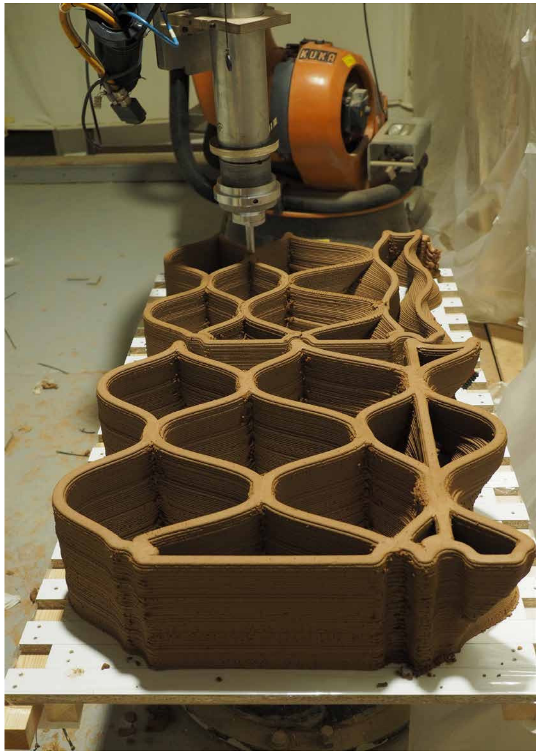

Fig 10: Execution of 2 bricks at IAAC's labs, image courtesy of IAAC

Once completed the design process, IAAC moved on to execute it. Throughout the entirety of the research process as well as the final project, the IAAC developed its models with a robotic arm adapted to extrude clay material. Simultaneously working with both computer-aided design and 1:1 scaled prototypes helped them develop and redefine the final designs to cater to specific needs throughout the production process. As established, the use of additive manufacturing and clay restricted the design, but their use of the Kuka robotic arm shaped the production process, limiting the project to discrete elements. The robot had a reach of around 2101-3101mm. When adapted with an extruder, it was able to regulate the pressure and extrude the clay-based material through a 8mm wide nozzle onto various platforms that could then be moved to a different area to complete the drying process.

The reasons for choosing the robotic arm, rather than other gantry printers, can be evident due to its availability and inexpensiveness, as stated by Anastasia Puzotava[39]. Nonetheless, in this particular case, the use of the robotic arm also benefited the final appearance of each piece. Because of its system and the tangential continuity method, the printer provides a smoother transition between print layers, providing a more constant rate of change in curvature and a more aesthetic appearance. This is apparent through the entirety of the facade bump textures, which would be almost impossible to print with TECLA's crane printer.

Due to the size and location of the robotic arm, the final pieces of the project were built on-site at the IAAC labs. The batch production of the 99 bricks was executed in an area of around 12 m^3. The availability of space and the lack of large-scale machinery allowed them to fabricate everything in the same lab. Albeit, this same production process could have been executed at any other facility or directly on-site. As explained in

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[39] Puzatova, Anastasia, et al. "Large-Scale 3D Printing for Construction Application by Means of Robotic Arm and Gantry 3D Printer: A Review." Buildings, vol. 12, no. 11, 2022, p. 2023., https://doi.org/10.3390/buildings12112023.

much simpler, faster, and more productive. As seen through the execution of TECLA, the printing speed of an entire building came down to 200h,[40] whereas Digital Adobe lasted around ten days. Due to the increased efficiency and fully automated process, printing could occur at all hours without supervision.

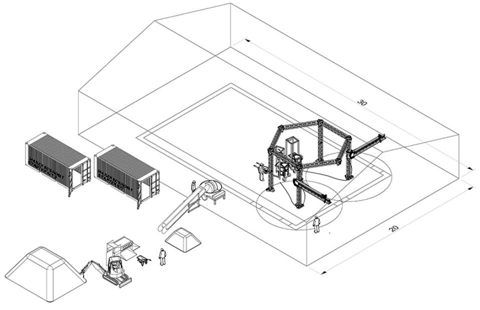

Fig 11: Construction setup of two simultaneous cranes and extraction of materials on site, drawing courtesy of WASP

With reduced costs on transportation of individual elements and the use of local materials, the production costs of TECLA boiled down to the cost of transporting, assembling, and disassembling the crane printer. As established by Yomna K. Abdallah, the cost of such a building could range from 4,000 to 9,000 dollars,[41] becoming much more affordable and readily available than any traditional construction.

Furthermore, the entirety of this print took place in Massa Lombarda at WASP's headquarters in an area over 1000m². Space availability must be considered to discuss the advantages and disadvantages of such a process. The materials, machinery, and print require additional space, which sometimes becomes limiting. Moreover, the execution of an entire building in an outdoor setting becomes highly dependent on weather conditions that can impact the drying and hardening of the building material. Meaning that if not supervised correctly, it could have a damaging effect on the building as a whole.

Lastly, the most crucial issue is the potential for printing errors. TECLA's print, if encountered any issues, has yet to be discussed publicly. Nevertheless, infinite printing errors could occur during the process, including layer adhesion issues, warping, extruder issues, misalignment, and more. In the case of discrete components, any issue can easily be mended or completely discarded if necessary. While in a continuous print, any setback could cause the failure of an entire building.

In conclusion, it is evident that the use of 3D printing technology has created a unique and environmentally friendly living space. Using a crane printer has enabled the printing of the structure in one continuous print, reducing waste and construction time. Additionally, using locally sourced materials such as clay and rice husks has guaranteed the continuous life cycle of the project. However, the limitations of using a crane printer, such as the need for ample open space and the potential for printing errors, must also be considered. As seen in the Digital Adobe case study, the decision to use individual printed elements may have been a viable alternative to reduce printing errors and allow for more design flexibility.

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40. Moretti, Francesca, et al. WASP, WASP World's Advanced Saving Project, 8 Nov. 2021, https://www.3dwasp.com/en/3d-printed-house-tecla/

41. Abdallah, Yomna K., and Alberto T. Estévez. "3D-Printed Biodigital Clay Bricks." Biomimetics, vol. 6, no. 4, 38. 2021, p. 59., https://doi.org/10.3390/biomimetics6040059.

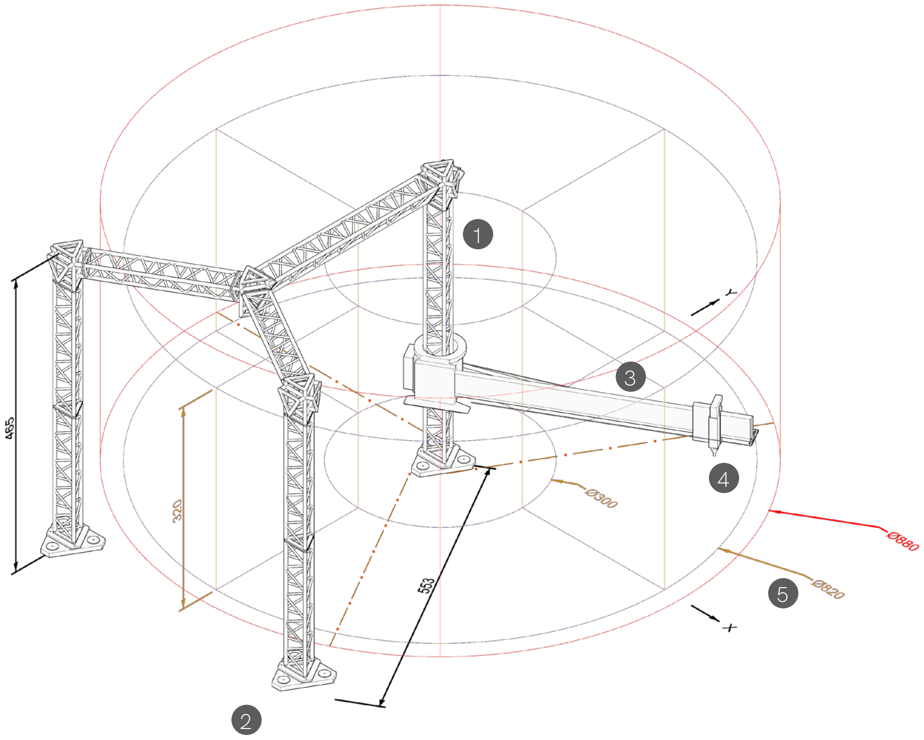
a research paper by Anastasia Puzatova, many robotic arm 3D printers are set up with a mobile platform and external energy sources, allowing them to be much more flexible than gantry printers. While at the same time also being more accessible and cost-efficient in comparison.

Apart from the space occupied by the extruding process, there was a recycling, a mixing, and a drying area. The process occupied a total of 44m³. Considering the dimensions needed for large-scale construction through gantry-printers and continuous construction, this becomes a significant advantage for projects lacking space.

However, it must be noted that such a process then included the need for transportation and assembly on-site. Requiring additional equipment and labor, opposing the DIY argument of the project. As explained through their youtube video, the final assembly was executed within five days and required four people and additional scaffolding to assemble the entirety of the wall.

Even though the final assembly process can resemble that of traditional construction with bricks, we have to consider the effectiveness and lack of material waste generated in comparison. The 3D production of bricks generates precisely the quantity needed for each project, with the added benefit of complete customization if needed. So even with the added cost and transportation carbon emissions, this process becomes much more sustainable than many traditional methods.

In conclusion, the design and execution strategy of Digital Adobe is a prime example of the potential and emerging research into 3D printing in construction. The use of clay as a material, along with a hybrid approach of printing individual blocks and assembling them on-site, allowed for increased flexibility and customization while still maintaining the structural integrity of the building. The use of a robotic arm, while presenting some limitations in terms of print volume and speed, offered greater precision and control in the printing process. On the other hand, a gantry printer, like WASP's crane printer, could offer faster overall print speeds and potentially larger continuous print volumes but may lack the precision required for intricate designs.



1 WASP crane, controlled through computer g-code

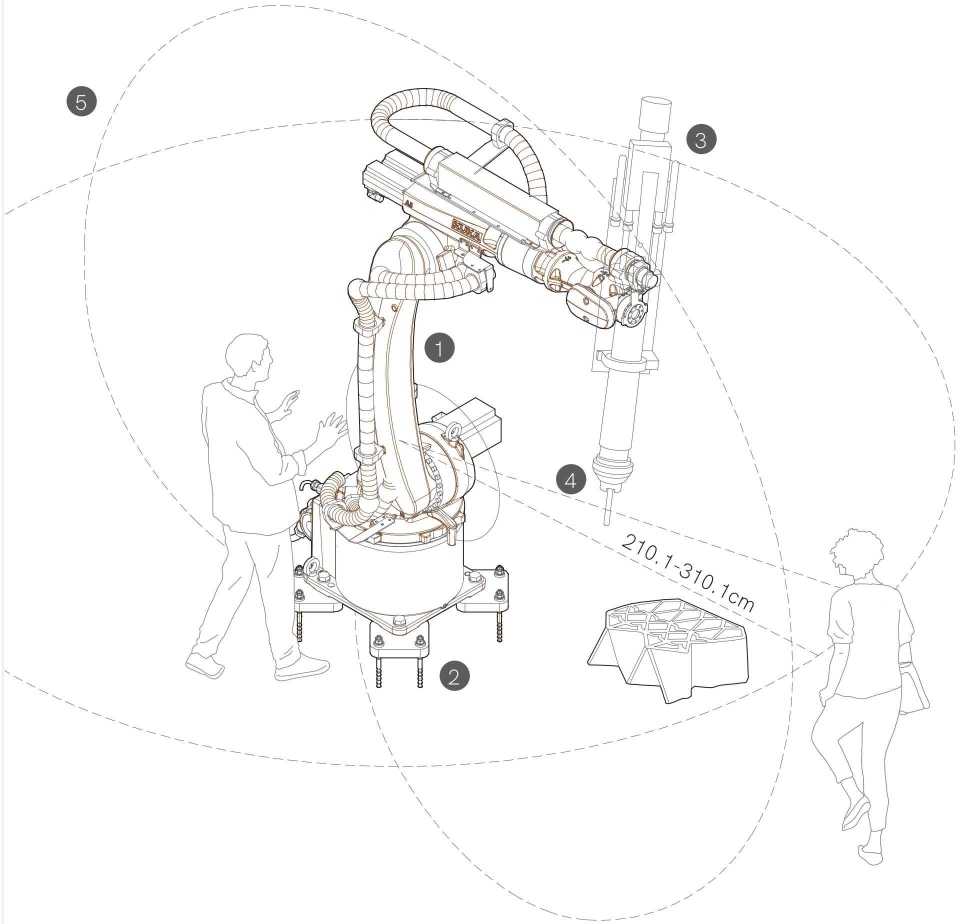
2 Ancorage to floor

3 Extruder mecanism, controles placement and extrusion of material

4 Extruder nozzle, controls thickness of extrusion

5 Horizontal span of extruder

Diagram courtesy of WASP of one of TECLA's crane printers, showing components and reach



1 Kuka robotic arm, control through computer g-code

2 Ancorage to floor, wall or ceiling

3 Extruder mecanism, controles pressure and extrusion of material

4 Extruder nozzle, controls thickness of extrusion

5 Span of robotic arm

Drawing generated by author of Digital Adobe's robotic arm, showing components and reach

CLAY 3D PRINTING

IS IT THE VIABLE?

Once analyzed the material properties, 3D printing processes, and how they were used to their advantage in two case studies, we can ask ourselves the actual viability of 3D printing with clay. Moreover, is it the future of architecture?

As explained very clearly by Attaran Mohsen in a paper about the rise of 3D printing, there are five key benefits to additive manufacturing over traditional methods: Cost, speed, quality, innovation/transformation, and impact.[42] Undeniably, many of these benefits relate directly to its environmental impact, one of the main factors for which 3D printing clay is advertised.

The efficiency, on-demand, and mass customization of all the building elements allow the process to have a much lower carbon footprint. Through the use of a few restricting parameters, there is a reduction in prototyping time as well as a reduction in development costs. While simultaneously maintaining the possibility of mass customization, as seen in Digital Adobe. This mass production through mass customization also benefits from decentralized manufacturing. Offering the possibility to produce elements to the users liking and in any location, reducing the supply chain, and omitting the need for intermediaries while still maintaining the quality of the final pieces.

In the case of individual printed elements and continuous printed architecture projects, we can observe the production of very complex workpieces at a much lower cost than traditional architecture. While in the case of large-scale architecture, it noticeably reduces labor costs and logistics. On the same line, the ability to manufacture the projects at the final destination reduces transportation costs and carbon footprint. Howbeit, we must consider that this benefit can be discarded in the case of discrete printing.

Using clay in these scenarios further reduces production and construction costs. With the capability to extract clay from many nearby locations or recycle past constructions to produce new buildings, there is no longer a need for complex production lines and transportation to and from the factories. It becomes widely available to the entire population, no matter their economic situation.

We have to take into account, on the other hand, that many of the large and complex structures require considerable amounts of energy, and the carbon footprint that these technologies leave has yet to be fully comprehended. Additionally, although idealized as user-friendly and customizable, many 3D printing jobs require specific knowledge and training, which could not be available to those who need it the most.

Nevertheless, and most importantly, 3D printing allows for the implantation of more sustainable practices through

[42] Attaran, Mohsen. "The Rise of 3-D Printing: The Advantages of Additive Manufacturing over Traditional Manufacturing." Business Horizons, vol. 60, no. 5, 2017, pp. 677–688., https://doi.org/10.1016/j.bushor.2017.05.011.

a wider variety of materials. Currently, cement is the most common material used in construction, and its production is the third biggest generator of CO2 emissions. Rather than retrofitting a centuries-old technology by trying to decarbonize the process through 3D printing technology, embracing sustainable alternatives is possible. As seen throughout this paper, this becomes the case of clay 3D printing. As established, it has many issues as a traditional construction material, but with a 3DP process, limitations are reduced significantly. Finally, providing the potential to generate rapid and effective construction solutions that could solve issues of material efficiency and emergency housing.

Ultimately, achieving carbon-neutral construction with either Clay 3D printing or other sustainable materials will come down to the consumer demand and the builder's willingness to embrace greener alternatives.[43] Yet, in the current climate, we can break it down and state that it has the capability to challenge many traditional manufacturing constraints but will not replace existing conventional production methods.

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[43] Romani, Alessia, et al. "Design, Materials, and Extrusion-Based Additive Manufacturing in Circular Economy Contexts: From Waste to New Products." Sustainability, vol. 13, no. 13, 2021, p. 7269., https://doi.org/10.3390/su13137269.

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