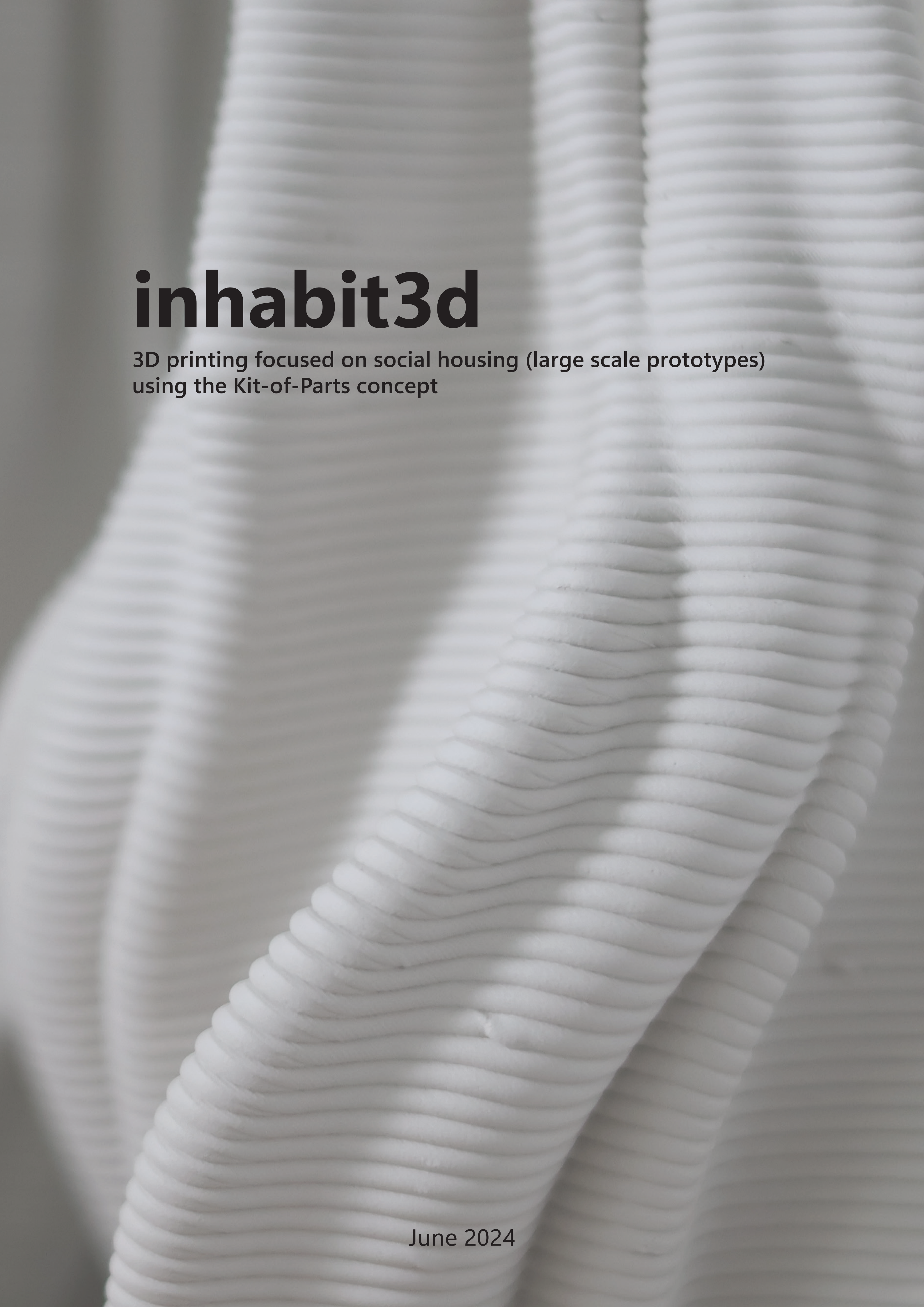

inhabit3d

3D printing focused on social housing (large scale prototypes) using the Kit-of-Parts concept

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To my mother and father.
Everything you taught me led me towards this journey, and without you, would not have been possible. Thank you for your endless support and love.

To my family and my chosen family.
Who, from far away, always found a way to be with me.

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Abstract

In times where the global housing crisis needs innovative construction methods, 3D printing in concrete arises as a suitable option. Identified as an efficient solution that minimizes construction waste, reduces labor and material costs, and prevents construction errors and cost overruns. This research explores the potential of concrete, an accessible and cost-effective material, in 3D printed housing projects.

The research emphasizes the importance of modular design for efficient construction and user customization by involving the Kit-of-Parts methodology, creating modular components for easy assembly, enhances design efficiency, cost savings, and flexibility. The thesis explores the integration of complex geometries and non-traditional forms to maximize structural integrity and aesthetic appeal. Experimentation with different material properties and construction techniques is conducted to optimize the 3D printing process for housing applications.

A key aspect of the research is the integration of user customization in social housing design, aiming to improve living quality by allowing users to influence the architectural layout according to their needs. The study includes designing housing units with interchangeable components and exploring different building iterations and their structural viability.

The thesis concludes by demonstrating the practical application of the proposed concepts through physical prototypes, highlighting the potential of 3D printing in revolutionizing the construction industry, particularly in addressing the affordable housing crisis.

Contents

1. Introduction.......... 10
   1.1 Background
   1.2 Problem Statement
      1.2.1 Lack of housing
      1.2.2 3D printing actuality and limitations
   1.3 Research Questions
   1.4 Objective
   1.5 Research Methodology
      1.5.1 Literature review
      1.5.2 Design
      1.5.3 Experimentation
      1.5.4 Prototyping

2. Literature Review.......... 19
   2.1 Kit of Parts
      2.1.1 Definition and relevance
      2.1.2 Classification
   2.2 Social Housing
      2.2.1 Definition and relevance
      2.2.2 What makes an architecture project social?
   2.3 Technology in 3D Printing
      2.3.1 Types
      2.3.2 Techniques
      2.3.3 Constraints in fabrication
   2.4 Architectural geometry
      2.4.1 Vault as starting point
      2.4.2 Undulations

3. Design Phase.......... 37
   3.1 The organization – Building level
      3.1.1 Building components
      3.1.2 Grid mechanism
      3.1.3 Building iterations

   3.2 The unit – House level
      3.2.1 Housing components
      3.2.2 The module
      3.2.3 User customization

3.3 The construction – Structure level
3.3.1 Vault Study
3.3.2 Structural approach
3.3.3 Aggregation result
3.3.4 Kit-of-parts
3.3.5 Foundations
3.3.6 Construction process

4. Experimentation 54
4.1 3D Printing problems to address
4.1.1 Joint design and assembly
4.1.2 Physical limits
4.1.3 Infill
4.1.4 Texturing and aesthetics
4.1.5 Structural limits: form-finding
4.1.6 Interior furniture
4.1.7 Assembly with other building elements

4.2 Clay-gun testing
4.3 Clay consistency test
4.4 Testing criteria

5. Prototyping 62
5.1 Model 1/20
5.2 Model 1/1

6. Conclusions 65
6.1 Answering the research questions
6.2 Future research

7. Reflection 68

8. Appendix 71
8.1 User customization examples
8.2 Printed models data

9. Bibliography 77

1. Introduction

1.1 Background

The global challenge of affordable housing has become an increasingly pressing issue, affecting diverse populations across the world [1]. Rapid urbanization with population growth, has led to a surge in demand for housing, intensifying the existing shortage of affordable options. At the same time, increasing real estate prices and static salaries have created a huge barrier for many individuals and families, pushing them to the limit of homelessness or precarious living conditions. The consequences of this crisis are high, impacting social stability and economic development. Governments and policymakers deal with the complex task of finding sustainable solutions, balancing the need for housing accessibility with the demands of a rapidly evolving urban landscape. For that matter, addressing the problem of affordable housing requires a multifaceted approach that includes innovative technology advances, community engagement, investment in affordable housing projects, among others.

The construction sector, which is the one called to go for an answer for the housing problem, has been using the latest technological advances leading us to a new concept known as *Construction 4.0*. It focuses on the digitalization of processes having 3D printing, the use of robotics. offsite and on-site construction, among others, as main examples within the category of physical systems, one of the three fields of transformation [2]; here we can see the importance of this technology for the current time and future.

Numerous studies support 3D printing in concrete might be one of the most efficient constructive methods. It can minimize construction waste and reduce the labor cost. In addition, has a potential to reduce material cost by cutting formwork usage. Also, being an automatized process, can avoid the construction errors and cost overruns [3]. From the sustainability and productivity point of view, can be a formidable solution for mass markets by using extruded geometric elements, which can be placed with freedom, that would lead to a low consume of material and the possibility to select a sustainable and ecological material [4]. This thesis focuses on the use of concrete as a material. It is easily accessible, cost-effective, and has been extensively researched and tested, making it a popular choice for housing.

All these characteristics point 3D printing in concrete as a promising solution for construction of houses in unfavorable contexts.

1.2 Problem statement

To tackle the critical challenges of the dwelling problem, it is necessary to develop solutions that not only prioritize speed, affordability, and flexibility but also recognize the significance of aesthetics for the residents. As urban populations continue to grow, there is a demand for housing that fulfils these diverse requirements. Traditional construction methods often struggle to address these needs simultaneously, which is where the utilization of modern technology may provide a solution.

1.2.1 Lack of housing

The affordability of housing has become a significant global challenge, impacting the economy, society, and the environment. The rise of housing prices and rents have made them less accessible and have resulted in social exclusion.

Moreover, house prices have beaten income growth in many countries, making housing costs the largest and fastest-growing household expense. The demand for affordable housing far exceeds the available supply, as most of governments investment in housing development has declined significantly since 2001. Constructing new housing is costly, while the demand for affordable housing continues to increase and change [1] this led to a shortage of dwellings.

For a better understanding, housing deficit describes a situation where the number of available rented properties in a specific area fails to meet the housing demands of its population. This deficit encapsulates scenarios where access to housing is unsatisfactory due to persistent uncertainty, such as informal rent, or access to homes that fail to meet the basic standards necessary for ensuring the quality life of its residents.

In the following lines different parts of the world will be presented with data to confirm the previous statements.

- Latin America and the Caribbean: Informal housing predominates in all countries, resulting in problems such as a lack of basic human necessities like electricity, potable water, and drainage, furthermore this intensified after the Covid-19 pandemic [5]. Oftentimes, it is the population itself that seeks out land to live on, even if these areas are not suitable for housing. This is how cities grow without proper planning. Figure 1 shows the percentages of the population without adequate housing or living in poor-quality housing [6].

Figure 1. Percentage of housing deficit for various countries in Latin America, 2012.

- Europe: The issue of housing shortages in Europe has become increasingly pressing as urban populations grow and the demand for affordable and comfortable living spaces exceeds the available supply. Figure 2 illustrates the percentages of people living in overcrowded conditions across the continent, highlighting that Eastern Europe faces a greater challenge in this regard.
  However, Figure 3 reveals that the overcrowding rate for young people is more than twice as high as the overall population. Examples as Denmark with 21.6% for young people vs 9.2% for all ages, the Netherlands presents a 7.5% to 3.4% ratio, and Finland 15.6% to 7.4%. This shows that while the general population in western European countries might be satisfied, the younger population will face an upcoming problem.

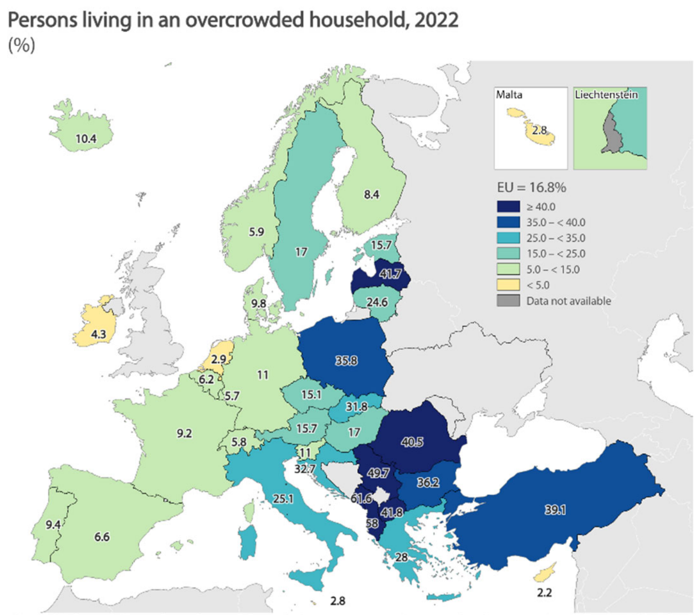


Figure 2. Percentages of people living in overcrowded households in Europe, 2022.

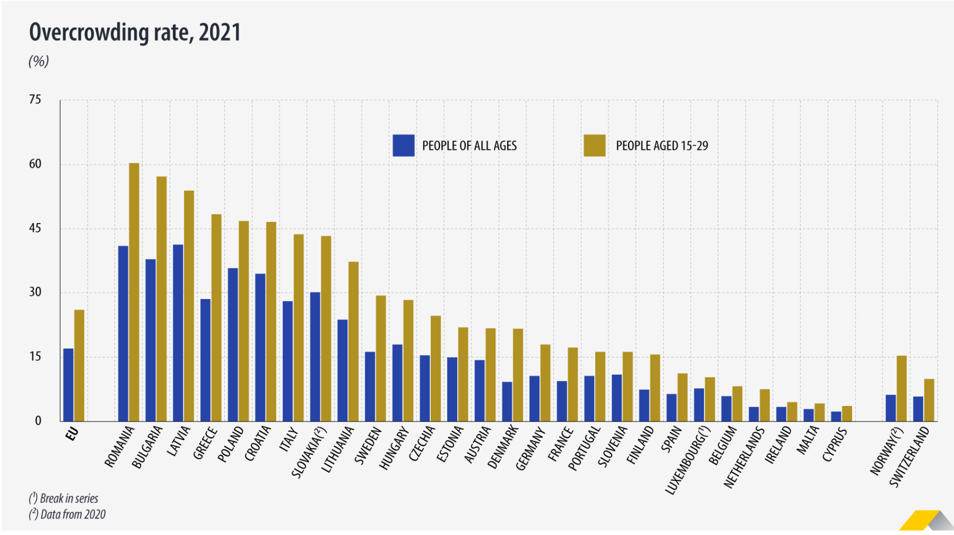


Figure 3. Overcrowding rate of young people vs. total population in Europe, 2021.

- The Netherlands: A primary issue facing this country is the housing shortage, particularly for young people and international students. The problem is likely to increase in the coming years. As of 2020, there was an estimated shortage of 315,000 homes, projected to rise to 415,000 by 2024 as is shown in Figure 4 [7]. However, more recent data suggests a shortage of 279,000 households in 2022, expected to reach 400,000 by 2025 [8]. To tackle this problem, the Ministry of the Interior and Kingdom Relations expects to build 845,000 homes over the next decade.

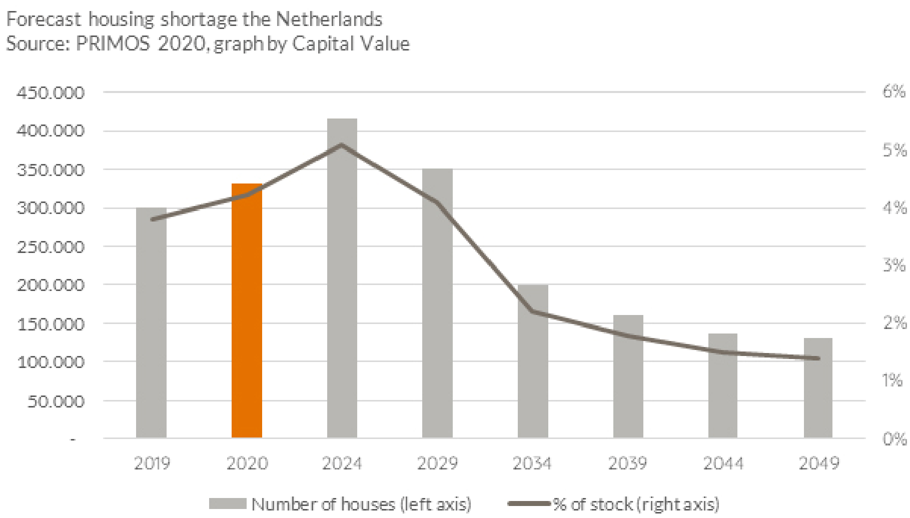


Figure 4.: Housing shortage in the Netherlands, 2020.

The presented data illustrates that the lack of quality housing is a global issue. It affects countries with diverse economic, political, and social circumstances, rather than being a problem specific to certain nations.

Thus, this thesis aims to provide a potential solution applicable in various contexts, recognizing the presence of unique location-specific variables and even the user's type or types that will be considered. More detail on this topic will be presented in the next chapters.

1.2.2 3D printing actuality and limitations

In the last decade, various 3D printing housing projects have been developed worldwide, having more presence in the United States and in Europe, due to the ease of access to this technology. A common characteristic for the most of these projects is their final form, a simple extrusion of a specific floor plan, as can be observed in Figures 5 and 6 below.

Figure 5, 6 accordingly. (Left): The ICON housing project. Austin, USA. (Right) The Milestone Project. Eindhoven, the Netherlands.

These examples illustrate how the dimensions of the 3D printer and the constraints set by the crane can restrict design possibilities. For larger constructions, a bigger crane is necessary if the whole structure is printed simultaneously, it means every time the crane must be modified. Additionally, the construction must fit within the printer's accessible and structured area.

Furthermore, 3D printing is an additive manufacturing process which uses the layer-by-layer technique, and masonry structures are also a layer-by-layer constructions but using a brick as prime element. This led us to conclude that every construction made by masonry can be done with 3D printing as well and arises the inquiry if the form and shape can go beyond what is already built with the use of this technology.

While today we see this type of construction, in 1958 Eladio Dieste was already was able to explore these shapes in walls and roofs. Extending the axis to non-vertical directions -or branching- can be achieved, as shown by architects such as Antonio Gaudi. Giving a distinctive and organic aesthetic of his architectural creations. Giving the almost certain that these forms are not the limit for the 3D printing.

Figure 7, 8 accordingly: (Left) Church of Christ the Worker and Our Lady of Lourdes. Canelones, Uruguay. (Right) Julio Herrera y Obes Warehouse. Montevideo, Uruguay – Eladio Dieste.

However, while the 3D printing process offers many advantages in terms of time and cost savings, is also important to identify its weaknesses when it comes to constructing dwellings.

The issue of the object's size and the crane's reachable area can be addressed by dividing the object into smaller, prefabricated elements, as suggested by the kit-of-parts construction approach; this concept will be expanded upon in the next chapter. Another potential solution involves adjusting the production method, as these smaller parts could be printed in advance and then assembled on site.

The process of printing can be faster compared to a construction made by workers [7] but might be not fast enough to make an impact in the mass production system. This limitation can arise from the various elements required for printing or the complex path the printing arm must follow. Two other factors which can affect the printing speed are the balance between the material's stability and flow, and the nozzle's speed. Firstly, the concrete must be easily pumpable and maintain a consistent flow before extrusion, but also stable and strong enough to receive the further material layers. Secondly, the nozzle speed is crucial and must be fast enough to prevent the underlying layer from setting too much, which could compromise the structure's stability. However, it should also be slow enough to allow lower levels to support the weight of the new concrete without collapsing [8].

In other disadvantages, the built house does not allow major changes to the exterior or interior form, this is not just for the 3D printing technology, but traditional constructions might be easier to make changes in the walls or roofs. If the user needs to modify the layout for various reasons, it will no longer be possible, and they will have to demolish and rebuild it, or discarding it and in need of a new home. Even making repairs to this type of construction with 3D printing could be a significant problem.

For these reasons, 3D printing might have a lot of improvements, in terms of the technological process, in the future but for now new techniques or ways to think the manufacturing are needed. Exploring other fields of production can be highly beneficial in terms of understanding, enhancing, and applying other techniques to achieve the desired objectives. This is particularly relevant in the construction industry, which is relatively new in adopting mass production methods for housing.

1.3 Research question

To address a complex problem, a strategy involving multiple fields of action is required. That is why this thesis will include the concept of a kit-of-parts and the use of form finding. This, in conjunction, aims to solve the manufacturing of social housing, simultaneously serving as evidence that technology has much to offer in terms of formal results that challenges 3D printing manufacturing.

This leads to the question:

How can 3D printing produce social housing units, and at the same time enhance construction efficiency, architectural adaptability, and encourage innovation in form and shape?

In the field of the Design Informatics, sub questions also arise, as:

- What is the ideal workflow for design and production for housing projects produced by 3D printing?
- How does the different constraints, that leads to a generative design, affects the different housing configurations?
- What other techniques of 3D printing can be used to enhance the form or shape of the object?
- What constraints need to be considered in the fabrication of the prototypes?
- Which techniques of 3D printing can be used to optimize the material, time, and structure of the object?

On the other side, from the Architectural point of view the interrogations are,

- Which characteristics in an architectural project makes it a social?
- How can the interlocking or assembly enhance the shape of the final project?
- How can 3D printing finishes be designed to prevent monotony and negative impact in the user's living space?
- How can the functionality of a housing space limit the design in form and shape?
- How can the diversity of users can influence the final shape of the project? As different users have different lifestyles and ways to use their own space.

1.4 Objective

The final product of the thesis will be an architectural project for a social housing project. The design will incorporate the concept of a kit-of-parts, enhancing the shape and form of the housing units and the overall building by including a computational workflow and designing for 3D printing.

As the kit-of-parts concept is being used, a comprehensive library of the final typologies that encompass all the designed parts will also be introduced. This innovative approach not only ensures the seamless integration of customer needs but also emphasizes a user-centric methodology considering customer satisfaction and engagement.

Additionally, physical prototypes of the housing units or parts will be produced using the robot arm available in the LAMA lab. Depending on the design and time constraints, the prototypes may be printed in either a certain scale or in full scale. Understanding the material which will be use also is a part of the thesis.

1.5 Research Methodology

The study within this thesis adopts a pragmatic and scientific methodology, which can be categorized into four primary domains: literature review, design, laboratory experiments, and prototyping. These domains are interlinked, particularly starting from the second one, and numerous modifications and enhancements are expected to happen throughout the research process.

1.5.1 Literature review

In this phase, extensive research is conducted on current papers and publications to become familiar with the main topics of the thesis, such as 3D printing and its relation to housing projects. Furthermore, additional research will be conducted on the most important concepts that this study aims to explore, such as kit-of-parts, social housing, and ongoing research projects in the field of form finding in 3D printing.

The most relevant sources of this topics are mainly from researchers as Shajay Boosham, Vishu Bhooshan, from the 3D printing field. Papers and study cases from distinguish universities as ETH Zürich and IAAC from Barcelona are also taken in consideration, and previous thesis projects from BK at the TU Delft has also been found relevant.

1.5.2 Design

It involves applying the findings from the literature review to answer the main research question and sub-questions effectively.

It begins with the analysis of a dwelling, breaking it down into smaller components that can be redesigned using 3D printing techniques. Once all the components are identified, various alternatives will be incorporated into the design to cater to different user needs. During this process, issues such as interlocking between the parts and housing units will be addressed. Ultimately, this stage aims to complete the library for the kit-of-parts.

However, it's important to note that subsequent phases may lead to changes in the design, making the process iterative.

1.5.3 Experimentation

This stage involves testing the material for use in 3D printers. The chosen material for the next stages will be clay, as the robot arm available can only print in this material, even when the proposed study will focus in concrete.

The objective is to understand the behaviour of clay, its composition, and the challenges to address, including factors such as viscosity, humidity, and printing velocity. This testing will be performed with tools provided by the LAMA lab.

1.5.4 Prototyping

In this phase, the first experiments will be conducted in the LAMA lab and under the supervision of Paul de Ruiter.

Here, the initial design iterations, either partial or complete, will be printed based on a basic understanding of the materials and printer tool. These iterations will determine the feasibility of larger or more complex tests and provide the first indication of whether any design changes are necessary.

Furthermore, the stage will finish with the printing the prototype or prototypes of the design on the larger scale possible. The changes and improvements seen in the test results will be taken into consideration to have the most suitable final product, furthermore the thesis will finish with the conclusions, final comments, and further research suggestions.

2. Literature Review

This chapter serves as an analysis of existing research relevant to the four main topics of this thesis: kit-of-parts, social housing, 3D printing and shape in architecture. Its aim is to provide a structured overview of the current state of knowledge in these fields and lay the foundation to answer the main research question and sub-questions.

2.1 Kit-of-parts concept

2.1.1 Definition and relevance

The kit-of-parts concept, as a general definition, is a design and manufacturing approach that involves organizing a complex structure or system into standardized, modular components or elements. This method is utilized in various manufacturing fields, including construction, automotive manufacturing, furniture production or electronics.

In architecture, Scott Howe defines it as a method that arranges its individual components in a building into standardized assemblies of easily manufacturable parts. These collections of components take in consideration problems as transportation or shipping constraints by design them with a suitable size [9]. It can be compared to a LEGO set, conformed by a library of various pieces that can be arranged in numerous and different ways to ultimately form a larger component as can be seen in Fig. 9.

Nevertheless, this concept is not an invention of the modern era, Bernard Rudofsky stands that the use of prefabrication and standardization in construction can be seen as early solutions that anticipate modern technology advancements [10]. Over history, various builders, from Roman military engineers to medieval master guilds and early industrialists in Great Britain, have prepared components like pre-cut stones, wooden beams, and corrugated iron sheets off-site to streamline on-site construction. Furthermore, another example of this approach can be seen in traditional Japanese houses, where sawyers and master carpenters simplified construction and even considered the provision of replacement parts in case of earthquakes [11].

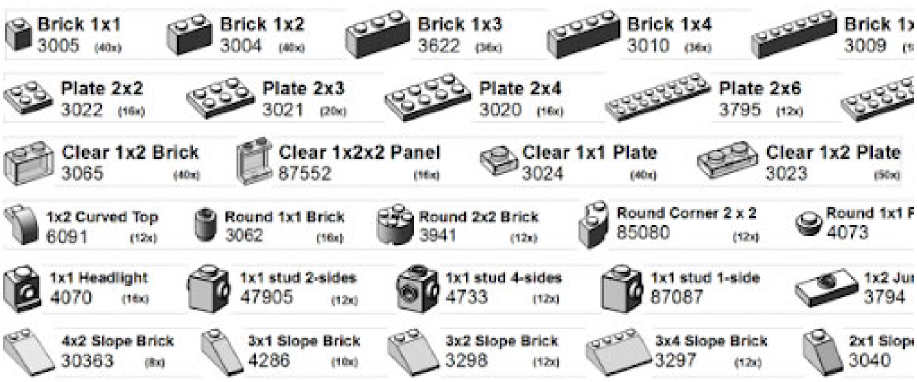


Figure 9: Kit-of-parts of a Lego set.

Some of the most relevant advantages of this method within the construction field include:

Design efficiency is achieved by using standardized components and assemblies. This eliminates the need for complex and time-consuming custom designs for every project. Furthermore, a repetitive component can be manufactured with high precision and undergo rigorous quality control, ensuring improved overall construction quality and consistency while controlling the production at the same time. Also, the standardized nature of components simplifies maintenance and repairs with an easy replacement, this saves the issues of demolitions.

In terms of cost savings, it can be achieved through reduced labour efforts and minimized material waste. Additionally, time efficiency can be improved by enabling quicker assembly and construction, as workers become familiar with standardized components this leads to shorter project timelines. Furthermore, the inclusion of robots allows for automation, further enhancing time savings making it sustainability as well.

Flexibility is also a key attribute, as it allows for the adaptation of the design to different project requirements. The layout can easily be adjusted to accommodate growth or shrinking. Additionally, by being modular offers the advantage of replicability, providing the option to reproduce the design in multiple locations or the same module to reassembly elsewhere.

Following with other advantages, when it is combined with 3D printing as manufacturing method, introduces a transformative approach to how objects and structures are designed, produced, and assembled. This methodology significantly improves flexibility and efficiency at various production stages by enabling smaller, customizable piece printing.

Firstly, it permits component customization to meet specific user needs, ensuring each part can be designed and printed with exact specifications. This personalization level is especially beneficial in industries where tailored solutions are crucial.

Moreover, printing in smaller segments makes part transportation more manageable and cost-effective. They can be compactly packed and shipped to different locations, avoiding the logistical difficulties associated with larger pieces. Upon arrival, these parts can be assembled on-site, simplifying the construction process, and enabling a modular building approach. This not only saves assembly time but also allows for easy component modification or upgrading, accommodating future needs or changes.

In conclusion, integrating the "Kit-of-parts" concept with 3D printing technologies offers a progressive strategy that leverages customization, transportability, and on-site assembly, ushering in a new era of efficient and adaptable manufacturing.

In summary, the kit-of-parts concept in construction addresses many of the challenges associated with traditional construction methods, offering benefits in terms of cost, time, quality, sustainability, adaptability, simplifies manufacturing processes, enhances product consistency and making it a valuable approach for different construction projects, including housing and it adapts perfectly with the 3D printing manufacturing.

2.1.2 Classification

Howe classifies the methodology of kit-of-parts and prefabricated systems in four main types: systems based on joints, systems based on panels, systems based on modules, and special construction systems [9].

- Joint-based: involves pre-cutting materials for later assembly and construction. These systems have clear distinctions between members and joints, with special design or connection techniques that enhance assembly and erection time. They can be represented virtually in a computer and are suitable for kit-of-parts concepts. Well-designed joint-based systems can also facilitate automated construction techniques.

- Panel-based: incorporates structure and cladding into one-piece assemblies, have evolved from wood frame to various materials like metal and pre-cast concrete. They are easier to represent geometrically in the computer and may be more suited for automated construction technology than joint-based systems.

- Module-based: offers advanced prefab solutions with pre-assembled portions or blocks that can be easily assembled on-site. These systems require fewer components than panel or joint-based systems, with some capable of forming a self-contained building as a single unit. Robotic construction systems can be designed for efficient assembly, and modules can be manufactured off-site.

- Special Construction: includes deployable and inflatable structures, have been researched and developed for quick deployment in various construction environments. These structures, such as deployable folding truss systems and swing-open modules, offer compact and lightweight profiles but present challenges in providing openings. Inflatable modules and structural systems are also designed to be lightweight and portable during shipping and storage, expanding to appropriate sizes when inflated. These special structures have potential applications in emergency housing, large-scale construction sites, and military barracks.

In summary, the presented types of kit-of-part approaches provide significant knowledge to choose which one is applicable to the thesis project. Considering the typology of housing and the size of the project, the Module-based approach is the most favourable.

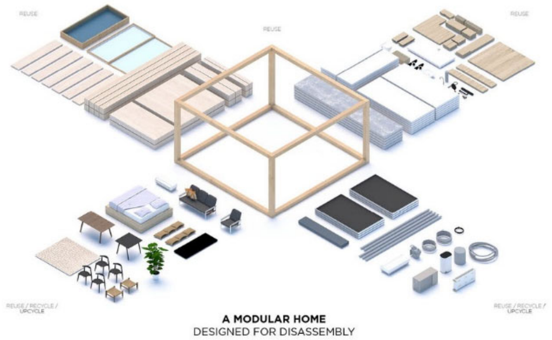


Figure 10, 11: Kit of parts. Urban Villa Project, 2018 - EFFEKT.

2.2 Social Housing

Other of the main research areas of this thesis is the "social housing" approach that the project aims to include. Throughout the history of architecture, numerous projects of this nature have been undertaken, and various approaches to this concept have been developed. The following subsections will provide a definition of this concept and present a different case study.

2.2.1 Definition and relevance

Translated in the most basic conception, housing denotes the appropriate physical environment which serves as a residence for individuals or families, facilitating their complete development and the realization of their goals, requirements, and desires. In a more expansive perspective, housing extends beyond merely the physical dwelling or "roof" encompassing the adjacent land, infrastructure, and communal facilities within a particular area and the framework of social, cultural, economic, political, technological, and physical influences [12].

Furthermore, in its process also includes various crucial stages such as planning, design, construction, provision, occupancy, and management. And when the term “social” is included, it refers to the housing for the most needed population which will improve their residential circumstances [12].

For Javier Sánchez [13], “the functionalist thinking reduced the concept of "social housing" to "minimum housing" and subsequently to "cheap housing" ”. This translated into a reduction in the quality of space and materials resulted in compromised living conditions. In this line, for Ernesto Alva, there is no housing which can supreme the concept of social, as we all belong to a certain society. Many times, the idea of “social housing” is related to dwellings for poor people or certain workers with a low income [12].

Overall, is important to have a clear understanding of the idea of "social housing" to propose a project which can fulfil the needs of the user, their immediate environment as the city and their context. In the next sub section, different study cases will be presented in order to define the approach the proposal will have in this matter.

2.2.2 What makes an architecture project social?

Answering this question may be difficult and open to different opinions or approaches when it comes to an architectural project. However, by examining various examples, it is possible to gain a general understanding that aligns with the goals of this research.

- Quinta Monroy, 2003 – Alejandro Aravena.

This dwelling in Chile, has been a case study of social housing for the design decision of leaving one part of the housing unit empty. First, as a terrace or outdoor space but throughout the years it ended intervened by its occupants following their own necessities: a new dormitory for a coming son, a bigger social area, or a covered terrace, etc.

Figure 12, 13 accordingly: Comparison of the housing project before (left) and after (right) the user's intervention. Iquique, Chile.

Quinta Monroy, in a way, sacrifices the beauty that arises from the purity of its volume in order to prioritize functionality. The space for future expansion is provided, and its intervention does not compromise other aspects of the house, such as circulation through different spaces or ventilation of other rooms. In other words, it offers a guided approach to growing and inhabiting one's home. This is done regardless of whether these additions enhance or detract from the overall volume in terms of materiality or scale.

As can be seen, this is example of a "social" project where the space and form can mutate depending on the user preferences making it flexible and customer-oriented approach.

- R50 Baugruppen, 2013 – Jesko Fezer, Heide & von Beckerath

This project shows a collaborative living, or “cohousing”, is a type of living arrangement where residents can access fully equipped private apartments as well as shared common spaces in a building that is developed through a collective effort from all owners and residents.

R50 is another example of a customer-oriented approach, but as different with Quinta Monroy, its design is particularly for a known resident. At the point of a thorough evaluation of residential reference systems for residents was conducted, considering desired room sizes and spatial relationships.

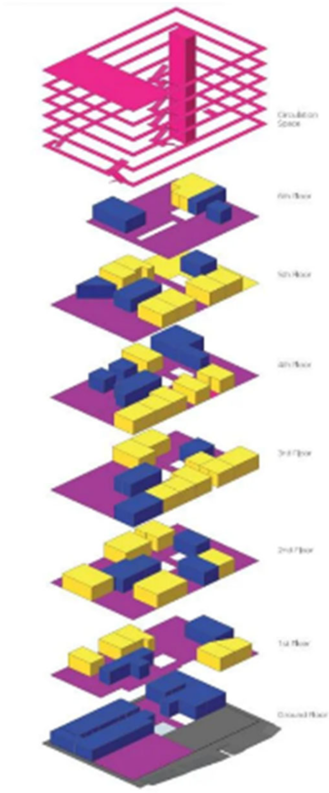
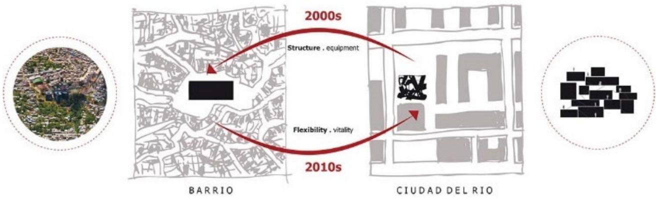


Figure 14, 15, 16 accordingly: (Upper left) Participatory design meetings. (Bottom left) Exterior photo of the built project. (Right) Axonometry view showing the distribution and the different housing typologies. Berlin, Germany.

- Museum of Modern Art MAMM, 2015 – 51-1 Architects

The winner proposal for the expansion of the Museum of Modern Art (MAMM) in Colombia was unique in terms of bringing an unorganized urban grid to the plot with its characteristics.

The architect De Rivero explains it as "importing the informal city of stacked houses in the hills, where one's roof is the upstairs neighbour's terrace, the new MAMM is laid out as a cascade of connected terraces open to the public. Inside, the blocks are a sequence of spaces displaying artwork; outside, they create a public realm that is continuous up to the fifth floor. With the combination of both, multiple new ways to display the art emerge."



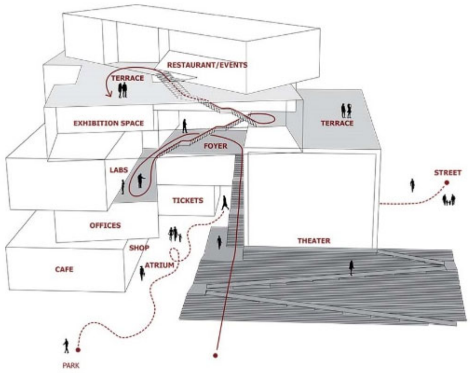


Figure 17, 18: (Left) Urban approach. (Right) Axonometry with the exterior and public spaces. Medellin, Colombia.

MAMM illustrates another type of "social" approach, with formal gestures which leads to social cohesion between the citizens.

- Fernando Botero Park Library, 2010 – G Ateliers Architecture

The Fernando Botero Library Park is a key component of an ambitious master plan, which is a groundbreaking initiative in its city's history. It seeks to rejuvenate the city centre by introducing cultural amenities and services designed to address the pressing social requirements of a predominantly low-income population which has historically been excluded from the State's social investment policies.

In this case, by placing a service building in a context creates pertinency sense and social cohesion, another approach for a "social" project.


Figure 19, 20 accordingly: (Left) Building in its context. (Right) Exterior photo of the common and open spaces within the building. Medellin, Colombia.

Other housing projects were also studied to have an extensive understanding of the typology. The Nakagin Capsule Tower [Fig. 21] aims at adaptable, growing, and interchangeable building outcomes. The prefabricated capsules can be connected and combined with increasing spaces between them, giving freedom along the time to reconfigured for future users. Each self-contained unit were identical. On the other side, Habitat 67 [Fig. 22], with an interlocking of prefabricated concrete typologies was stacked in multiple configurations, providing each unit at least one private terrace, suburban garden home.

Studying cases of massive housing, outstands the Maison Medicale by Lucien Kroll. Collaborating with students, Kroll created a series of ecological, quirky buildings connected by meandering paths and small squares. This design also allowed for customization by the residents; each student living there could choose their own facade and personalize the common spaces on the top level [14] [Fig. 23].

Moreover, Lacaton & Vassal's project involves renovating an existing building by adding winter gardens and balconies. This allows each apartment to benefit from additional space, increased natural light, greater flexibility of use, and enhanced views. This renovation also provides each apartment with its own private outdoor space.

Figure 21, 22, 23 accordingly: (Left) Habitat 67, construction. Montreal, Canada. (Middle) Nakagin Capsule Tower, construction. Tokyo, Japan. (Left) La Maison Medicale. Brussels, Belgium.

After of a more extensive research and gather the most representative project which can illustrate the definition of “social” in an architecture project and translated to the housing field, some general ideas can be concluded.

Is not only about physical or spatial approach, but also considerations for the target user, project management, and the investment plan. A holistic approach is taken, involving collaboration with various disciplines beyond just architects or engineers [6]. For this research, the concept of social housing is not related to the economic conditions of the user, but in the way the dwelling, as a spatial building, can improve the living quality of its inhabitants. Furthermore, a housing project should be flexible and versatile in order to receive life.

The presented examples, particularly the housing projects, exemplify adaptability, customization, and efficient use of space in architecture. Projects such as the Nakagin Capsule Tower and Habitat 67 showcase the versatility of prefabricated modules by offering dynamic, expandable living environments with unique private spaces. Habitat 67 also introduces a functional approach with the interlocking system between modules. The Maison Medicale highlights participatory design by enabling residents to personalize their units and communal areas. Collectively, these case studies illustrate the crucial role of forward-thinking architectural practices in addressing modern housing needs and enhancing urban life.

For the purpose of this thesis, we will incorporate the approaches of user customization and the creation of socialization spaces within the home design. This aims to strengthen the connection between the user and their living space by allowing it to reflect their personality. This concept aligns with the use of the kit-of-parts strategy. Here, different components of the home can be swapped based on the user's needs and preferences, a flexibility not possible with current construction methods.

2.3 Technology in 3D printing

Additive manufacturing, commonly referred to as 3D printing, is a method employed in the design and production stages by architects and designers. Originally developed in the 1980s for rapid prototyping, has evolved significantly over the decades to become a viable industrial-production technology, this transformation is marked by improvements in precision, repeatability, and the diversity of materials that can be used, enabling the creation of complex shapes and geometries that are difficult or impossible to achieve through traditional manufacturing methods. Innovations such as hollow parts and internal truss structures for weight reduction highlight the technology's unique capabilities [15].

The concept of 3D printing was first imagined in science fiction since 1945 in stories before transitioning into reality with the development of additive manufacturing equipment and materials in the 1980s. The first patent that resembles modern 3D printing was filed in 1971, and since then, the field has seen rapid advancements, including the introduction of various 3D printing processes like selective laser melting in 1995 [16]. The expiration of FDM (Filament Deposition Modelling) patents in 2009 encouraged further growth and innovation, allowing for more widespread use and the development of new applications, such as sustainable development tools for the changing world and the printing of functional electronics. Throughout the last years, it has transformed numerous fields, such as product design [17], fashion [18], and sculpture [19], thanks to the precision and rapidity offered by desktop 3D printers.

Furthermore, the incorporation of industrial robots for bigger projects is transferring automation and process management techniques [20] from the automotive and aerospace sectors [21] to the fields of architecture, engineering, and construction. However, this particular use of technology is still in the developmental phase.

3D printing represents the next phase in the transition towards mass customization in the cyber-physical era. The objective is to enhance computational geometry by incorporating as many physical constraints as possible, enabling direct manipulation of geometry. The layers of the printed material must overlap to a certain extent in order to maintain stability. However, it's important to consider constraints such as material viscosity and drying time. These constraints determine the feasibility of different shapes, allowing for the development of a language for printable geometry.

2.3.1 Types of 3D Printing

Almost every conceivable object can now be produced through 3D printing, from pencil holders to rocket engines. Despite differences in these technologies, they share key elements. Firstly, the process begins with a digital model created using computer-aided design (CAD) software. This design file is then processed using special build-preparation software that divides it into slices or layers. This software, often specific to the type of 3D printer and its brand, converts the sliced model data into path instructions for the 3D printer to follow [23].

Additive manufacturing can be categorized based on the products they create or the materials they use. However, the International Standards Organization (ISO) has established seven general types for global structure. These include: (1) Material Extrusion, (2) Vat Polymerization, (3) Powder Bed Fusion, (4) Material Jetting, (5) Binder Jetting, (6) Directed Energy Deposition, and (7) Sheet Lamination [21]. For terms of more used and relevant to this thesis, only the first three types will be mentioned.

- Material Extrusion

As its name indicates, is a material being extruded through a nozzle [Fig. 24]. Typically, the material is a plastic filament pushed through a heated nozzle that near-melts it in the process. The printer deposits the material on a build platform along a path determined by the build preparation software. The filament then cools and solidifies to form a solid object [22].

Extrusion allows for the use of various materials, including plastics, metal pastes, concrete, bio-gels, and a variety of foods, hence its broad applicability. This method encompasses subtypes such as Fused Deposition Modelling (FDM), construction 3D printing, micro 3D printing, bio 3D printing, and Fused Granulate Modelling (FGM). The materials used range from plastics and metals to food and concrete, with a dimensional accuracy of ±0.5% (lower limit ±0.5 mm). This technique is commonly used in creating prototypes, electrical housings, form and fit testing, jigs and fixtures, investment casting patterns, and even houses. Despite its low cost and material versatility, it often results in lower material properties such as strength and durability, and its dimensional accuracy is not as high as other methods [23].

- Vat Polymerization

Vat polymerization, also known as resin 3D printing, uses a light source to selectively solidify a photopolymer, polymers that react to a light, resin in a vat [Fig. 25]. In this process, light is accurately targeted to a specific point or area of the liquid plastic, corresponding to a slice of the 3D model, to cure it. Once the initial layer is hardened, the build platform is slightly moved up or down, typically between 0.01 and 0.05 mm, depending on the printer. The subsequent layer is then cured, adhering to the previous one; this process is repeated until the 3D object is formed. Once the 3D printing process is complete, the object is cleaned to remove any remaining liquid resin and then post-cured in sunlight or a UV chamber. This step enhances the mechanical properties of the part, making it usable [22].

The three most common vat polymerization methods are stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD), also known as masked stereolithography (MSLA). The principal difference between these types of 3D printing technology lies in the light source and its usage in curing the resin [23].

- Powder Bed Fusion:

PBF operates by using an energy source to merge powdered material (plastic, ceramic or metal) together. A blade or roller, which has been recoated, distributes a fine layer of powder over a construction surface; then, the energy source selectively heats or sinters the required material for that layer. Following this, the build plate lowers to allow for the application of the next layer. This cycle repeats until the entire object is created, with the final product embedded and supported within a bed of unfused powder [24].

This 3D printing type can vary depending on whether the material used is plastic or metal. Despite this, PBF can produce parts with high mechanical properties such as strength, wear resistance, and durability. These parts are suitable for end-use applications in consumer products, machinery, and tooling. Subtypes of this process includes Selective Laser Sintering (SLS), Laser Powder Bed Fusion (LPBF), and Electron Beam Melting (EBM), are primarily distinguished by the material and energy source used [23].

This thesis has extensively examined 3D printing technologies, highlighting their central role in modern manufacturing across various industries. It detailed the foundational process of these technologies, starting with digital modelling using CAD software, and then generating slice-based path instructions tailored for specific 3D printers.

The study further explored the primary additive manufacturing types classified by the ISO: Material Extrusion, Vat Polymerization, and Powder Bed Fusion. Each type is distinguished by its material handling and product creation processes. Material Extrusion, while versatile and cost-effective, has some limitations in strength and accuracy. Despite these limitations, it is crucial in producing diverse objects, from plastics to food. Vat Polymerization offers precision in curing resin, yielding parts with improved mechanical properties, making it suitable for detailed final products. Powder Bed Fusion excels in creating high-strength components, essential for end-use applications in various sectors.

Together, these technologies represent significant advancements in additive manufacturing and underscore the potential for future innovation. They enable the creation of complex, customized, and high-performance parts across multiple fields.

This thesis will concentrate on the material extrusion type, as this is the method employed by 3D printers in housing projects. Moreover, it aligns with the printers accessible for this study and available in the LAMA lab.

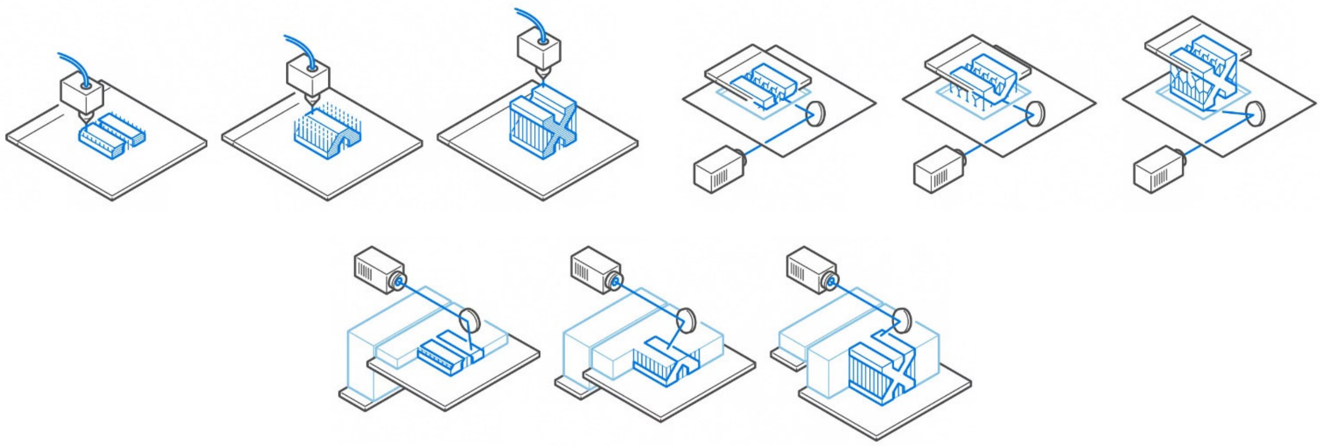


Figure 24, 25, 26 accordingly: (Upper left) Material extrusion diagram. (Upper right) Vat polymerization diagram. (Bottom) Powder bed fusion diagram.

2.3.2 Techniques in 3D printing

In the exploration of the complexities of the design process, understanding the differences and possibilities offered by various 3D printing techniques becomes crucial. Despite conventional methods being used for prototype production, different and interesting practices are shown in the subsequent section. These will act as a starting point and reference for the proposal practice of the investigation.

- Villa Roccia, 2011 – James Gardiner

The project use construction 3D printing techniques to enhance the function and design based on a potential of buildings elements by printing parts of the final object and flipping them. This approach avoids the difficulties that 3D printing has not yet completely solved as thickness the overhang.

This expression describes the gradual agglomeration of parts into larger assemblies [Fig. 27], through discreet stages to form the whole. It highlights a technique that goes beyond off a 3d printing methodology [28].

- 3D printed Shelter, 2014 – 3M futureLAB + UCLA

Another innovative approach is the inclusion of other building elements as furniture or plumbing that can be fused to walls or columns. It includes an integrated design technique and gives speed, automatization, and the possibility to address high-volume projects made it one the most economical options. In the mini apartment, along with the walls a table, a bed, a sink, and kitchen furniture were printed [Fig. 28].

Figure 27, 28 accordingly: (Left) Villa Roccia 3D printing prototype. (Right) 3D printed shelter. Munich, Germany. – 3M FutureLab + UCLA.

- Striatus Bridge, 2021 – Zaha Hadid Architects

The bridge functions as a series of leaning unreinforced voussoir arches. It is structured with discretization perpendicular to the main flow of compressive forces, using the same principles as arched Roman bridges made of stone [26]. Furthermore, the technique of printing by using a robot arm allows an oblique plane of printing and finishing [Fig. 29].

This referent can illustrate different problems in 3d printing and its solutions. Partitioning a bigger element into small pieces and the considerations for the foundation. Also, showcases the infill path, important when optimization for material saving and structural behaviour are desired [Fig. 30].

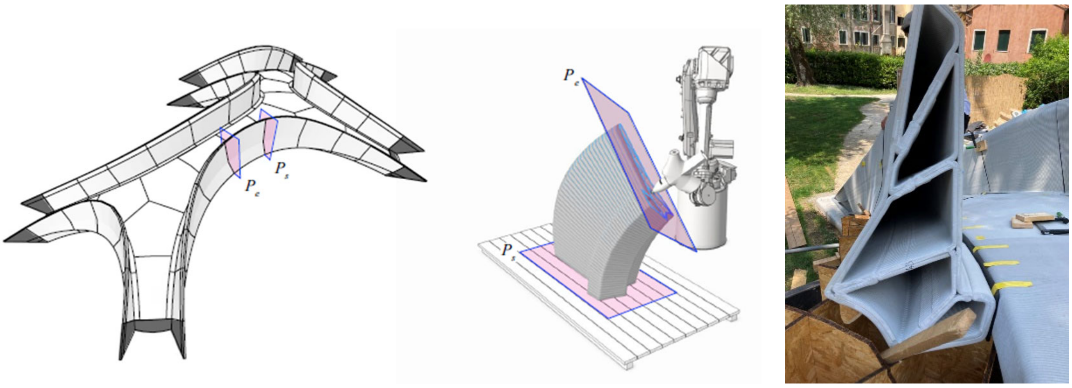


Figure 29, 30 accordingly: (Left) Oblique printing technique. (Right) Section view of one of the bridge's pieces. Venice, Italy

- Preschool in Aix-en-Provence, 2018 – XtreeE

Instead of 3D printing the column itself, the company 3D printed a hollow formwork [Fig. 31], or outer layer, for the complex concrete column, which was then filled with concrete. Then, after the final geometry of the outer structure was designed by topological optimisation, it was divided into four parts for fabrication. The 4-metre-high column was placed on site, filed to remove the appearance of each printed layer, creating a smooth surface [Fig. 32].

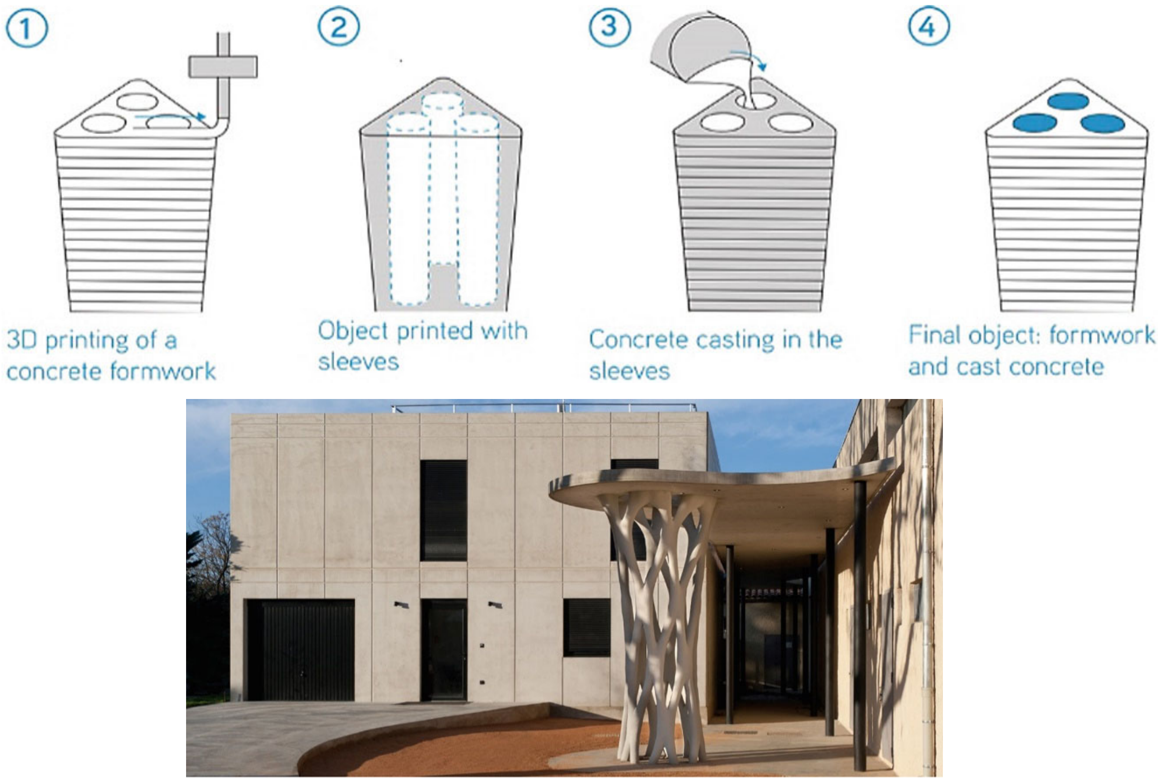


Figure 31, 32 accordingly: (Upper) Manufacturing process diagram. (Bottom) Finished prototype. Aix-en-Provence, France.

- Building Architecture Continuity, 2019 – IAAC Barcelona

This project employs continuous printing and cantilever geometries to enhance the structural capacities and spatial qualities of its expected results. Research succeeded to demonstrate the language and style of large-scale 3D printing various full-scale prototypes [Fig. 33].

The project's development is based on an informed architectural design, using parametric modelling and performance assessment methods. In addition to the performance achieved during the design process, the project also promotes the effective use of construction methods and materials: on-site robots enable the utilization of local and natural materials for building. Working on different scales with different materials gave them a deeper understanding of how 3D printing at large-scales changed with different machines. Also, the design had to be adapted for every scale not only to make up for change in machinery but also because of material change on every scale [27].

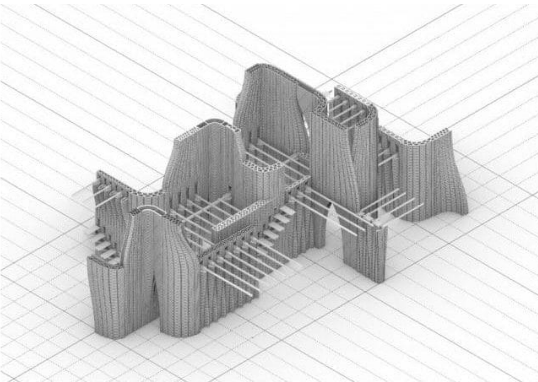



Figure 33, 34 accordingly: (Left) Housing diagram. (Right) Assembly solution for the wooden stair. Barcelona, Spain

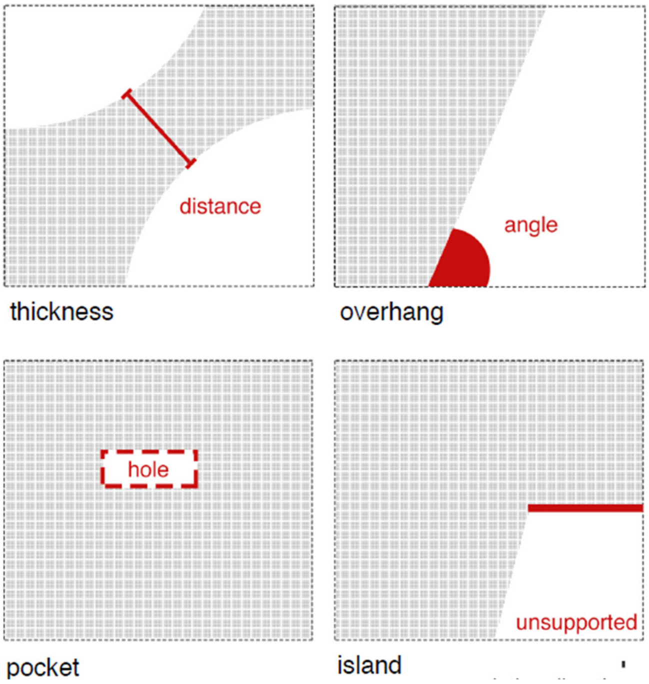
In conclusion, this chapter has showcased the significant impact of 3D printing in architecture through the examination of various pioneering projects. Projects as Villa Roccia and the 3D Printed Shelter showcase innovative adaptations of 3D printing to streamline construction processes and integrate functional elements directly into building structures. The Striatus Bridge highlights the use of robotic printing techniques to enhance structural integrity by emulating ancient design principles. Meanwhile, the Preschool in Aix-en-Provence and IAAC Barcelona's projects illustrate the potential for precise control over complex geometries and the adaptability of 3D printing to various scales and materials. Collectively, these cases illustrate how 3D printing is revolutionizing architectural design and construction, offering sustainable, innovative, and efficient solutions.

The thesis will primarily focus on three 3D printing approaches. Firstly, it will consider unit partition to break the project into smaller pieces, enabling integration with the kit-of-parts concept. Secondly, it will explore non-planar printing techniques to justify the use of 3D printers and robotic arms. Lastly, it will incorporate various materials and textures into the design, aiming to create a more humanistic environment for the user, as being surrounded by the same concrete or clay could be uncomfortable.

2.3.3 Constraints in fabrication

The are still difficulties that 3D printing has not yet completely solved, such as thickness, pockets, overhang, and island [Fig. 35] which usually depend on the machine and material.

As a layer-by-layer technique, it can only be applied to an existing surface or extend beyond the lower layer to a certain extent. Most of the time, by cooling the material instantly and reducing the speed of the extruder's movement, the limit can be extended and prevent the printing material from falling and solidifying outside the intended geometry. Nevertheless, material falling is sometimes desirable for the design [Fig. 36].



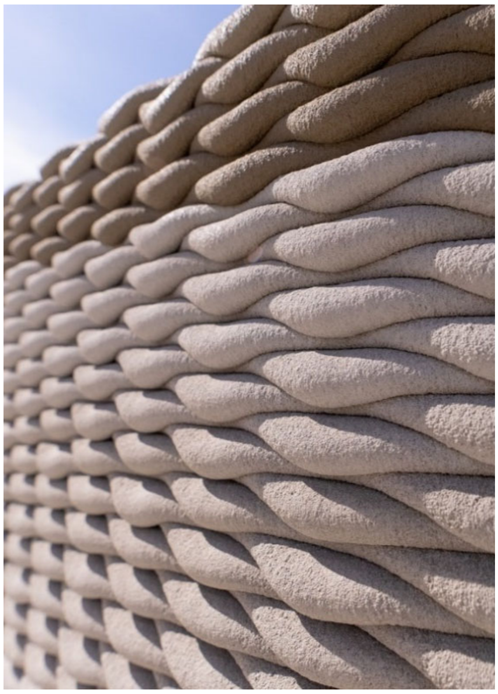


Figure 35, 36 accordingly: (Left) Constraints of 3D printing [25]. (Right) ICON's textured wall.

Other elements, foreign to the original geometry, can also be used as support to prevent collapse under a large cantilever. These frameworks are typically printed along with the design when the scale is small. For larger scales, the framework can be made of wood as a in concrete structures.

These problems and constraints, specifically the overhang and the inclusion of holes within the printing will be thoroughly addressed and attempted to be solved through laboratory experiments. They will then be further refined during the prototyping phase.

2.4 Architectural geometry

Throughout the problem statement, there is a mention of the desire to explore and contribute unconventional forms and aesthetics. However, it is important to note that this objective should be achieved in a way that is supported by technical and meaningful aspects, rather than being gratuitous.

2.4.1 Vault as starting point

If the larger span in desired and as 3D printing works with compression structures, vaults arise as an option. They efficiently distributing weight and force down and outward along their curved form. When loaded, the arched shape channels these forces towards the ground, with the stress managed across the vault's curve towards supporting walls or columns. The reason vaults are strong is because of their shape and the materials used, such as stone or brick. These materials are excellent under compression and can be seen throughout the history in cathedrals and bridges, showcases the vault's ability to stably bear significant loads through its compressive design.

Additionally, considering that the vault is a continuous form, it aligns well with 3D printing techniques. Consequently, the vault will be utilized as an initial form to explore its inherent limitations. Other factors, such as the dimensions of the arch, will be determined through the study of the housing unit and taking in consideration its various components. At first glance, the size might pose a challenge during production. However, this is in line with the 'kit-of-parts' approach embraced by this study. This strategy involves the division of larger elements into smaller components to simplify the printing process.

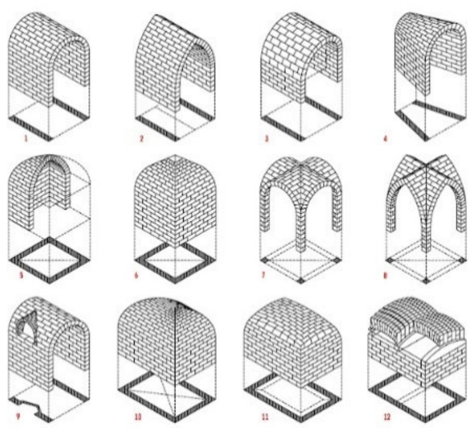


Figure 37: Vault shape configuration and variations study.

2.4.2 Undulation

A series of undulations in the three-dimensional profile of the structure will be study to introduce to the design. Since these forms will be built using robots in a layered manner, it increases the stability of the material and the overall strength of the structure by increasing the contact area between subsequent layers, thus increasing the overall perimeter and surface to surface contact.

Even when the overall shape could be seen as an entire structure, just the addition of curves within it can help to make it structurally stronger. A prove of this is the 3D printed wall made by the IACC University [Fig. 38]. In a different scale, Richard Serra applied this principle in his installations by incorporating curves on a flat surface, allowing the structure to stand by itself [Fig. 39].

Figure 38, 39 accordingly: (Left) Wall 3D printed in clay, 2018. IAAC, Barcelona. (Right) Cycle installation, 2011. Richard Sierra.

3. Design Phase

This chapter serves as the pivotal stage where conceptual ideas take tangible form, bridging the research and practical application. It is structured into four distinct yet interrelated stages: The Organization, as the building level, focused on the macro point of view; The Unit, as the house level, studying the micro point of view of the project and the Construction, as the structure level, where details and construction process is shown. Through this sequential approach, the design phase ensures a comprehensive exploration of architectural possibilities, leading to a coherent and innovative final proposal.

The inhabit3D project is structured around several key components, starting with Location, which is not strictly defined but is adaptable for replicable housing solutions. These solutions are designed to work on two types of plots: slope and flat, with a focus on production on site to ensure flexibility and efficiency. The project emphasizes Social Housing, targeting customer-oriented designs that consider user type, housing typology, and social cohesion, facilitated through common spaces that encourage community interaction. A crucial element of the project is 3D Printing, which utilizes materials such as concrete for the conceptual part and clay for the prototyping and emphasizes innovative techniques and experimentation to push the boundaries of construction. The concept includes a Kit of Parts, comprising a form library that breaks down housing components into individual pieces, allowing for modular and scalable construction. The Vault as Starting Shape provides a foundational architectural form that guides the design and construction process. Together, these components create a comprehensive framework for developing sustainable, adaptable, and socially cohesive housing solutions [Fig. 40].

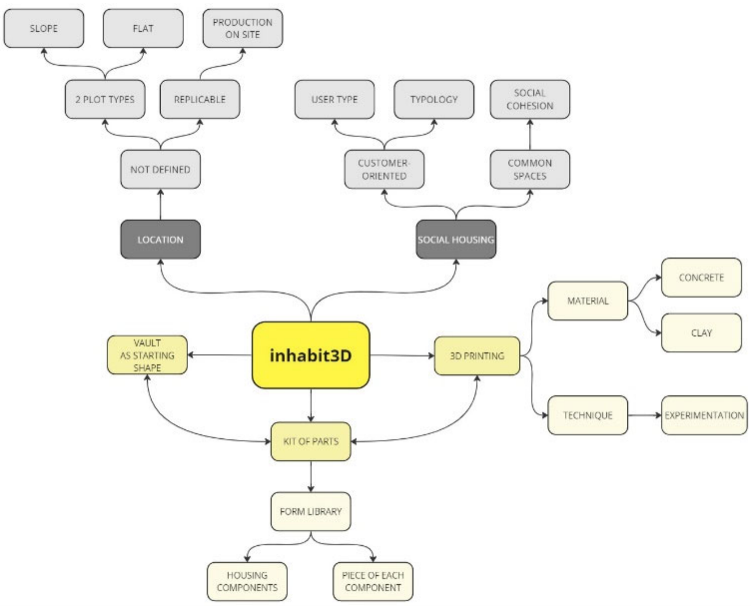


Figure 40: Proposal overview. Own work.

3.1 The organization – building level

In this sub section, and with a macro perspective, an overview of the various iterations for the entire household are introduced. For this, the first step is to set the components that will constitute the aggregation. Following this, a three-dimensional grid is employed to facilitate the movement and expansion of these elements. Ultimately, this procedure leads to the determination of the different building iterations.

3.1.1 Building components

Understanding that each household member has specific space requirements can determine in the preliminary design and shape of the housing units. For instance, a single person or a couple may find a flat sufficient, while a family of four with a pet may require additional space. The preferred number of levels can also be a constraint and influence the decision.

This suggests that each user should have a unique "module". Prior to determining the precise dimensions or square footage of these modules, this study begins by setting a fundamental scale and different shapes for the apartments.

To simplify the process, five different iterations were chosen to be used. One option for a single module must be in one level (A1). Three options using two modules, two in two-story shape (B1, B2) and other one in one-story (C1). Finally, two more options with three modules, one in three levels (D1) and the other in L-shape in two floors (D2). These iterations and its codification can be seen in [Fig.41].

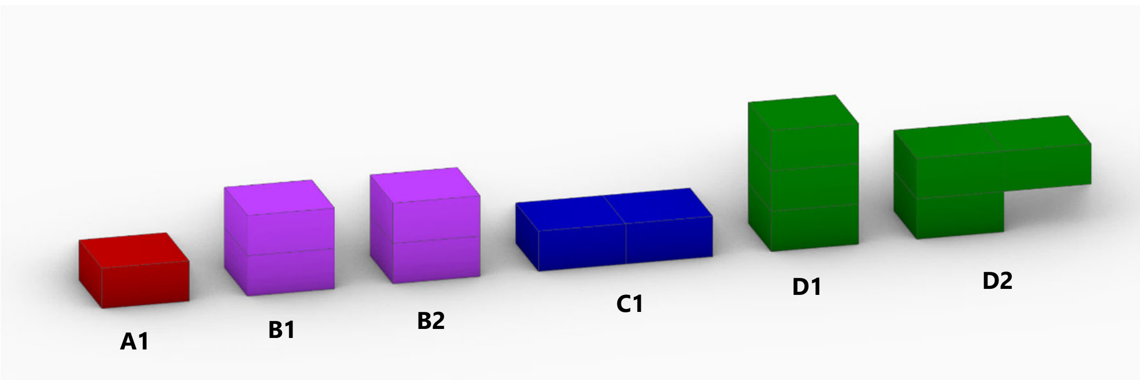


Figure 41: Shape iterations of housing units. Own work.

3.1.2 *Grid mechanism*

After stablishing the units, the plot to intervene is first subdivided into a 3D grid, which acts as the environment for the module's growth. It will have a starting point where the first agent is seeded. And through some basic rulesets it will start and continuously growing. It can also happen to have two or more seeds depending on the plot size.

The growing process can only happen with adjacent spaces to the seed. For this case, by using a neighbour in the same level it will be denominated as "growing", while when it happens in other levels it will be denominated as "branching". These concepts will facilitate the understanding in the logic of expansion of the units.

As ruleset examples, it can turn left or right after hitting a boundary, to branch when a unit is placed or after 3 or 4 units together one common unit or terrace must be placed. This path of growth will also give the logic for the circulation of the building. [Fig. 42] illustrates the logic of the grid mechanism.

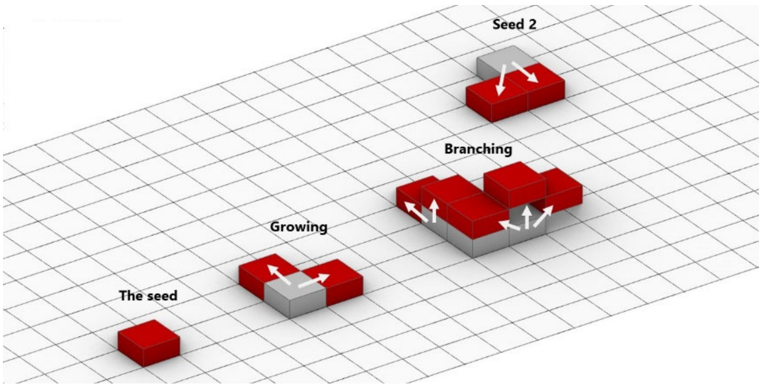


Figure 42: Grid mechanism and the logic of growth of the building components. Own work.

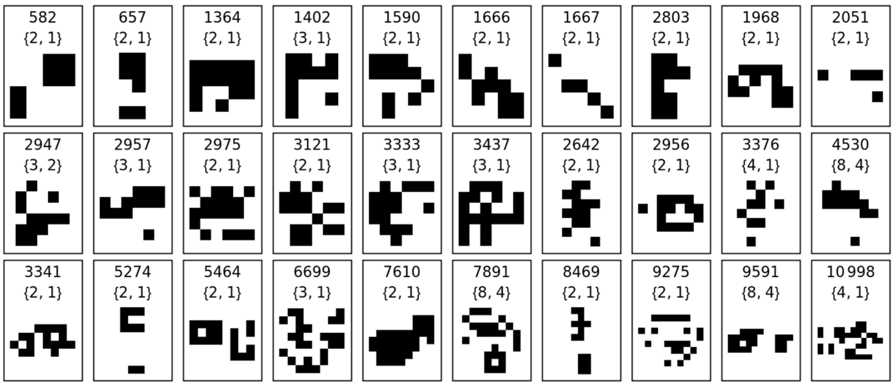
With current computational tools, this logical process can be automated to predict the overall building iteration in advance or to simulate its changes based on user input when they are about to purchase their plot. Moreover, this process can serve as a decision-making tool for users and a strategy to sell housing units. During this decision-making process, the user can explore various options as simulate their potential neighbours and how they would be affected depending on the access to natural light or distance to the vertical core circulation, among others. The final product of this process should be friendly enough for its easy understanding, one approach would be the gaming interfaces.

Several existing computational processes can be used as an initial step within these parameters. These include the Cellular Automaton, the L-systems (Lindenmayer Systems), Genetic Algorithm and Fractals (Mandelbrot Set). However, the application of these processes would require the set of rules previously mentioned. In order to extend how this process work, in the following lines the two first ones mentioned will be explained.

A cellular automaton is composed of a grid of cells, each in one of a finite number of states, such as "on" or "off", or "alive" or "dead", as demonstrated in Conway's Game of Life. The grid can exist in any finite number of dimensions, with two-dimensional space being the most common. The process begins by altering a cell's state according to a set of rules. These usually depend on the states of neighbouring cells, considering the state of a cell and its immediate neighbours to the north, south, east, west, and diagonals. Finally, the whole grid is updated all at once in discrete time steps, forming a new generation where the rules have been applied to all cells [Fig. 43].

Alternatively, L-systems, proposed by Aristid Lindenmayer, are a mathematical formalism used to describe plant cell behaviour and model plant growth processes. An L-system begins with an initial string of characters, typically representing a plant's seed or initial trunk. It employs a set of production rules to substitute characters in the string with groups of characters. These rules are iteratively and simultaneously applied to all characters, creating new strings over several generations [Fig. 44].

Cellular automata and L-systems offer powerful frameworks for simulating systems where global behaviour arises from applying local rules repeatedly. Due to their visual and dynamic characteristics, they are ideally suited for educational and research purposes in complex systems, computer graphics, and biological modelling.



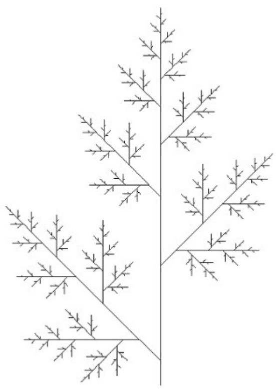


Figure 43, 44 accordingly: (Left) Gliders in cellular automata. (Right) Leaf L-system by Paul Bourke.

3.1.3 Building iterations

Two growth strategies will be explored: by stacking and staggering the different building units. The first option is the most logic, however by staggering them might result into a more interesting in terms of formal outcome. The result will vary based on the size of the plot and the stories required or desired. For example, a plot can have both side neighbours or be situated in a corner.

The two first iterations shown in [Fig. 45] were result of stacking the modules and the third by having them staggered to make a dynamic composition. Furthermore, due to the construction process of additive manufacturing and to the existing examples of housing with this technology, all the proposal options will reach a maximum of four levels.

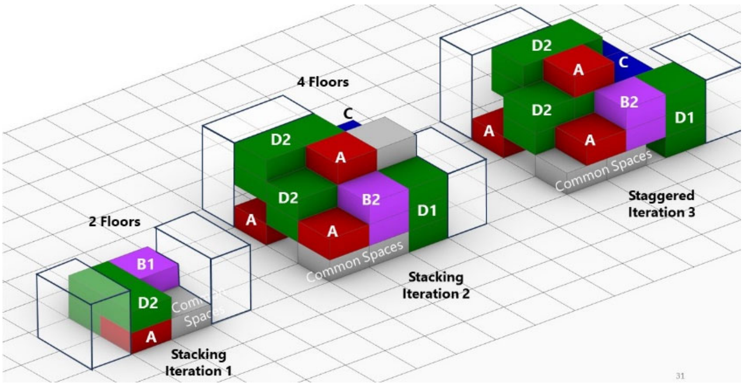


Figure 45: Building iterations results. Own work.

The next explorations shown in Fig. 46 can also work for bigger plots and form different community's live styles. The model will grow by repeating a certain module or creating new iterations. Wall Iteration 2 demonstrates how modularity allows for design flexibility by shifting a whole or half module, we can strategically position main entrances.

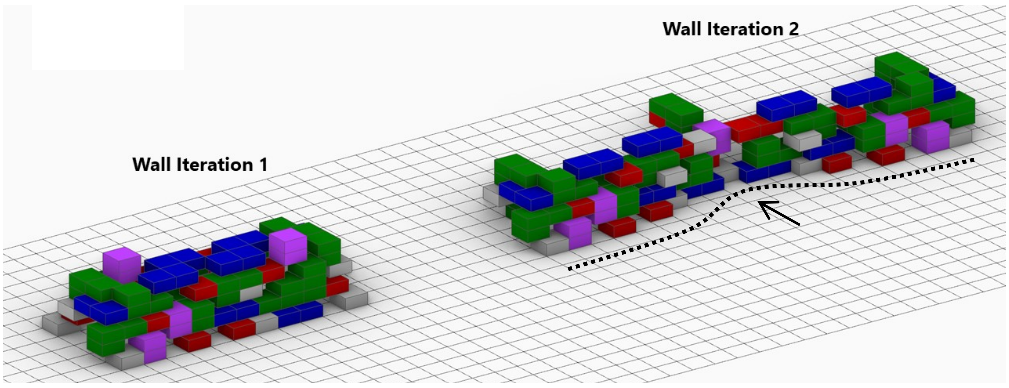


Figure 46: Large scale building iterations results. Own work.

As the project aims to tackle different locations and circumstances, an iteration considering a non-planar plot was also explored. Finding a perfect planar slope is rare, if the system can work without intervening the original plot would mean cost and time savings [Fig. 47].

Even when other considerations are not included as structural details, type of soil or climate, this study tries to be replicable enough to be an option of solution for housing problems. Further studies will be needed including the location's specific circumstances.

After the study of different building iterations, the second stacking iteration, from Fig. 44, was chosen to develop. This choice was made considering its moderate size and complexity, which makes it an appropriate case study to delve into within the available timeframe.

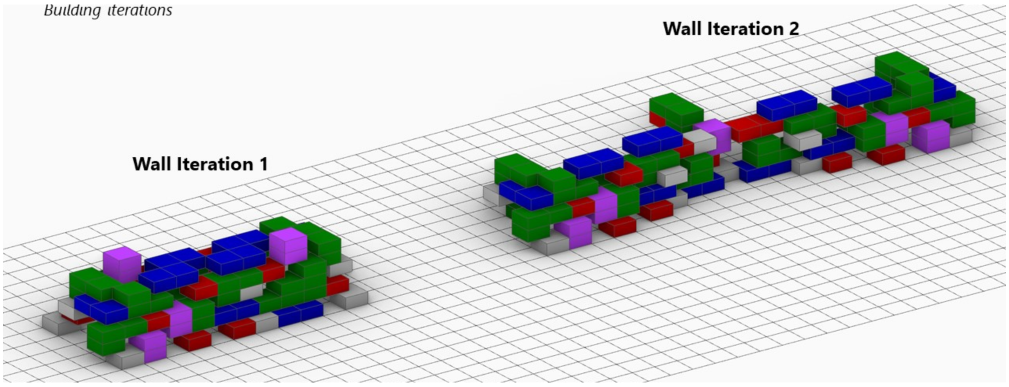


Figure 47: Slope iteration result. Own work.

It is relevant to mention that the staggered iteration was discarded due to its structural complexity. Structural continuity and the kit-of-parts concept were in risk, this will be explained in the further sections.

3.2 The unit – house level

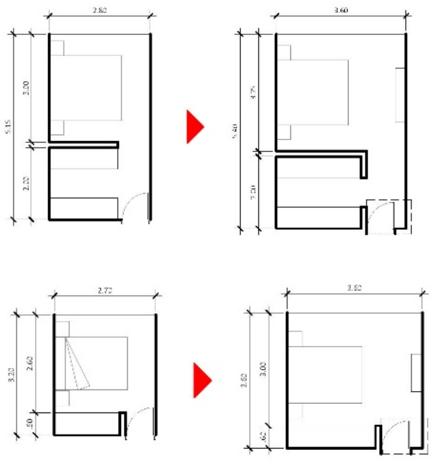
In the continuation of the design process, focus now on the house level. This involves identifying and analysing the different areas or housing components of the user's inhabit space. Following this, the conformation of the module and the iterations in its distribution based on the number of modules acquired are assessed. Lastly, the user customization is explored, with examples of different lifestyles and their subsequent impact on the housing design.

3.2.1 Housing components

The first step in forming a living unit is to identify the different housing components. A living unit typically includes bedrooms, bathrooms, social areas, a kitchen, laundry space, circulation areas, and terraces or balconies.

Mixing these housing components to set a module can be difficult due to their variety of sizes and shapes. One of the design concepts is the modularity of these components and how they can be added, exchanged, or removed according of the user preference. To achieve this, a study of each housing components was done [Fig. 48], resulting in a standardized library of components with similar measures. Following the anthropometric study, was concluded that the sizes should maintain modules of 90 centimetres.

At the end of this process, 27 different housing components were identified and codified properly [Fig. 49]. This is the first library where the user can start building their own apartment and way of living.



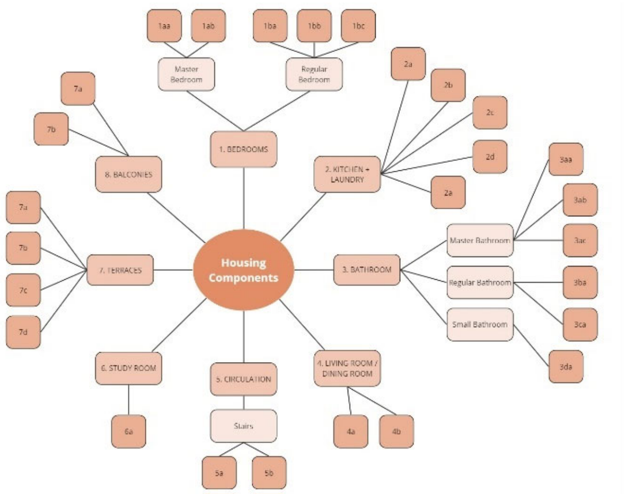


Figure 48, 49 accordingly: (Left) Standardization of bedrooms to modular sizes. (Right) Housing components iterations and codification. Own work.

3.2.2 The module

The conclusion of the previous study set that it was best to have an inner grid of 90cm. And having the module as a 7.20 by 7.20m space. Then, all the housing components can take place in this grid, forming the house unit as shows [Fig. 50].

Now, the modules previously seen in [Fig. 40] can have a measurements and square meters. The module's footage is 51.8 m2, two modules will lead to 103.6 m2 and for the three-module housing will reach 155.4 m2. The next step will be the user customization.

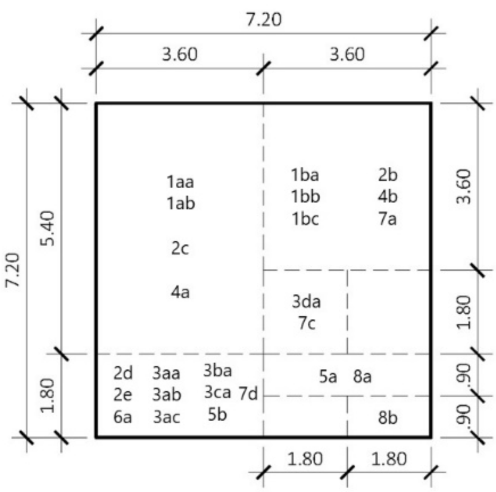


Figure 50: 7.2m x 7.2m module with the codes of housing components in it. Own work.

3.2.3 User customization

One of the first concepts this thesis aimed to include is the social approach. By making the architecture of the project influenced by their users is one way to achieve this.

Users can influence the design in various ways: they can determine the location within the building, the functional organization, and the amount of square footage used. They may also choose to leave some areas with no intervention to create patios. Additionally, they can influence the number and type of openings or windows on the facade.

Furthermore, the diversity among users is vast because everyone uses their space differently. To illustrate this diversity, will be analysed three different types of users and how their lifestyles affect their space usage. The study will first consider a single adult man, then a young couple without children, and finally a traditional four-member family composed of a husband, wife, and two children.

To exemplify the user customization process, in the next lines a real case of a single man will be presented. This study began with a residential reference system based on the desired room sizes and spatial relationships, which can be seen in the wish-list diagram, a result of the user's description of ideal living space [Fig. 51].

"Mauricio a 31-year-old lawyer, wanted a bedroom and social part, both connected to a balcony. A medium size living room and integrated kitchen where he can have guest and dinner with friends. Double sink and a bathtub were a must for him. For the common spaces he would like to have a gym. First, he wanted to invest owning 1 module, but he wants the possibility to a short future to add one more module."

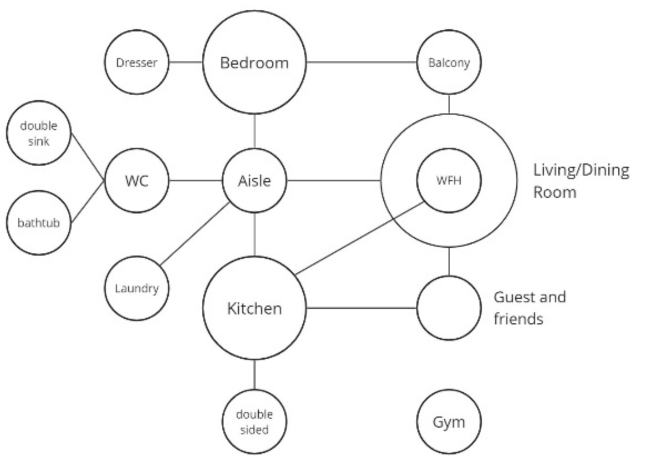


Figure 51: User #1 wish-list diagram. Own work.

With this data, a one-module house unit is formed by taking the pre-designed components, as can be seen in [Fig. 52].

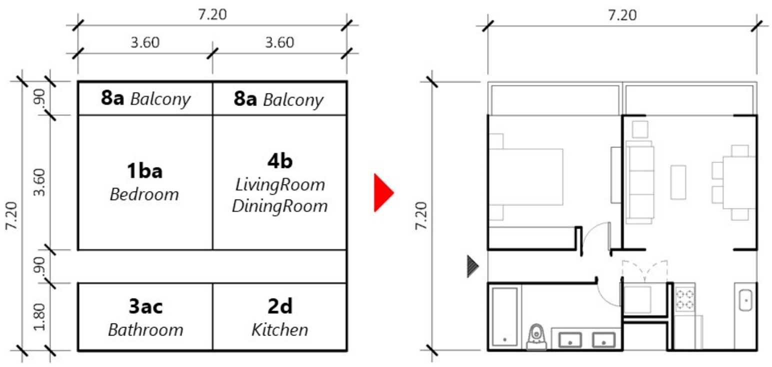


Figure 52: Single user's module with the codes of housing components in it and final distribution. Own work.

The same process was also applied to the other two users: the young couple and the four-member family. Their outcomes were documented separately to avoid making this section too lengthy and repetitive. These details can be found in the appendix section.

It is important to note that once the housing components have been selected, the design process and the combination of these components can be automated using computational tools. Different iterations can be generated by these tools using the same components.

3.3 The construction – structure level

In the next sub section, from a constructive perspective, an overview of how materialize the design resulted from the previous section is presented. For this, the study for the initial form with the structural logic are explained. Following this, the aggregation result is achieved, including the set of kit-of-parts. Ultimately, the construction process and the foundations are detailed.

3.3.1 Vault study

The vault was initially chosen for the architectural aspect and the reasons were already mentioned. Throughout the process, an exploration of various vault shapes was done [Fig. 53]. Despite having a square module and floorplan, the vault can still result in different shapes. Also, thinking in advance how these vaults could be broken in similar parts was addressed.

This study and the modelling were done in the Maya software, where working with NURBS facilitates the design of a geometry which seeks a fluent and complexity which justifies the use of the 3D printing technology.

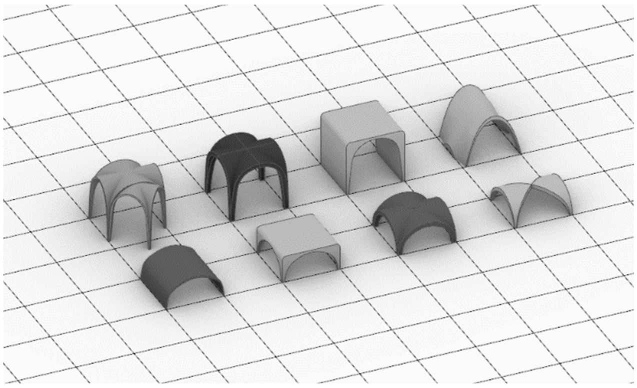


Figure 53: Vault options explored. Own work.

3.3.2 Structural approach

Addressing the structural aspect, once again the vault was an efficient option for larger spans and for compression structure.

In previous sections, two different building composition options were explored. Initially, the staggered option seemed preferable due to its dynamic architecture and increased options for terraces and exterior spaces. However, both options were analysed for their structural logic.

In the stacked option [Fig. 54], forces are transmitted vertically; the continuity of the columns is clear, and there's no doubt it could function well. On the other hand, the staggered option [Fig. 55] shows a transmission that changes along with the arches without continuity.

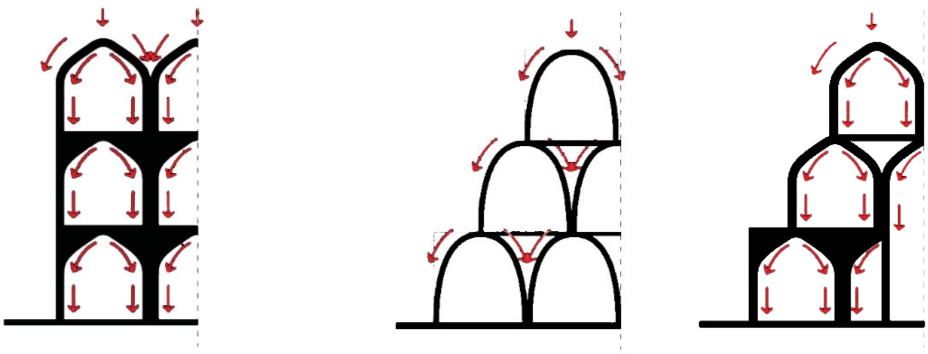


Figure 54, 55 accordingly: (Left) Compressive force diagram of stacking vaults. (Right) Compressive force diagram of staggered vaults. Own work.

After discussions with specialists from the structural department, it was concluded that the staggered option could work. This would involve varying the sizes of vertical structural elements on each level and reinforcing the slab, which was the one in charge to transmit forces to the vertical elements on the next level.

Despite potential architectural drawbacks, like a loss of aesthetic appearance and a deviation from the kit-of-parts concept, -the final library would not only be divided by housing components, but for levels as well- the decision to proceed with the staggered option was the ideal.

3.3.3 Aggregation result

Initially, what began as a mere volumetry study has the potential to evolve significantly. With the concepts, structural input, and throughout different studies, it could ultimately lead to the final massing of the structure. This transformation emphasizes the importance of initial research and the potential depth of impact it can have on the outcome.

The different housing units are shown in [Fig. 56], illustrating how these are conformed and the architectural design. For then, to finalize in the final aggregation.

The image in [Fig. 57] illustrate the concept of different levels, each with varying housing units and communal spaces for user interaction. This design fosters social cohesion and spatial relationships among users. Also shows the different types of facades, ones with four windows, two window, or the type of enclosure within the windows, among others.

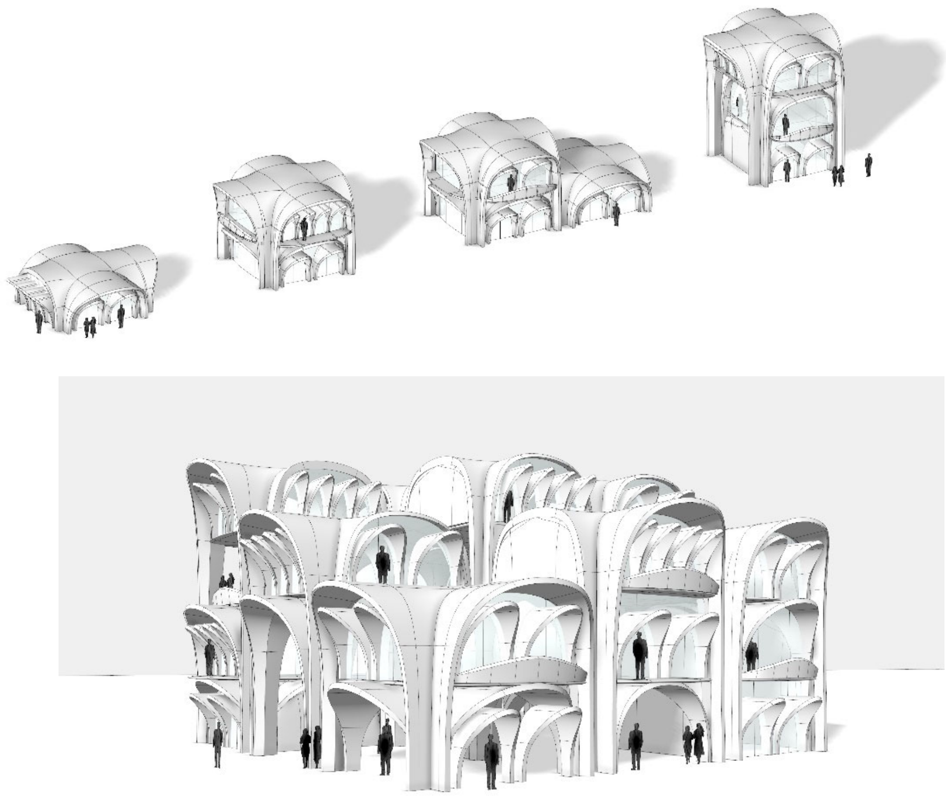


Figure 56, 57 accordingly: Final aggregation renders. Own work.

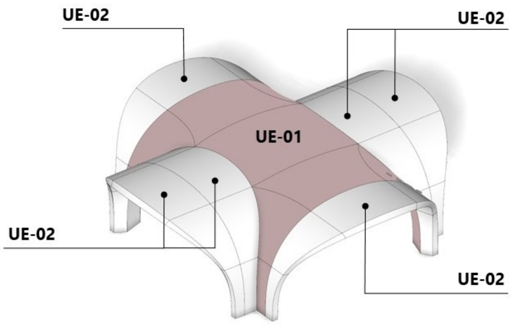
However, it is crucial to note that this is just one example out of hundreds. Depending on the user's preference or a change in the ownership of a housing unit, the outcome may vary. Therefore, it should not be perceived as the final representation of the project, but rather a potential visualization of what it could look like [Fig. 58].

Figure 58: Final aggregation render. Own work.

3.3.4 Kit-of-parts

The inclusion of the kit-of-parts approach is crucial in this thesis. In this section the logic of how to break the housing unit will be shown and the parts which it is conformed. An overview of a one-module housing unit will be analysed below.

Starting with the outer layer, the principal covering serves as the integrator of all other elements within. This is marked in red in [Fig. 59, 60] and labelled as UE-01; labelled as UE-02 there are the complementary elements which are repetitive and similar. Then, UE-01 and UE-02 are further divided into smaller pieces, as shown in [Fig. 61]. Although the shapes might look almost identical, some of them are mirror images of each other and therefore cannot share the same code as they differ in both shape and printing process.



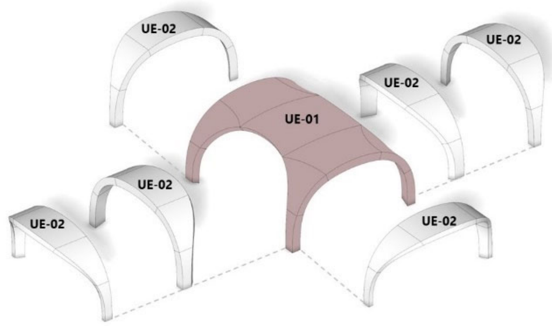


Figure 59, 60 accordingly: Kit of Parts of the housing module. Own work.

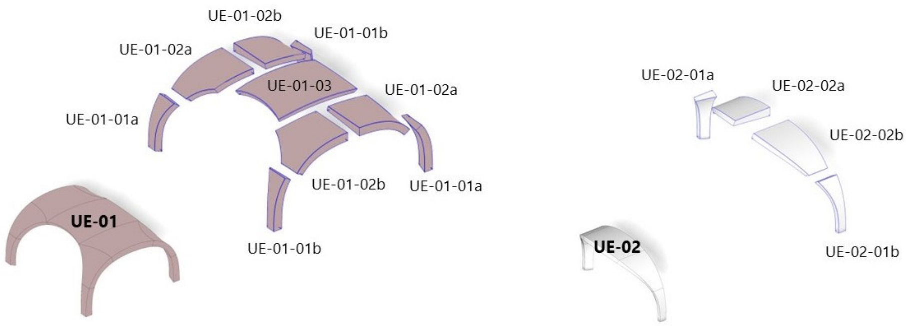


Figure 61: Kit of Parts of the housing module. Own work.

These last smaller parts will be the ones to print, and it is important to set the starting baseline where they will be printed. Having pieces with different directions of the printing lines would lead to a special study of the joint. The printing base for the pieces can be seen in [Fig. 62].

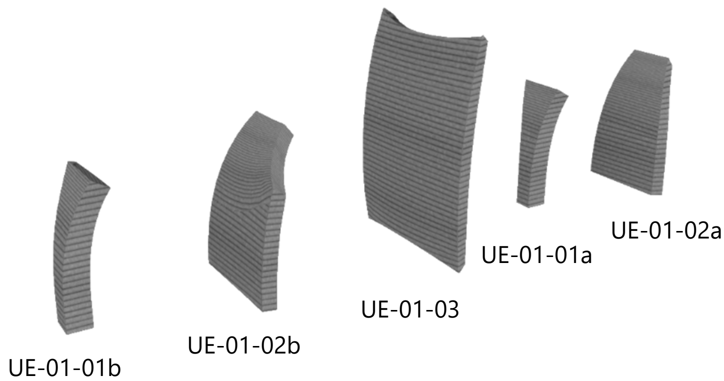


Figure 62: Kit of Parts units with their printing direction. Own work.

When the scale is adjusted, housing units can be fragmented into smaller components. The interior of each unit is composed of all the housing elements discussed in previous sections. The exterior, with different number of windows, enclosure for facades, the option of glass or a close wall. The user can just leave the core of the housing unit and not include the smaller parts, if roof in balconies is not desired, or to the contrary, to add another one for extra shading. Different types of balconies and railings are also customizable.

In [Fig. 63], a one-floor housing unit is presented with all its parts disassembled. Next to it, a two-floor housing unit is illustrated, which requires the inclusion of a floor and stairs, as well as the addition of a second layer of roofing to consolidate the first floor. Despite consisting of two floors, the unit gives the impression of being a single entity from the exterior. This visual demonstration illustrates the potential for a single-floor unit to be expanded into a two-floor unit.

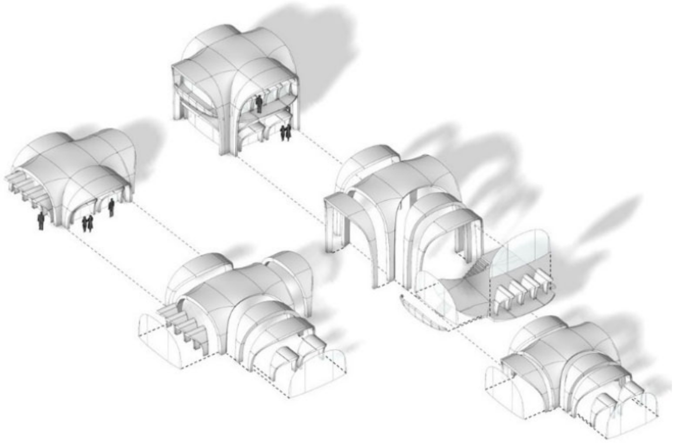


Figure 63: Kit of Parts components of a one and two-floor housing units. Own work.

Moreover, [Fig. 64] illustrates the same logic for a three-housing unit on two floors and four floors, respectively. These images also indicate that as more additions are made, the unit becomes more complex, but it always uses the same elements.

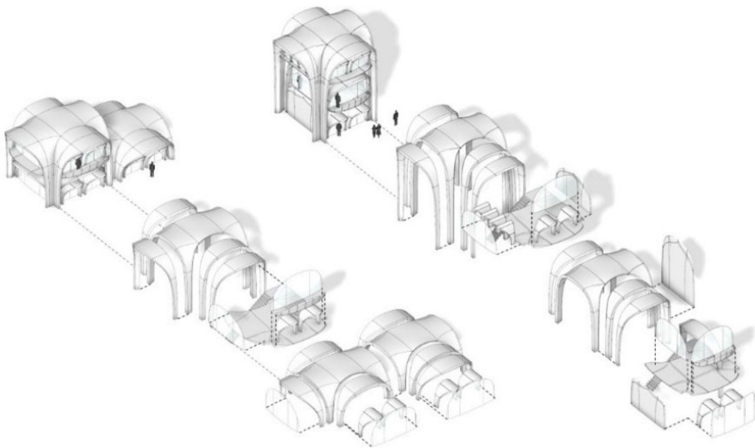


Figure 64: Kit of Parts components of a three-housing units in three and four floors. Own work.

Furthermore, in the housing project there are not only the housing units, but the vertical circulations -conformed by stairs and lifters-, common spaces as children playground or party areas -which can exist without a roof- urban furniture, etc. A basic study is shown in [Fig. 65] below. Again, these configurations are done with the same pieces used for the housing units.

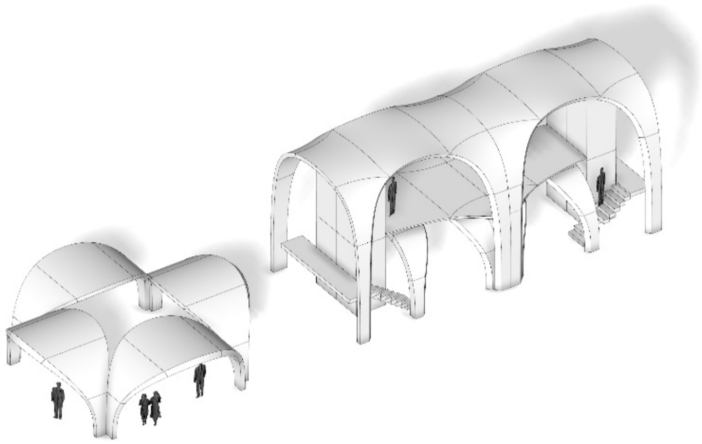


Figure 65: Kit of Parts of the housing unit's complementary elements. Own work.

Another important concept taken in consideration is the multi-material approach, this means using various materials in the construction process to leverage the unique properties of each. This method enhances structural integrity and design flexibility, enabling the creation of more dynamic and responsive living environments. While concrete provides excellent durability and foundational strength, an over-reliance on it can result in monotonous living spaces that might negatively impact in the bell being of the user. By integrating materials such as wood for warmth and natural aesthetics, glass for openness and natural light, and recycled plastics for sustainable, customizable interior finishes, we can create homes that are not only robust but also comfortable and stimulating. This blend of materials allows for a more nuanced and human-centric approach to architecture, fostering environments that are both functional and emotionally enriching.

In this line, some parts of the housing unit are proposed to be printed in wood [Fig. 66]. In first term, the slabs, to make them lighter and to be able to connect it to the possible wooden beams to structure it to the concrete walls [Fig. 67]. Secondly, a roof for the public spaces can be added, if rain or direct sun are causing discomfort. Lastly, the interior parts of the elements UE-02 can be added, with organic shapes, more related to the material [Fig. 68].

All these variations lead to a formal difference from what is concrete and wood and a connection between the material, fabrication method and architectural piece.

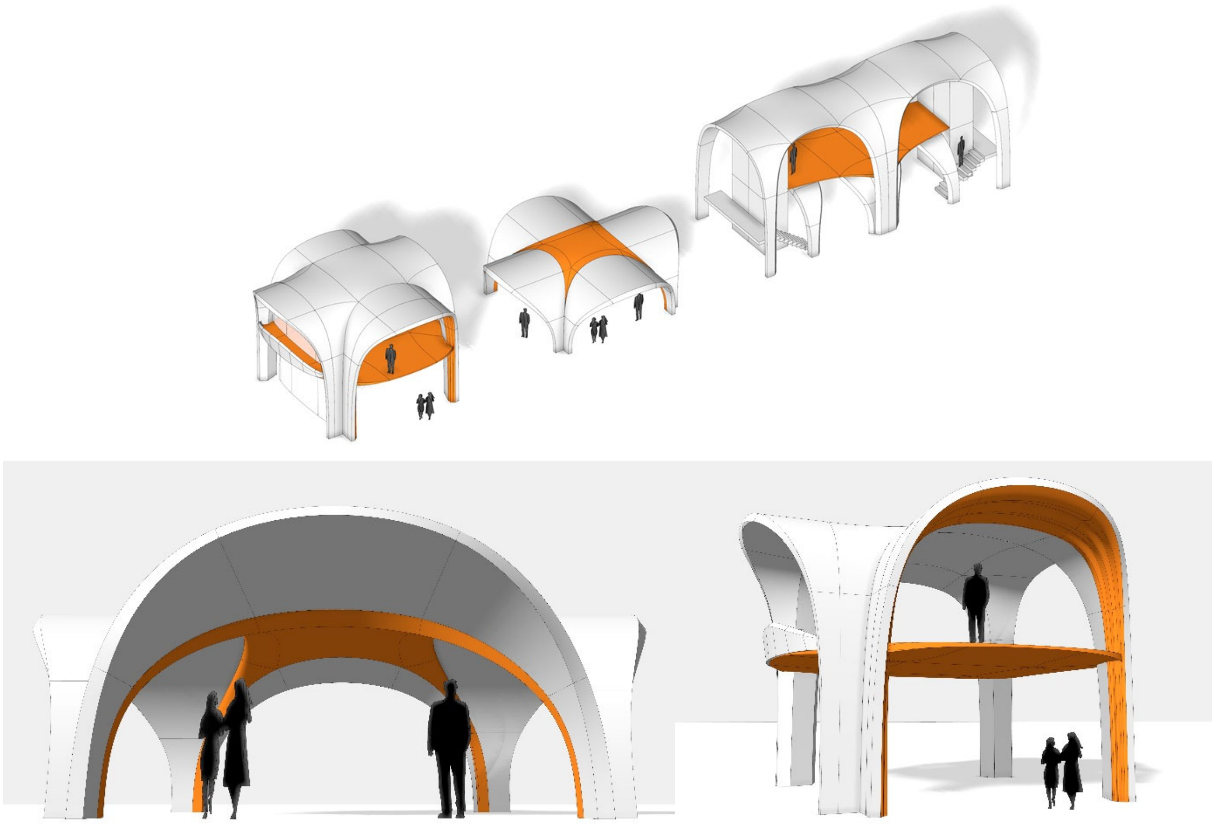


Figure 65, 66, 67 accordingly: (Upper) 3D printed elements in wood. (Bottom left) Public unit with wooden roof. (Bottom right) Interior face of a housing unit with wooden piece. Own work.

Finally, every housing unit or common spaces units will be composed of their own Kit-of-parts. To exemplify this [Fig. 69] show a unit and all the pieces needed to be printed to conform it and a chart [Fig. 70].

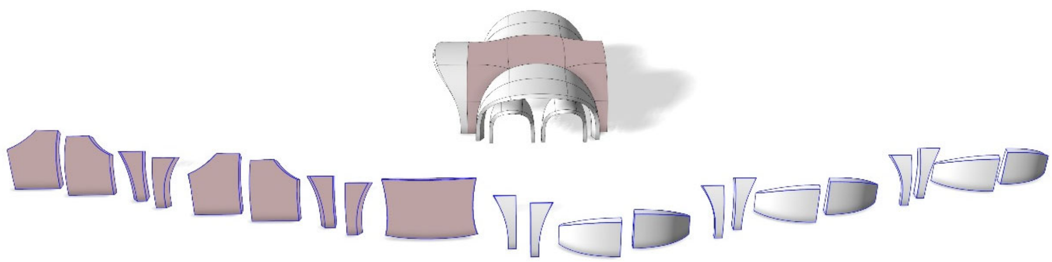


Figure 69: Housing unit and its Kit-of-Parts. Own work.

Code	# components	Sub code		# pieces/component	# total pieces
UE-01	1	UE-01-01	UE-01-01a	2	**9**
			UE-01-01b	2	
		UE-01-02	UE-01-02a	2	
			UE-01-02b	2	
		UE-01-03	-	1	
UE-02	3	UE-02-01	UE-02-01a	1	**12**
			UE-02-01b	1	
		UE-02-02	UE-02-02a	1	
			UE-02-02b	1	

Figure 70: Chart to record the pieces. Own work.

3.3.5 Foundations

For the foundation logic, a buried base will be placed in every corner of the grid. Composed by a concrete base of 1.7 by 1.7m, with a steel plate and steel bars that will interlock within the structure of the 3D printed legs, as shows [Fig. 71].

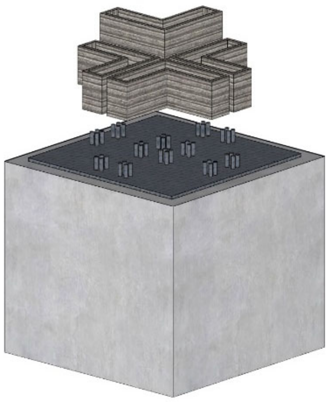


Figure 71: Proposal's foundation scheme. Own work.

Existing references of foundations for 3d printed structures were taken in consideration for the proposal. In [Fig. 72], the Apis Cor 3D printed tiny house's foundation type is illustrated, this presents four metal bars which screw together with inner metal structure within the 3D printed element. Also, in [Fig. 73], the connection of the Striatus Bridge to the ground consists in a concrete base with metal plates which structure and receive the coming forces.

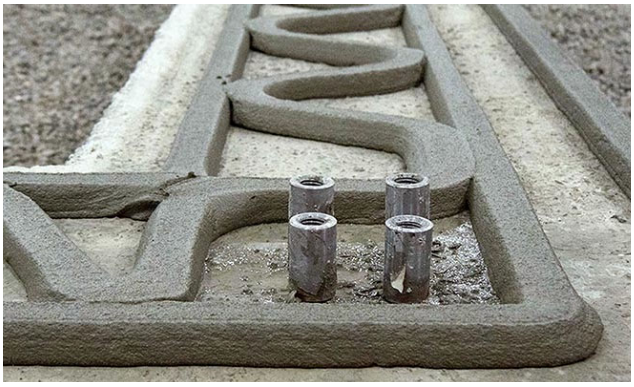


Figure 72, 73 accordingly: (Left) Apis Cor 3D printed house. Russia. (Right) Striatus Bridge's foundation.

3.3.6 Construction process

The concept of the construction process aims to be smart. This means to produce the pieces on-site, saving time if more pieces are needed or saving costs by setting up a small factory in the plot.

It will start with a container that will get to the plot to intervene. Secondly, the production area will be set with all the materials needed that came inside the container: 3D printer robot arm, cement, mixer, and tools. After, the 3D printer will remain in the base of the container and with a riel will move to print the series of Kit-of-Parts. At last, the printed elements will be placed and assembled by a spider crane [Fig. 74].

Human assistance will be also needed, but not more than 3 people, which will save costs by not hiring much human labour.

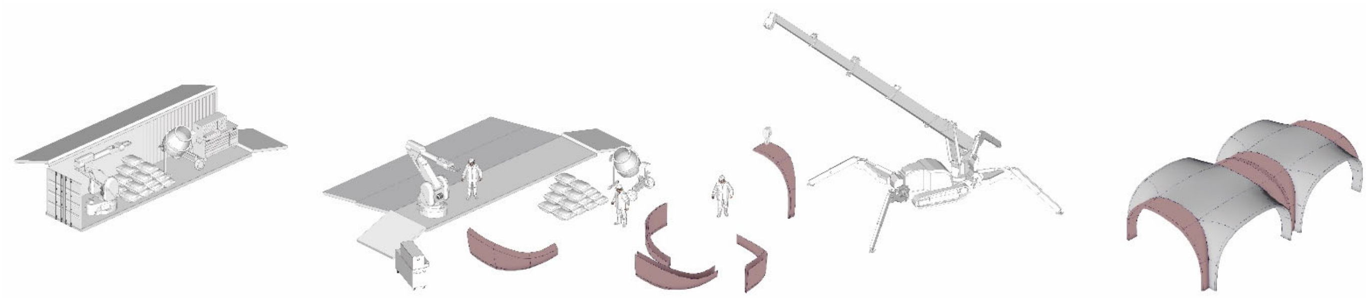


Figure 74: Construction process. Own work.

4. Experimentation

This phase initiates the practical aspect of the proposal, consisting of three main parts. First, identifying the potential problems within 3D printing through a reflection, considering all the knowledge and references acquired till now. The subsequent parts involve practical tests, including the clay-gun test and the consistency test. These tests will serve as the foundation to apply later to the design and proposal.

4.1 3D Printing problems to address

This section outlines the various challenges that need to be tackled in the context of 3D printing for construction, focused on large-scale prototypes as a housing project. Each branch of the diagram in [Fig. 75] represents a specific area of concern, highlighting the complexities and interdisciplinary nature of addressing these issues.

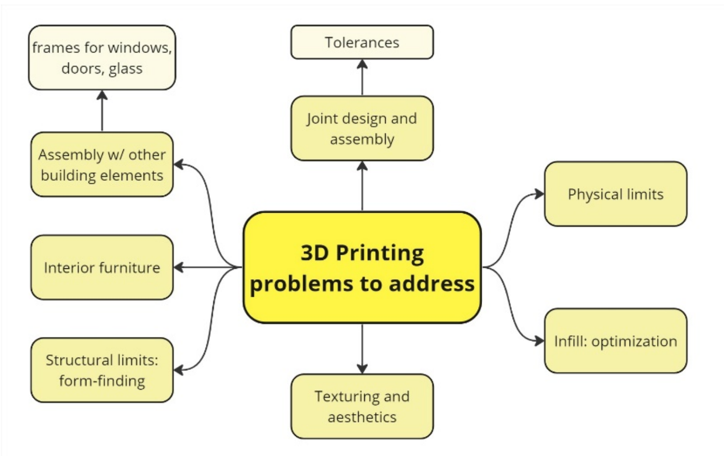


Figure 75: Mental chart of 3D Printing problems the project could face. Own work.

4.1.1 Joint Design and Assembly:

Proper joint design is essential to create robust and reliable connections between different printed parts. This involves considering the types of joints (e.g., dovetail, mortise, and tenon) and the material properties to ensure durability and ease of assembly.

Tolerances must be taken in consideration; this aspect focuses on the precision required in the dimensions of printed parts. Tolerances are critical in ensuring that different components fit together correctly. Variations can lead to misalignment, weakening the structure and making assembly difficult.

4.1.2 *Physical limits*

The physical limits of 3D printing refer to the maximum size, in high and wide, length of cantilevers, and resolution that printers can achieve. These limits affect the overall design and feasibility of printing large-scale structures. Overcoming these constraints requires a series of tests in different terms, it also depends on the type of material and its properties.

4.1.3 *Infill*

Infill patterns and densities are crucial in determining the strength, weight, and quantity of material usage of printed objects. Optimizing infill can lead to significant improvements in the structural performance and cost-effectiveness, in time and costs, of 3D printed parts. Different patterns, such as honeycomb or grid, offer varying benefits that need to be balanced based on the application. Designing the infill is also possible, which grants the G-code designer more control over the printing process.

4.1.4 *Texturing and aesthetics*

The surface finish and visual appeal of 3D printed objects are important, especially in consumer-facing products and architectural elements, considering it will be the layer exposed to the user. Achieving desirable textures and aesthetics often involves post-processing steps or advanced printing techniques that can add complexity and cost.

4.1.5 *Structural limits and form-finding*

Form-finding involves using computational methods to determine the most efficient shapes and structures for a given material and load-bearing requirement. This process is crucial in 3D printing to ensure that printed structures are not only aesthetically pleasing but also structurally sound and material efficient. It has a close relation with the infill study.

4.1.6 *Interior walls and furniture*

The integration of interior furniture within 3D printed structures presents unique challenges, including the need for customized designs that fit within the larger architectural context. Different aesthetics can be achieved with the interior walls, making them no entirely filled but with textures and holes which can cooperate in the ventilation and thermal comfort.

4.1.7 *Assembly with other building elements*

3D printed structures often need to be integrated with other building elements such as windows, doors, and glass. This integration requires precise measurements and considerations for how these elements will fit and function together. Ensuring compatibility and ease of assembly is crucial for practical implementation.

Frames for windows, doors and glass panels must be designed to fit seamlessly into the 3D printed structure, considering both aesthetic and functional aspects. Proper frames ensure that windows and doors operate smoothly and maintain the overall structural integrity. That is why the 3D printed piece must take in consideration how these elements fit and be integrally designed.

Each of these areas requires detailed study and innovative solutions to harness the full potential of 3D printing technology in various applications. Addressing these problems can lead to more efficient, cost-effective, and aesthetically pleasing printed structures and products. Not all the mentioned problems will be addressed due to the limited time frame, but it is important to have identified them.

4.2 Clay-gun testing

In this subsection, the material testing phase utilized a clay gun to have the first experience close to a printing and explore the consistency of clay for the printing procedure. The experiment involved extruding the clay through the gun to create a variety of shapes and structures.

The tools used for this test are shown in [Fig. 76], first there is the clay gun, which is composed by the proper electrical gun and the cartridge -Wolfcraft brand- and a block of clay whom supplier was WASP company.

Furthermore, in the actual testing, the first issues were being noticeable: for many tries the first layer was not sticking to the cardboard base [Fig. 77]. Was decided to add a thin first layer of watered clay to assure the glueing between the extrusion and the base. And secondly, the clay seemed a little hard, as was noticed during the use of the gun.

This test concluded that the clay as it was, needed to be mixed with water and that a rugous base was also needed but still adding the thin layer of watered clay. The outcome was a handmade form that strikingly resembled a bird nest [Fig. 78].

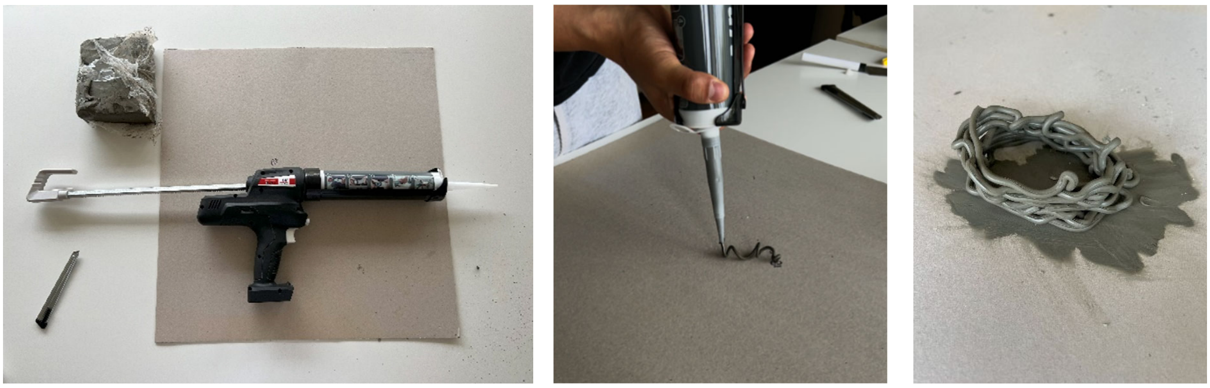


Figure 76, 77, 78 accordingly: (Left) Materials for the test. (Middle) Procedure of the testing. (Right) Final outcome of the testing.

4.3 Clay consistency test

The consistency clay test involves evaluating the workability and flow characteristics of clay for 3D printing purposes. To achieve this, a portion of clay is placed inside a syringe, ensuring it is free from air bubbles. The syringe, ideally 5ml size, is then pressed to extrude the clay through its nozzle; the extruded clay should form a continuous strand and be able to maintain its shape without collapsing.

The key metric is the angle at which the clay strand maintains stability; it should reach a predetermined angle, around 15 to 30 degrees, without breaking or sagging as shown in [Fig. 79]. This angle indicates that the clay has the right consistency for printing, balancing between flowability and structural integrity, this will allow a smooth print. A straight and horizontal extrusion would indicate that the material still too hard; on the other side, a collapsed extrusion facing almost the ground means it is too soft [29].

Figure 79: Clay consistency test. Own work.

4.4 Testing criteria

In this section various testing criteria essential for evaluating the performance and capabilities of the clay used for 3D printing, for then applied to construction and design. These are shown in [Fig. 80] below.

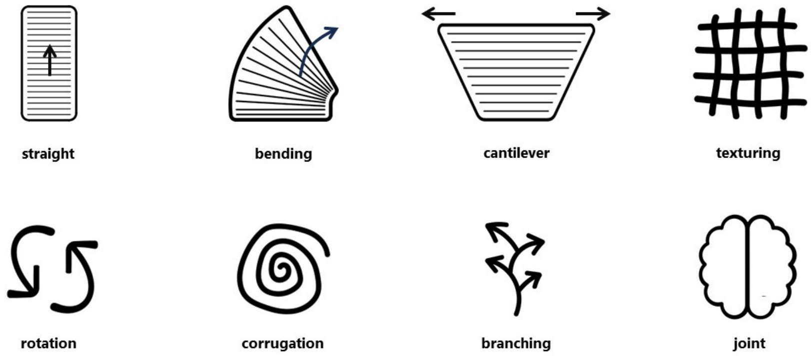


Figure 80: Testing criteria diagram. Own work.

- **Straight**

This test assesses the printer's ability to create vertical and basic shapes without deviation. It is fundamental for ensuring the accuracy and precision of basic geometric forms. Here the models Test 01, and Test 02 were produced, both showcasing the seam line with a layer-by-layer printing. Printing data and details can be seen in Appendix section [Fig. 81, Fig. 82].

Figure 81, 82 accordingly: (Left) Test 01 and Test 02. (Right) Test 01 showing the seam line. Own work.

- **Bending**

This criterion examines the printer’s capacity to produce curved elements. It evaluates how well the material can be manipulated into non-linear shapes, which is crucial for creating organic and fluid designs. Unfortunately, this was not achieved due to time constraints, but it was doable in the WASP printer.

- **Cantilever**

This test focuses on the printer's ability to produce structures that extend horizontally without support. It evaluates the strength and stability of overhanging parts, which are critical for architectural features. Here the model Test 03 was produced, this time eliminating the seam with a continuous layer printing. Printing data and details can be seen in Appendix section [Fig. 83, Fig. 84].

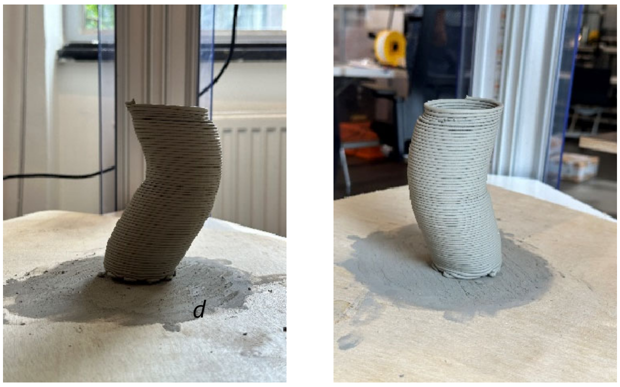


Figure 83, 84 accordingly: Test 03 (Left) Model just printed. (Right) Model dry. Own work.

- **Texturing**

This criterion looks at the surface finish capabilities of the printer. It assesses the ability to create various textures and patterns on the printed object, which is important for both aesthetic appeal and functional grip surfaces.

- **Rotation**

This test involves creating shapes that include rotational elements. It evaluates the precision in printing objects with rotational symmetry or complex curves, having the same shape at the beginning but during the extrusion to change in shape and size. The model Test 04 and Test 05 were produced, with a layer-by-layer printing. Printing data and details can be seen in Appendix section.

- **Corrugation**

This criterion examines the ability to produce repetitive ridges and grooves. It tests the printer's precision in creating corrugated structures that add strength and flexibility, useful in lightweight structural elements. The models Test 04, Test 05 and Test 06 were produced, with a layer-by-layer printing and continuous printing, accordingly. Printing data and details can be seen in Appendix section.

Figure 85, 86, 87, 88 accordingly: Test 04 (Left and Middle left) Model dry. (Middle right) Test 05. (Left) Test 06. Own work.

- **Branching**

This test evaluates the printer's capacity to create structures that branch out from a central point. It is essential for assessing the printer's ability to produce complex, tree-like structures with multiple directions of growth. The first test was a failure due to the central part between the branches, it could not structure. For that reason, the second test tried to replicate a branching in a "fake" way; by printing separately elements and then making them joint together again.

The models Test 07, and Test 08 were produced, with a continuous printing. Printing data and details can be seen in Appendix section [Fig. 89, Fig. 90, Fig. 91].

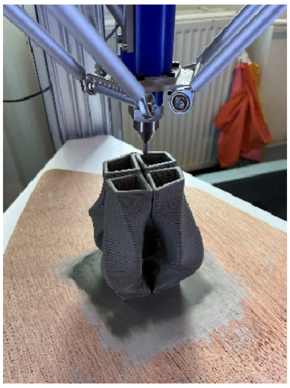
  

Figure 89, 90, 91 accordingly: (Left) Test 07. (Middle) Test 08. Fresh model. (Right) Test 08. During printing. Own work.

- **Joint**

This criterion tests the printer's precision in creating interlocking parts. It is crucial for assembling multiple printed components together securely, ensuring that joints are tight and reliable. The model Test 09 was produced, with a continuous printing set up, but as three figures were printed at the same time it did not work, finally the piece was printed layer-by-layer. Printing data and details can be seen in Appendix section [Fig. 92, Fig. 93].

Figure 92, 93 accordingly: Clay consistency test. Own work.

Each of these testing criteria ensures that the 3D printing process can meet the diverse requirements of modern design and construction, from basic shapes to complex, load-bearing structures.

Also, during the experimentation stage a lot was learned, the failures taught more than successful models. The images below show some of the considerations and accidents this process had to go through. [Fig. 94] showcase the right moment after the connector hoe between the tank and extruder detached, causing an explosion of the material. Moreover, the first printing test were not successful due to the incorrect consistency of the material, causing a non-continuous extrusion [Fig. 95].

On the other hand, a strategy discovered during the test was to include a layer of fresh mixed clay to secure the adhesion of the extruding material to the base, which in this case was wooden boards [Fig. 96]. Ultimately, [Fig. 97] represent a collided model, which could not withstand the cantilever. Nevertheless, it was an aesthetic failure, almost an art piece.

Figure 94, 95, 96, 97 accordingly: (Left) Material explosion. (Middle left) Printing failure. (Middle right) Adhesion strategy. (Right) Collided test. Own work.

5. Prototyping

This stage represents the culmination of both the research and practical phases, uniting theoretical insights and practical findings to construct the final models. These prototypes serve as proof of concept, validating the feasibility of the proposed 3D printing techniques and designs. This stage aims to confirm the research outcomes and establish a solid basis for future real-world applications in 3D printed construction.

It includes two primary models. The first is a 1/20 scale model of a Kit-of-Parts, made up of all its components. This model demonstrates the construction process. The second is a life-size (1/1 scale) model of a part of the housing unit, applying the testing criteria from the previous section.

5.1 Model 1/20

With the objective of demonstrate the construction method and to have a physical model of the Kit-of-Parts library, the elements coded as UE-01 and UE-02 [Fig. 60] and all its elements were printed [Fig. 60] showcases the set of pieces and [Fig. 98] the built model [Fig. 99].

The material chosen was PLA, as it was not necessary to use clay for the purpose of this model. The printer used was the Anycubic Chiron.

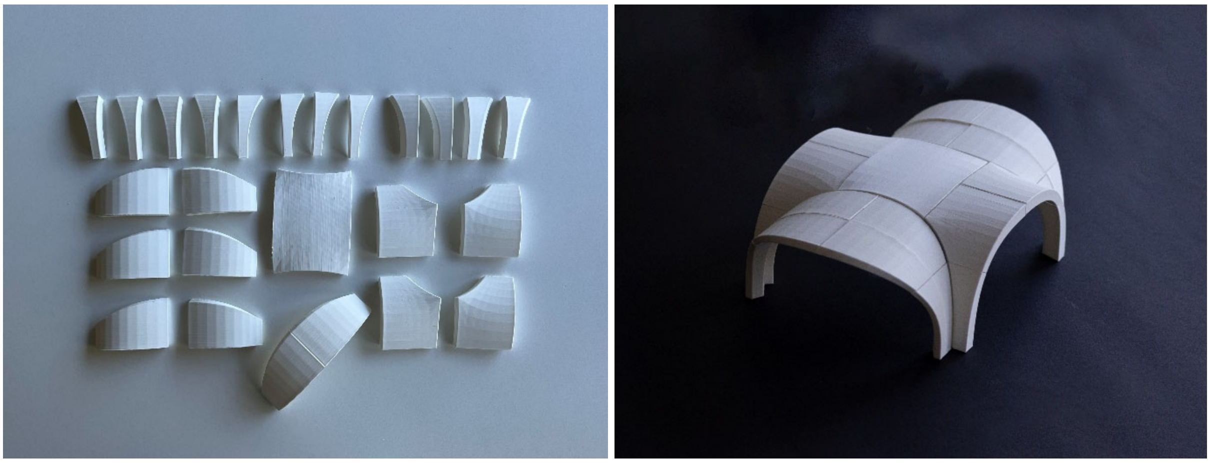


Figure 98, 99 accordingly: (Left) Set of Kit-of-Parts. (Right) Built model. Own work.

5.2 Model 1/1

The objective of this study, from the beginning, was to reach a human scale, demonstrating that all designs and proposals could be constructed and function in real life. This makes it a viable project from both an architectural and production point of view.

To achieve this, a portion of the aggregation result was utilized. The intersection of a column and an arch provides an opportunity to highlight a functional component while incorporating the studied criteria of the 3D printing method to improve the aesthetics. In [Fig. 100] can be seen the design process from the initial shape (right) until the final (left) which incorporates branching, corrugation and rotation in the design.

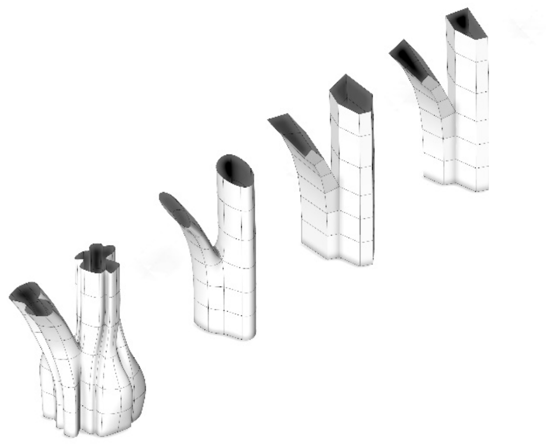


Figure 100: From right to left, the design process of the column. Own work.

Once the final model was complete, it was divided into two sections to simulate the joint between the printed pieces, enhancing its realism. The section was cut vertically, as if a column were cut, it should be from the sturdiest part, not the branches.

Furthermore, it is now possible to study and design the joint. Various scenarios were discussed, and the conclusion was reached that a new piece was needed to absorb potential inaccuracies. -This was confirmed during the experimentation stage-. These inaccuracies could occur on the surface of the piece due to printing and, if the contact surface is two perfectly produced pieces, then the joint will be secure and stable [Fig. 101].

This joint component is proposed to be made of metal plates and produced by laser cut, due to its irregular shape. It is designed to fit the perimeter of the 3D printed piece, taking the form of a ring. This ring incorporates four holes for screws to connect the two metal components, with each column part having one. The connection between the metal ring and the 3D printed ring is facilitated by a vertical section that serves as the contact area. The design of this component is similar to a pipe flange, as shown in [Fig. 102].

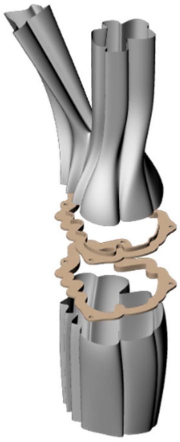


Figure 101, 102 accordingly: (Left) Column pieces with joint pieces. (Right) Joint metal pieces. Own work.

For the model this ring was produced by also 3D printing but with PLA and screwed as the same way it would be in reality. Finally, [Fig. 103] and [Fig. 104] presents the produced 1/1 scale model.

Figure 103, 104 accordingly: Photography of the final model. Own work.

6. Conclusions

This chapter synthesizes the results from the research and experimentation phases, addressing the primary research question and its related sub-questions but also what can be done if this research could continue. It highlights how the integration of 3D printing technology, user customization, and innovative design approaches can enhance the production of social housing units. The insights gained through the iterative process of design and prototyping provide a comprehensive understanding of the potential and limitations of 3D printing in this context.

6.1 Answering the research questions

Answering the main research question:

How can 3D printing, produce social housing units, and at the same time enhance construction efficiency, architectural adaptability, and encourage innovation in form and shape?

The results in terms of design and prototyping were as expected; however, the interior part of the housing units was not addressed due the limited time. Furthermore, by utilizing the kit-of-parts, user-customization, and multi-material approaches, the research demonstrated that 3D printing can significantly enhance construction efficiency and architectural adaptability. In this line, it was found fundamental to design specifically for the kit-of-parts approach to fully exploit its benefits, starting with a desired shape and then think how it can be divided to be efficient printed is crucial.

The process was highly iterative between the design and experimentation phases, allowing for continuous refinement and improvement of the test models. This iterative process ensured that the final prototypes were both practical and innovative, meeting the diverse needs of social housing and aesthetics.

And the sub-questions

What other techniques within 3D printing can be used to enhance the form or shape of an object? What constraints need to be considered in the fabrication of the prototypes?

Combining different 3D printing testing criteria was essential in exploring and pushing the boundaries of form and shape. The choice of material proved crucial; in this case, the mixing of clay presented significant challenges and led to many printing errors. This highlighted the importance of material properties in the printing process.

Additionally, the limitations of the 3D printer itself, specifically with the WASP printer, were a constraint. These constraints informed the design adjustments and highlighted areas for future technological improvements of the thesis.

Which characteristics in an architectural project makes it a social? How can 3D printing finishes be designed to prevent monotony and negative impact in the user's living space? How can the diversity of users influence the final shape of the project?

The final aggregation design, including terraces and common spaces, fosters social cohesion among users. The inclusion of a multi-material approach and diverse texturing criteria enhances the visual and tactile quality of 3D printed concrete walls, preventing monotony and creating a more engaging living environment. The final design reflects each user's preferences in terms of functionality, which is also translated into the façade design. This user-oriented approach ensures that the housing units are not only functional but also personalized, contributing to a sense of ownership and community among residents, achieving the social concept for the proposal.

In summary, this research has demonstrated the potential of 3D printing in producing adaptable, efficient, and socially engaging housing units. The iterative design process, attention to material properties, and integration of user preferences are key factors that contribute to the success of the project. This study provides a framework for future research in the field, being a possible solution for more innovative and sustainable housing solutions.

6.2 Future research

Moving forward, multiple areas have been identified for future research to expand on the findings of this thesis.

Firstly, including non-planar printing using a robot arm could expand the possibilities of 3D printing shapes and forms. Gaining more control over the G-code would allow for the creation of more complex and varied geometries, enhancing the architectural adaptability and aesthetic potential of 3D printed structures.

Secondly, automating the aggregation of housing units through simple and user-friendly platforms can improve user interaction and customization. Such platforms would enable potential residents to participate actively in the design process, ensuring their needs and preferences are met efficiently.

Thirdly, automating the interior distribution of housing units using a library of pre-designed rooms can improve the design process. This would allow for faster customization of interior layouts to satisfy user requirements, enhancing both functionality and comfort.

Finally, the area of interior design presents vast opportunities for exploration. This includes printing integrated furniture, plumbing, and other fixtures directly into the housing units. Such advancements could lead to more cohesive and efficient designs, reducing the need for separate manufacturing processes and installations.

By addressing these areas, future research can continue to push the boundaries of what is possible with 3D printing in construction, further enhancing the efficiency, adaptability, and innovation in social housing projects.

7. Reflection

7.1 Graduation Process

How is your graduation topic positioned in the studio?

This thesis engages two chairs within the Faculty of Architecture. The first is the Design Informatics chair from the Building Technology master track, and the second is the Architecture Design chair from the Architecture master track.

The Digital Technologies Chair offers insight into current production methods, assessment criteria for model fabrication, and the primary workflow, including the necessary design and production software. Additionally, the Architecture Chair addresses functionality, social aspects, architectural concepts, and the overall feasibility of the design.

Together, the chairs provide the necessary knowledge to address a mixed approach, where design of a housing project is dictated by production technology, complexity in form and design, and aesthetic considerations. This work's interdisciplinary nature embodies the spirit of the Building Technology and the MSc Architecture, Urbanism and Building Sciences, enhancing the comprehensive and varied perspective from its students and professionals.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

The complexity of a housing project using a specific approach for fabrication needed more than one methodology. For that matter, the thesis consists of four parts: the literature review, design phase, experimentation and prototyping of the design.

The primary focus was experimenting with 3D printing. For this, a design was needed that could relate to a real scenario, potentially providing solutions to current problems. The proposal is grounded in the concepts of social housing, customer-oriented design, kit-of-parts production, and the pursuit of architectural aesthetics through printing technology.

The approach worked as expected with all parts came together in the end. The process was cyclical, as during the experimentation’s results was needed to go back to the design and make the necessary variations to improve the outcomes.

How are research and design related?

To achieve the desired outcome, a comprehensive research and investigation must be conducted on various key concepts. These include the kit-of-parts approach as a construction method, 3D printing as the production technology, social approach as an architectural design strategy, and the vault as the initial architectural shape. By combining these elements with functionality, user customization, and architectural aesthetics, a project complex enough to utilize 3D printing technology was designed.

However, during the experimentation phase, many insights were gained through trial and error. This was a crucial part of understanding the limitations of 3D printing techniques. Thus, by the prototyping stage, the desired result was achieved within possible parameters.

Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

Fortunately, no ethical issues were encountered during the thesis process. However, a personal decision that could potentially impact one's morality was made at the onset of the investigation.

The city of Lima in Peru was initially selected as the site for the case study due to the constant and ongoing housing issues the country has faced. But following the author's personal experience of living in Europe and the Netherlands for studies, it was realized that the issue of housing deficit is not confined to Latin America but is a worldwide problem. Addressing this topic and finding a solution that can be replicated in different contexts changed from being a moral decision to an obligation as an architect. Consequently, personal preferences, including focusing on the author's home country, were set aside.

7.2 Societal Impact

To what extent are the results applicable in practice?

Through the course of research and the study of current investigations, it has become evident that 3D printing is a technique still undergoing exploration and has not yet fulfilled its entire potential. Numerous universities, researchers, and companies in the construction and architectural field are persistently uncovering new forms and pushing the boundaries. Furthermore, given that this thesis focuses on a tangible issue such as the lack of social housing, it proposes a solution that may be implemented in the foreseeable future. Indeed, a multitude of actors from both the private and public sectors might - and indeed should - express interest in the advancement of these investigations.

To what extent has the projected innovation been achieved?

The final outcome met expectations, for this a key aspect of the process was the goal to merge concepts and techniques to optimize a housing project's production. Additionally, being the first to use the faculty lab's 3D printer was a continuous learning experience not only for the author but also for the lab experts, resulting in aesthetically pleasing print shapes and building elements.

Does the project contribute to sustainable development? What is the impact of your project on sustainability (people, planet, profit/prosperity)?

The literature review has already established that technologies like 3D printing can save costs, reduce time, and minimize human labour. At the same time, it is essential that everyone has access to a decent place to live and grow within a community.

These necessities align in the context of quickly producing feasible housing for underdeveloped countries. By combining the kit-of-parts approach with 3D printing, we can reduce material waste and errors during the production of housing parts.

How does the project affect architecture and the built environment?

The integration of 3D printing and a kit-of-parts approach in social housing projects can significantly transform architecture and urban spaces. This innovative blend enables the creation of unique, aesthetically pleasing designs that are often difficult to achieve with traditional construction methods.

In particular, 3D printing allows for intricate and organic forms, enhancing the visual appeal of each housing unit, while the kit-of-parts approach ensures easy assembly and modularity. This combination can lead to more sustainable and efficient construction processes, reducing waste and speeding up project timelines.

Additionally, these flexible technologies enable architects to design socially inclusive spaces that cater to various needs, promoting a sense of community and belonging. In summary, the fusion of 3D printing and modular construction methods promises to enhance the quality and creativity of social housing, making it more responsive to modern architectural needs and aesthetic desires.

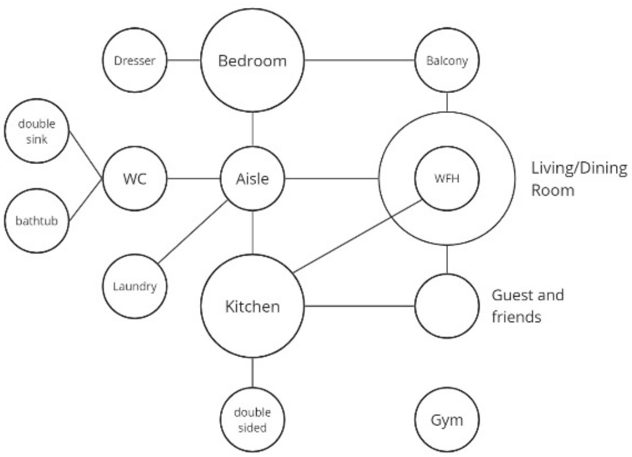
8. Appendix

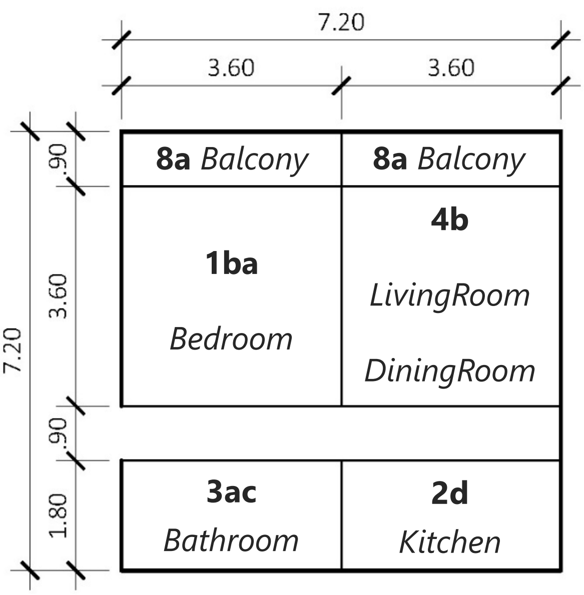
I. User customization

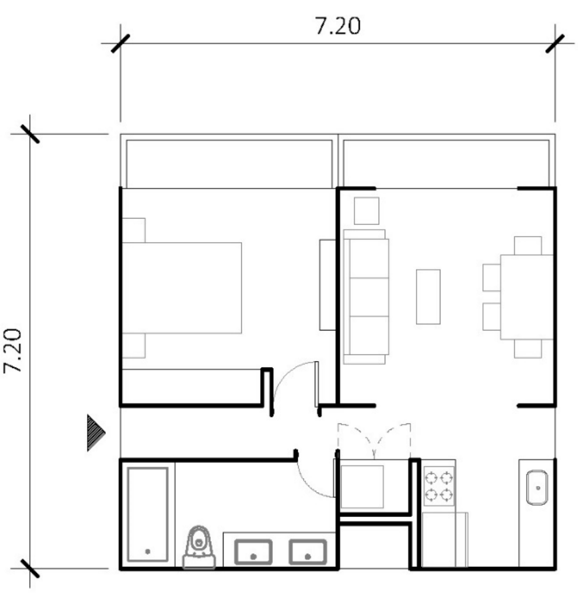
User 1: single person

Mauricio Villagra

"Mauricio a 31-year-old lawyer, wanted a bedroom and social part, both connected to a balcony. A medium size living room and integrated kitchen where he can have guest and dinner with friends. Double sink and a bathtub were a must for him. For the common spaces he would like to have a gym. First, he wanted to invest owning 1 module, but he wants the possibility to a short future to add one more module."





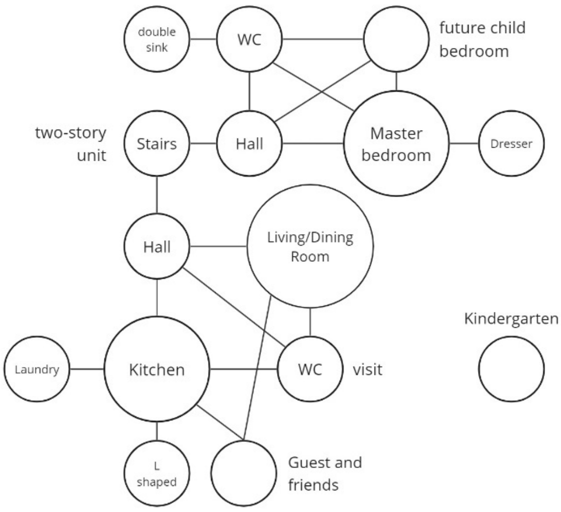


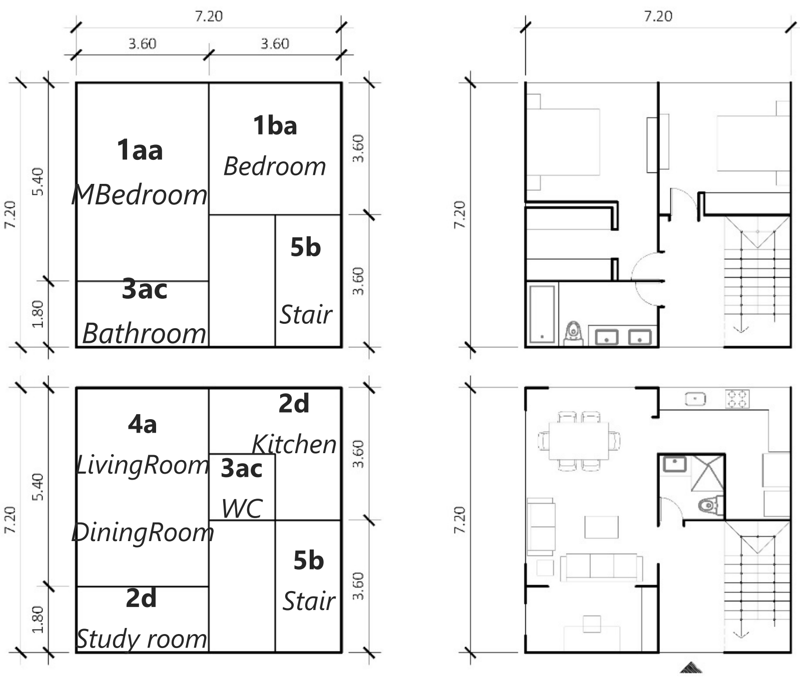
User 2: couple

Diana Morales & Andrew Humphreys

"Diana a public persecutor and Andrew, an architect are living together and want to invest in their home for the next 15 years. A big living room connected to a space we can have an office to use when we work from home. Bathroom in both floors would be ideal. A second room for our future child in the same floor with our bedroom.

In the common spaces I would like to have a kindergarten. We would like to invest in a 2-module house, if our family keep growing"



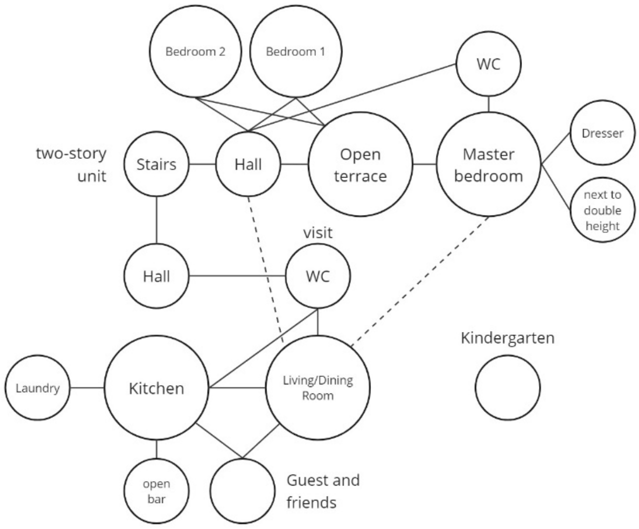


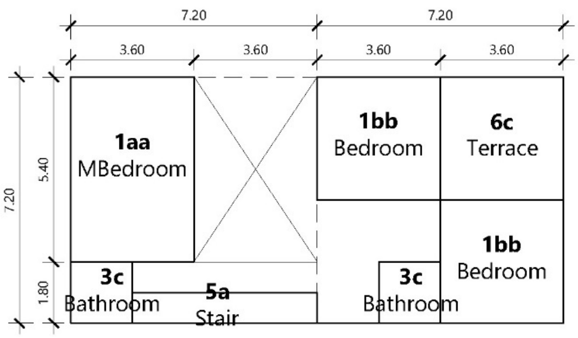
User 3: family

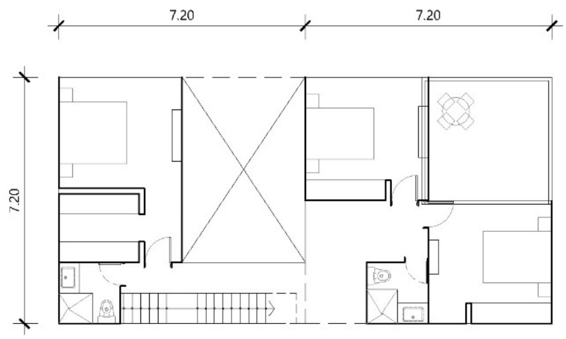
Stephanie & Jim +2 children

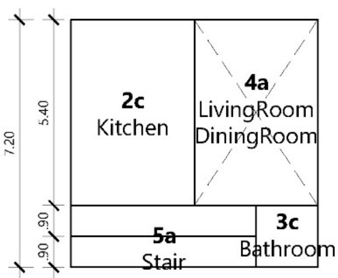
"Stephanie always imagined her home as a two-floor house, with a double hight living room where she can put her mother's chandelier. The first floor for the kitchen and receive visits. On the second floor the bedrooms. She prefers having more privacy and not having her children's room next to hers. Jim just needs an open space far away from the master bedroom to play his guitar. The children will be pleased with a big terrace, which eventually can be other use.

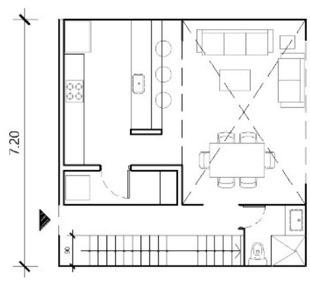
In the common spaces she prefers BBQ zones and open cinemas"











II. Printed models data

Test 01

Printing time: 22 min
Height: 7.3 cm
Base/Top wide: 8.2 / 6.2 cm
Weight (dry): 178 g
Nozzle: 3 mm

Test 02

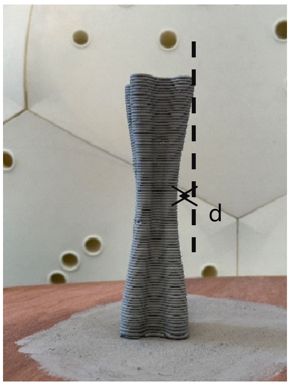
Printing time: 18 min
Height: 8.2 cm
Base/Top wide: 6.9 / 5.2 cm
Weight (dry): 172 g
Nozzle: 3 mm

Test 03

Printing time: 26 min
Height: 12.5 cm
Base/Top wide: 6.0 / 5.4 cm
Weight (dry): 174 g
d: 2.7 cm
Nozzle: 4 mm

Test 04

Printing time: 34 min
Height: 18.7 cm
Base/Top wide: 7.2 cm
Base/Top narrow: 4.1 cm
Weight (dry): 286 g
d: 0.7 cm
Nozzle: 4 mm



Test 05

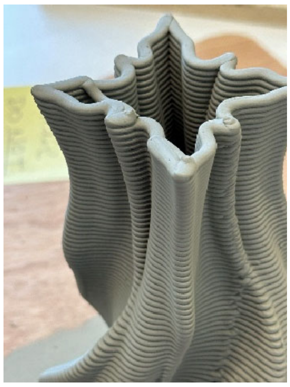
Printing time: 41 min
Height: 22.3 cm
Base/Top wide: 5.0 x 5.0 cm
Weight (dry): 506 g
d: 1.5 cm
Nozzle: 4 mm

Test 06

Printing time: 24 min
Height: 4.5 cm
Base wide: 6.8 x 7.0 cm
Weight (fresh): 284 g
Weight (dry): 236 g (-17%)
Nozzle: 4 mm
Layer height: 0.03

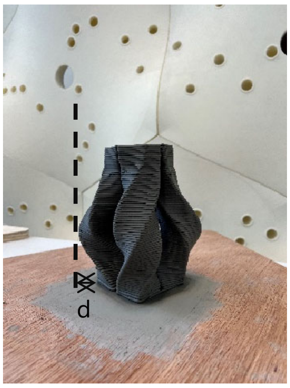
Test 07

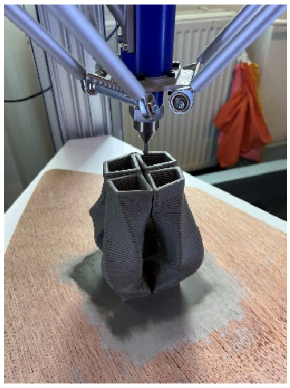
Printing time: 46 min
Height: 19.7 cm
Base/Top wide: 6.3 x 5.0 cm
Middle wide: 11.2 cm
Weight (dry): 532 g
d: 1.5 cm
Nozzle: 4 mm



Test 08

Printing time: 41 min
Height: 15.5 cm
Weight (fresh): 756 g
Weight (dry): 730 g (-3.5%)
d: 2.1 cm
Nozzle: 4 mm





Test 09

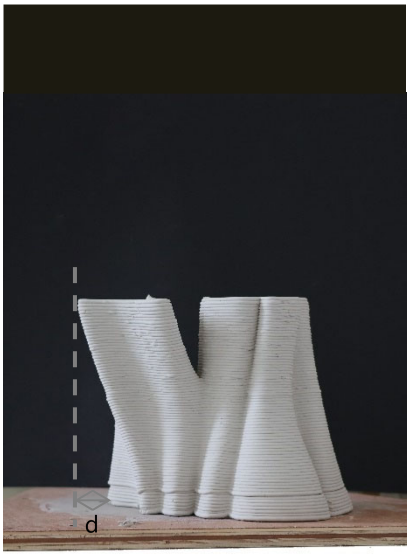
Printing time: 36 min
Height: 15.7 cm
Weight (fresh): 922 g
Weight (dry): 768 g (-17%)
d: 6.8 cm
Nozzle: 4 mm

Prototype 1

Printing time: 38 min
Height: 24.0 cm
Weight (fresh): 5622 g
Weight (dry): 4708 g (-13%)
d: 3.0 cm
Nozzle: 8 mm

Prototype 2

Printing time: 42 min
Height: 21.5 cm
Weight (fresh): 4656 g
Weight (dry): 3878 g
(-13%)
d: 6.0 cm
Nozzle: 8 mm



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