A COMPARATIVE REVIEW OF 3D PRINTING TECHNOLOGIES FOR THE CONSTRUCTION OF RESILIENT HOUSING

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **"A COMPARATIVE REVIEW OF 3D PRINTING TECHNOLOGIES FOR THE CONSTRUCTION OF RESILIENT HOUSING"** and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

A COMPARATIVE REVIEW OF 3D PRINTING TECHNOLOGIES FOR THE CONSTRUCTION OF RESILIENT HOUSING

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Architecture is related with the new improvements in technology since the beginning of the civilizations. With the social evolution several problems such as poverty, unemployment and immediate need for a shelter have arisen. These are just some of the difficulties families experience nowadays, in particular the low-income ones. Thus, along with many new technologies that affect and improve individuals' life, one in particular related with architecture has bloomed. 3D printing for construction is the newest as well as one of the best solutions to fulfil the need for affordable housing in a short time. The first step to understand it is to study the state of art of 3D printed buildings and their respective printers. Thereafter, by reflecting the knowledge there are developed several housing prototypes, based on the theoretical background, and adapted to the Tirana conditions. As a final analysis, the results depict which 3D printer is the best to fulfil this objective, along with the most appropriate house prototype.

Keywords: *3d printing, architectural design, housing units, residential units, low-cost housing, affordable houses.*

ABSTRAKT

NJE INSPEKTIM KRAHASIMOR I TEKNOLOGJISE SE PRINTIMIT 3D PER NDERTIMIN E GODINAVE TE QENDRUESHME

Bici, Andjol

Master Shkencor, Departamenti i Arkitektures

Udhëheqësi: Dr. Anna Yunitysna

Arkitektura eshte e lidhur me permiresimet e reja ne teknologji qe nga fillimi i qyteterimeve. Me evolucionin social jane shfaqur disa probleme si varferia, papunesia dhe nevoja imediate per nje strehe. Keto jane vetem disa nga veshtiresite qe perjetojne familjet ne ditet e sotme, vec;anerisht ato me te ardhura te uleta. Keshtu, se bashku me shume teknologji te reja qe ndikojne dhe permiresojne jeten e individeve, ka lulezuar nje ne vecanti e lidhur me arkitekturen. Printimi 3D per ndertim eshte teknologjia me e re si dhe nje nga zgjidhjet mete mira per te permbushur nevojen per strehim te perballueshem ne nje kohe te shkurter. Hapi i pare per ta kuptuar ate eshte studimi i gjendjes se artit te ndertesave te printuara 3D dhe printereve te tyre perkates. Me pas, duke pasqyruar njohurite, jane zhvilluar disa prototipe banesash, te bazuara ne sfondin teorik dhe te pershtatura me kushtet e Tiranes. Si analize perfundimtare, rezultatet pershkruajne se cili printer 3D eshte me i miri per te permbushur kete objektiv, se bashku me banesen e cila ploteson ne menyren me te mire nevojat perkatese individuale te banuesve te saj.

Fjalët kyçe: *printera 3D, dizajn arkitektonik, njesi shtepiash, rezidenca, shtepi me kosto te ulet, shtepi te perballueshme.*

I dedicate this thesis to my family who supported me through these 5 years of studying Architecture. Each year was hard and full of challenges, but they stood with me and motivated me to never give up on my great passion.

This study goes as a tribute to all people that lost their lives in 26.11.2019 earthquake, as well as to all the people that are losing their homes because of the war that has been happening in Ukraine during the time that this thesis is written.

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I want to thank my professor Dr. Anna Yunitysna for helping me writing this thesis. All the critics that I conducted with her helped me to improve the quality of my work, research and design.

I want to thank the Architecture Department Staff of Epoka University who taught me the basics of architecture and prepared the road toward my future profession.

I want to thank Epoka University which gave me the opportunity to be their student and develop further my biggest passion.

Special thanks go to my family for helping me with motivation, support and technical background. I want to thank my mother who was the first one to show me the 3D Printing technology back in 2017. I want to thank my father who shared with me all his construction background due to his profession as a Topographer. I want to thank my brother who helped me a lot in better understanding the different programs for architecture. I want to thank my uncle and his wife who helped me printing all the materials which were required during 5 years of study. Lot of thanks go to my grandparents who shared with me all their lifetime experiences in relation with architecture and construction methods. I want to thank my cousins for always supporting me with every difficult challenge that occurred during these studying years. Last but not least I want to thank my girlfriend who helped me with motivation, support, optimism and ideas to design.

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CHAPTER 1
INTRODUCTION

1.1. Problem statement

The poverty rate for Albania is increasing and the need for affordable housing is growing. After the earthquake that happened in 26.11.2019 in Tirana, Durrës, Krujë and Lezhë 202,291 people were affected which means around 50,573 families. From them over 10,566 families were directly influenced [1]. Then the upcoming year the COVID-19 pandemic started which made the necessity of owning a home much clearer. Also, it increased the prices of apartments in Tirana [2] at around 16% from 2019 to 2020. Furthermore, the prices were increased again from 2020-2021 about 10-15% [3]. From the legal statistics for year 2018-2020 in Tirana [4] there are in total 6,708 homeless families from which 1,829 have found shelter.

Thus, a permanent shelter in Tirana is essential for all families that can't afford it. The solution for this problem should be implemented fast and in efficient manner given that the COVID-19 pandemic is still present. So, by following the newest technology of 21'st century, the method of 3D printing buildings is seen as the most appropriate solution for this socio-economic situation.

1.2. Objectives

In this thesis, it is introduced in form of a research and a project an innovative way of building, that of printing houses instead of building them "brick by brick".

The main objective is to design a series of prototypes using a 3D printer that will later on serve the proposal of printing real-scale houses to accomplish the needs of low-income families.

Next objective is to verify that this way of building is efficient in terms of time and cost, which achieves the main commitment of this thesis, as well as depicting which prototype is more efficient in terms of cost and time based on the application of printing of small-scale model.

The last objective tends to prove that this innovation in Albania specifically in

Tirana is possible and it is the most efficient solution for affordable housing for low-income families.

1.3. Methodology

The first part of the research is related to the study of existing state of art of 3D printing technology of large-scale objects based on the study of recent research. Starting with a brief history of 3D printers, followed by an overview of different types of 3D printers in a small scale associated with a diagram. Afterwards, there are explained 3D printers in a large scale. Later 3D printers in a large scale are separated in 4 subchapters relating with different technology such as gantry, robotic arm, cable, and mixed 3D printers.

The second part is dedicated to different case studies around the world that are already build and serve as a real example of the possibilities and limitations of this technology. The aim is to add some practice-based information such as the height, area of the building, fully 3D printed or partially, sustainability, durability and other important settings which are very crucial in the design limitations.

Thirdly, all the information will be evaluated in a form of a table to make it easier understanding all restrictions and possibilities. It is significant for choosing the best form/shape also gives the best conclusion for all data gathered up to this point. The table is revised after modeling and prototype construction.

Following is the site selection and the analysis of that area. It is chosen based on planning regulations also the type of terrain where in this case a flat land is exceptional. Peripheral area outside of the city of Tirana is selected. Afterwards the site analysis takes place. They include location, circulation, building heights, climatic conditions, vegetation, and photos of the site, all of which are necessary for the next process.

As a result, the development of the prototypes starts by developing a set of criteria of 3D printed house which can be realized in Albania. The criteria of designing is set up by the previous summary and the table from the literature review with the aim to fulfil the main objective which is design a series of prototypes using a 3D printer that will later on serve the proposal of printing real-scale houses to accomplish the needs of low-income families. The list of criteria will include types of printers, the cost of building, types of professions needed and materials. All these restrictions are crucial to conduct a proper study to accomplish all the goals that were mentioned before. What follows is modeling of the prototypes in some specific software that are selected based on the literature review. There are different prototypes for different family scale and for distinctive constructing technologies. Some computer programs that are used are AutoCAD, SketchUp, … Further the models designed are sent to the printing lab to be printed as a 3D small scale prototype of the houses.

Moreover, when the design of the prototypes is conducted, their evaluation is needed. This is part of the thesis discussion. It is assessed using the criteria that were determined for 3D printed house suitable for Albania. These criteria linked with the prototypes that were designed complete this evaluation process.

The conclusion arises after reflecting the criteria that was chosen and then the appliance of it in the design process coming to the printed prototype by updating the table that was created in the literature review. Also, the advantages and disadvantages are mentioned to give the final results of how applicable this technology is. There are described all the limitations of the study along with the future research proposals.

1.4. Thesis overview

The thesis is organized in 6 chapters. It starts with the introduction of 3D printers and their state of art (Chapter 2). After that what follows is a series of case studies that are already finished in the world using 3D printing technology for construction. Right after the theoretical part is the site analysis (Chapter 3) which shows all the information needed for the selected area. Following is the development of prototypes (Chapter 4) where the housing prototypes are designed and 3D printed in a small scale, after which the discussion is presented and the designed prototypes are analyzed (Chapter 5). Lastly is the conclusion chapter (Chapter 6) in which the best 3D printer will be selected for this thesis objective.

CHAPTER 2

LITERATURE REVIEW

2.1. State of art of 3D printing technology

2.1.1. History of 3D printing technology

The technology of 3D printing is diverse in the ways it is applied. Addition technology is known mostly as 3D printing and is available not only for manufacturing and professional work but also for general public (Dunn, 2012). It uses different materials that depend on the size and the purpose of the 3D printer. The small-scale ones are available for everyone to create their desired shapes. It uses a composite of plastic which is called filament. This technology of printing is conducted by placing the material layer by layer while when placed it directly cools down due to its properties. Addition technology is what is needed to be researched for this thesis because part of this is large scale 3D printer for buildings. … ITENSITY OF 3D PRINTED BUILDINGS IN THE WORLD: This study discusses about patents taken from companies for 3D printing of buildings, number of inventions, and who are the leading companies in this field [5].

The history of 3D printer dates back in 1981 when Hideo Kodama came up with the idea to print in 3D layer by layer using photosensitive resin that was polymerized by ultraviolet light [6]. In upcoming years this technology became widely known and many research and new updated 3D printers were made. But the first patent for this technology was obtained by Charles Hull who developed Kodama's idea in a new functional and more efficient way.

First 3D printer to be commercially available was in 2006 when 3D printing technology (in small scale) helped companies to print the forms they wanted, but the price was high for individual usage. After 2010's prices started to drop, which led individuals all around the world to buy a 3D printer and the creations made with it became a trend worldwide of how vast the human imagination may be.

2.1.2. Overview of 3D printing technologies

There are 3D printers for various appliances such as manufacturing, architecture modeling, food, medicine, fashion, aircraft etc. Those are just a few of the fields this technology is applied and all of those 3D printers are different from each other. Based on the technology type [7] there are 7 3D printer groups directed energy deposition, binding jetting, materials jetting, materials extrusion, sheet lamination, vat photopolymerization and powder bed fusion. Each of these technologies has its own appliance adapted to different fields so there is no way to compare them between each other [8]. All of them are described in the diagram below to have a summarized information about materials and where they are used (Fig.1).

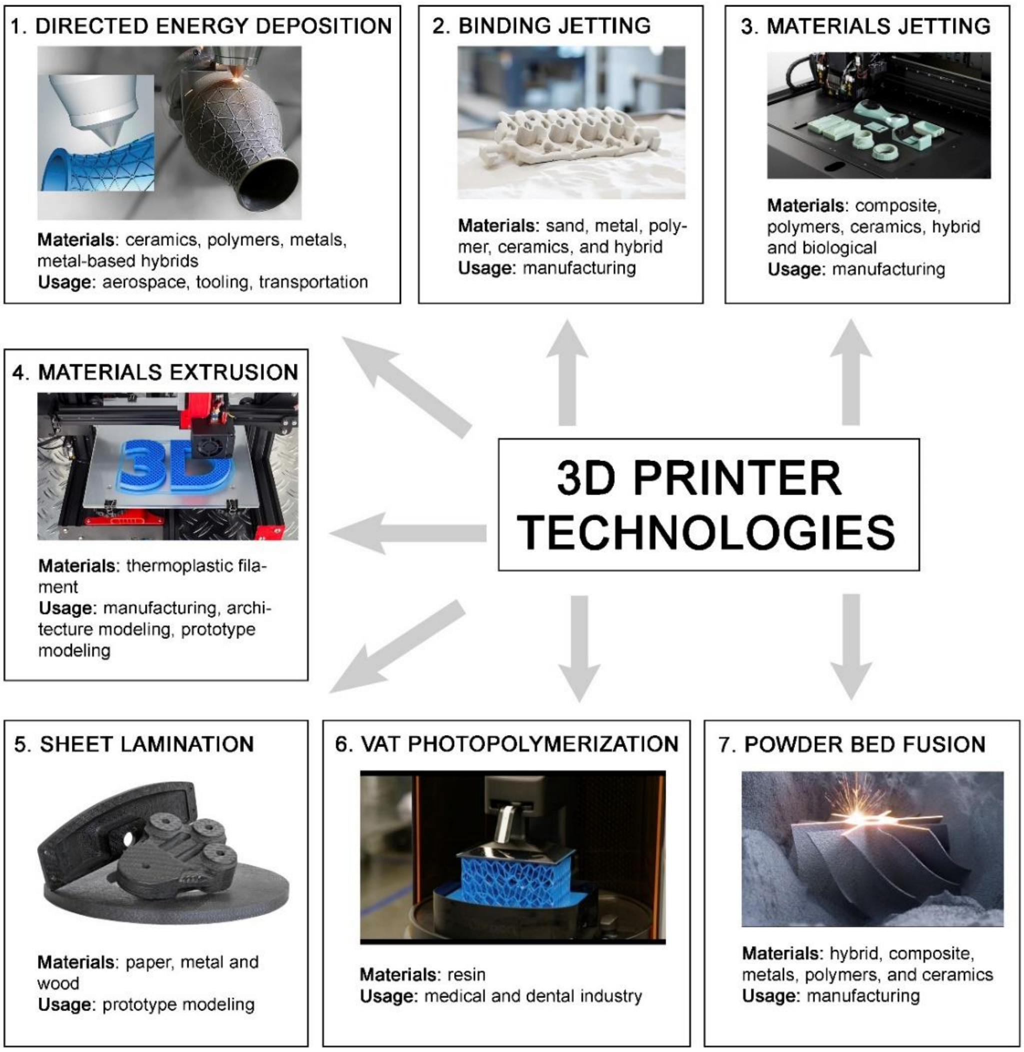

Figure 1. 3D Printer Technologies

To begin with, directed energy deposition 3D printer is utilized to repair or add material to components. As a printing material ceramics and polymers are used, although it is most commonly used with metallic materials and metal-based hybrids in the form of wire or powder. It uses a laser to apply the material in the surface which may be strait or parametric and it's used in aerospace, tooling, transportation, etc.

Binder jetting is a quick manufacturing and 3D printing technique that involves selectively depositing a liquid binding agent to combine powder particles. The materials that can be printed with it are sand, metal, polymer, ceramics, and hybrid. It is widely used in manufacturing because it is faster, simple, can print large objects and most importantly it is cheap.

Materials jetting 3D printer is used for printing objects or parts of objects by applying the material drop by drop and freezing it with an UV light. The materials that are used are composite, polymers, ceramics, hybrid and biological. This technology is used in manufacturing industry as it is very accurate and produces clean surfaces.

Materials extrusion is the technology of 3D printer which is widely known by most people. It uses a plastic filament which extrudes due to heating and is applied layer by layer. This material is in form of a wire that can be easily stretched in the presence of heat and then freezes in seconds after it is applied. Different from other technologies, this printer creates difficult shapes by also printing a thin layer that acts as a support. Manufacturing, architecture modeling, prototype modeling, etc are some of the fields this technology is applied.

Another 3D printing technology is that of sheet lamination which prints sheets of a material to be combined together and creating an object. This printer is the first that comes with full colors. Materials that are printed are paper, metal and wood. A great example of this technology is the first full color 3D printer MCOR Arke Color 3D Printer that prints with paper.

Vat photopolymerization is usually called stereolithography and it's used in medical industry, which includes hearing aids, facial prosthetics, surgical learning tools, and it is also used in dental industry. The process is simple. First a container is filled with liquid resin and later this 3D printer uses a laser or UV light to freeze the resin in the desired shape. It produces models which are durable, flexible, and extremely detailed with layers that are 4 times thinner than human hair.

The last one is powder bed fusion which uses either a laser or an electron beam to fuse or melt the powder together. The process is similar to directed energy deposition 3D printer because it combines the desired shape inside a layer of powder. The materials this technology uses are hybrid, composite, metals, polymers, and ceramics.

2.1.3. 3D printing at large scale

The first idea for a 3D printer that printed in a large scale 1:1 building was exposed by Dr. Behrokh Khoshnevis from University of Southern California in 2006 [9]. Later in 2014 a Dutch architecture firm (DUS Architect) started applying this knowledge in real life by printing with plastics a small cabin. Their idea was to integrate 3D printing technology in construction because of the rapid growth of the cities nowadays that needs a new efficient, sustainable, and faster way to build. After in 2015 that an interesting new appliance has come to life, that of 3D printing bridges with steel. It was made possible by MX3D which is a Printing firm based in Amsterdam, Netherlands. They printed it with a robotic arm and tested its durability by walking on it. And in 2016 Khoshnevis idea for a 3D printer that pours concrete to build buildings started applying in US and in China. Starting with US, the Massachusetts Institute of Technology [10] printed a dome using a 3D printer in form of a robotic arm modified as a crane which poured concrete in a circular path (Fig.2). Going with the 10 houses in China that were printed with a 3D printer for 24 hours. Also, China printed the first earthquake durable house.

Figure 2. MIT 3D printer

2.1.4. Gantry 3D printer

One of the most known 3D printing technologies is that of gantry 3D printer. It has a square metallic structure which includes a shaft that moves in x and y directions using rollers and in z direction by elevating the structure or the platform where the model is printed (Fig.3). This type of printer is used all over the world by any individual who wants to print their desired models because of its low price.

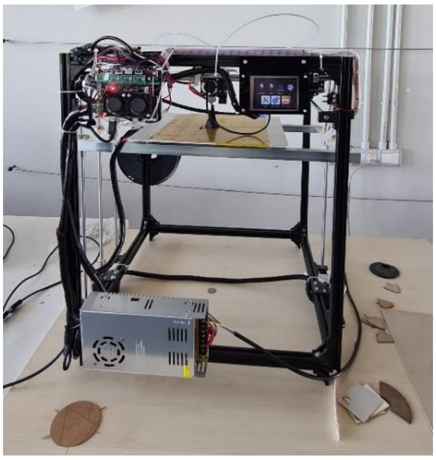

Figure 3. Gantry 3D printer for small models, image source (Epoka University | Lab)

This technology comes in a large scale that prints buildings. It is the first technology to print a building by pouring concrete that was built by University of South California and Dr. Khoshnevis in 2001 [11]. This printer was created as an experimental version to test the technology and the material but in a small scale rather than a real one (Fig.4). It used a clay material that was called Taylor Ball clay [12]. The printer in one side had a longer part to flatten the printed layers and creating a smoother face in the outside but not in the inside.

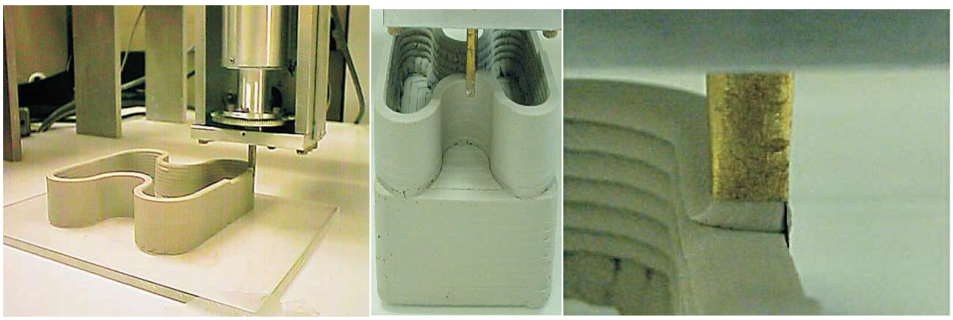

Figure 4. University of South California first experimental printer for building (year 2001), image source [12]

Another printer that uses the same technology is already used and build a whole neighborhood for homeless in Austin Texas [13]. Icon (a construction company) used Vulcano II a gantry 3D printer that is commercially available for every company that wants to build with this innovative technology (Fig.5). These walls are not covered after the building is done except for the windows (Fig.6). Houses are small with 37 m^2 area and are finished in about 24h. Also, it there were printed only the walls because the roof is added in a traditional way of construction. All of these buildings are built in an already places foundation that helps the printer to precisely pour concrete in a flat area. Icon is building another neighborhood now in Mexico by using the same technology. Even in this new project the roof/terrace is made after the walls are done in a traditional way (Fig.7).

Figure 5. Vulcano II 3D Printer Austin, Texas, US, image source [14]

Figure 6. Austin 3D printed houses, image source [15]

Figure 7. Vulcano II 3D Printer Tabasco, Mexico, image source [16]

Furthermore, Vulcano II is one of the best in this technology due to its functionality and fast building time. One of the greatest benefits of this 3D printer is that it's made for building buildings in a rural area where traditional construction is highly expensive due to lack of materials, weather, and electricity. So, this printer can print remotely from a smartphone application (BuildOS) using a material called "lavacrete" special mixture of concrete [17] which can withstand extreme weather and natural disasters also the nozzle diameter is 50 mm. It is 14.2m width, 11.1m printing width and 4.7m maximum height, 3.2m maximum printing height which allows only printing of 1 floor building (Fig.8) and maximum building volume 57.46 m^3 [18]. But the printing length is infinite which means you can print with a restricted width and height but with an unlimited length. This is one of the reasons why printing a series of housing is that simple and fast, just like manufacturing. The power this printer needs is 230/240 V single phase and the printing speed is 12.7-25.4cm/sec [19]. It can be operated by 4 to 6 people [20]. Also, the price for this printer is approximately 409.230 € [21].

Figure 8. Vulcano II 3D Printer digital model, image source [19]

Another printer which is claimed to be most sold 3D printer for construction is called BOD2. Different from Vulcano II this printer can have custom width and height up to 14.6m width, 50.52 m length and 8.1m heigh which can print 2 floor height buildings and is based in Denmark, Europe. Its printing speed is 100 cm/sec making it one of the fastest in the world [22]. It also uses flaps where 2 sides of the nozzle are longer to flatten the layers and to make wall surfaces both inside and outside smoother and more esthetic (Fig.9). Also, layer dimensions vary for width 30-300 mm and for height 10-40 mm and the nozzle (20-50 mm diameter) can be changed easily in less than 2 minutes to pour different layer dimensions and the maximum volume it can print is 6012 m^3 [23]. The printer itself is waterproof and can resist wet environments due to IP67 certification (Fig.10). It has 2 cameras on the printhead and can be easily remote-controlled using WiFi or LAN. Furthermore, there are needed only 2 operators for BOD2. Furthermore, this 3D printer can print even in uneven surfaces and adding needed material when in the end the top of the all the walls is at the same elevation. It needs 400 V, 3 phase power supply and uses COBOD Slice software for Windows and MacOS. The price of this printer is 272.820 €.

Figure 9. BOD2 3D Printer nozzle, image source [22]

Figure 10. BOD2 3D Printer, image source [24]

To continue with, there is another 3D printer in Europe that has great specifications. It is called BetAbram P1 and is produced by a Slovenian company [25] called Betabram (Fig.11). P1 is one of the 3 models this company offers and the only one that is specified as the 3D printer for construction use [26]. Largest 3D printer P1 prints 16m length, 9m width and 2.5m heigh, other printers have the same height but P2 has 12m length and 6m width, P3 has 4m length and 3m width. The material P1 uses is a mixture of concrete and it is needed after every 25 cm height to wait about 5-6 hours till the material dries (Fig.12) and the nozzle diameter is 40 mm. To produce the material, it is used a screw pomp and will print a maximum building volume of 328 m^3. There is taken as an example a 216 m^2 house building it in a traditional way will take 34 weeks and cost up to 114.574€ but with this 3D printer they calculated that this building will be completed in less than 10 weeks, will have 0% waste, and will cost 76.423€ or 38.151€ less than the traditional way. Its maximum printing speed is 50 cm/s, it needs 4kW to run and 2 operators for the process. Also, there are needed 1-2 people to operate it and P1 cost is around 32.000 € for the whole unit. It uses Betabram software for operation which is a modified CNC software. Betabram is creating another 3D printer for construction that is called Betabram Spider which can print multistorey buildings by fixing the printer structure in each floor.

Figure 11. BetAbram P1 3D Printer, image source www.youtube.com

Figure 12. BetAbram P1 3D Printer material, image source [26]

2.1.5. Robotic arm 3D printer

Another type of 3D printer functions with a robotic arm. This technology is widely known in manufacturing industry as helps to drastically reduce the labor force and complete many tasks in a short time (Fig.13). These so called ‘mechanical’ arm works like the real human arm which can move in a circular path (mounted in a single point) and easily/precisely complete assigned work [27]. But the robotic arm 3D printers for constructing buildings don’t weld or drill like in most manufactures but they just pour concrete in the defined track (Fig.14).

Figure 13. Example of a robotic arm, image source [27]

Figure 14. Example of a robotic arm 3D printer, image source [28]

Starting with an advanced robotic arm 3D printer for construction that is produced in France. It is called MAXI Printer and prints not more than 1 floor height (Fig.15). For this printer to print efficiently (fixed in one point) it is needed to pour the material in a circular. The company (Constructions-3D) states that this printer desired dimensions to print without changing the place are 9.5m width, 9.5m length and 3.3m height, but if the building is larger than that this printer can be set up in other locations [29]. The material it uses is concrete which is poured though the nozzle (20-50 mm diameter). Maximum area that it can build placed in a single point is 116.8 m^2 and the maximum volume is 385 m^3 [30]. MAXI Printer has 10 mm accuracy which is a great improvement considering that in the traditional way the accuracy is 2 cm and in some cases goes up to 5cm. Also, it has a printing speed up to 30 cm/s and uses an automated pumping system which is separated from the printer (Fig.16). To operate this 3D printer there are needed 2 people for all the tasks installation, printing, and cleaning [31]. It uses C3D Slicer Software which is made to operate this specific printer. MAXI Printer price is about 495,168 €.

Figure 15. MAXI Printer, image source [30]

Figure 16. MAXI Printer in operation, image source [29]

Passing to another robotic arm 3D printer that is located in Netherlands and it is called CyBe Construction CyBe RC 3Dp [32]. It is unique from other printers because the company CyBe offers 5 different 3D printers fixed (CYBE R 3DP), mobile (CyBe RC 3Dp), track (CyBe RT 3Dp), gantry (CyBe G 3Dp), gantry with robot (CyBe GR 3Dp). The printer that is designed for on site use is the second from the left (Fig.17) which uses the robotic arm and can print easily in multiple locations (CyBe RC 3Dp) because it is mounted in a crawler. The crawler is designed specifically for stability of the printer while moving (Fig.18). The material is custom made by CyBe and is called CyBe Mortar. It includes sulphate and chloride in small amounts but it's not metallic. This material can be set in 3 minutes and achieves the full strength in 1 hour. It is stated by the company that this material produces less CO_2 emissions compared to Portland cement at 32% less. To pour the material this printer uses a 25.4 mm diameter nozzle and prints at 50 cm/s speed [33]. Since this printer moves at a speed of 3 km/h with the crawler it can change places easily, thus width and length dimensions aren't necessary for this type of 3D printer. But it can print a building up to 3.5 m heigh or 1 floor heigh buildings only and can be set up in 1 to 2 hours. Interestingly it has an accuracy of 0.15 mm which is almost precise. Also, it can print a maximum area of 32.2 m^2 volume of 112.5 m^3 and can be operated for all tasks by not more than 2 people. To use this 3D printer, it is needed CyBe Artysan which is a slicing software that is created by the company, but for modelling phase they have created a plug in for Rhinoceros 6 or 7 called CyBe Chysel. CyBe RC 3Dp price is 186,427 €.

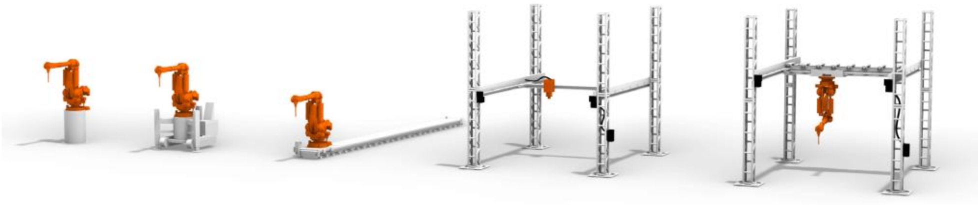

Figure 17. CyBe 3D Printers, image source [32]

Figure 18. CyBe RC 3Dp, image source [32]

Furthermore, another robotic arm 3D printer that is fixed in one point is called Apis Cor from the company with the same name based in United States. It has a maximum printing radius of 5.5 m and it can print up to 1 floor because of its maximum printing height of 3.2 [34]. Apis Cor 3D printer can print a maximum area of 95 m^2 and a volume of 295 m^3 when placed in a single point (Fig.19). The company does not specify any new custom material like Icon that created lavacrete, but they mention that is a traditional mixture of concrete with very small aggregate. It has an astonishing printing speed of 16.7 cm/s and an accuracy of 0.2 mm. There are needed 2 people to operate this printer for mounting and during the process, also it is weather resistant with respective certifications IP 65 and IP 67. A nice feature this robotic arm 3D printer has is that it is easy to move because it is mounted in a small crawler that moves remotely with their custom software called Apis Cor Software that requires a tablet (must have downloaded the software) which should be mounted in the 3D printer external equipment that has joysticks to remotely control the printer. Also, it is easy to transport this printer with its additional equipment to every construction site, because it can be transported with a regular tuck due to their small dimensions when folded (Fig.20). Apis

Cor company have estimated that the cost to print 1 m^2 wall is approximately 25 € [35]. The cost of this printer is not displayed by the company because they only sell it by leasing.

Figure 19. Apis Cor 3D printer, image source [34]

Figure 20. Apis Cor 3D printer transportation, image source [36]

2.1.6. Cable 3D printer

Another kind of 3D printer technology is that of cables. It looks similar to gantry because of the framing structure but in this case the printing head is not fixed in one axis that moves in one plain, but it is fixed in the corners of this framing structure with cables (Fig.21). These cables are responsible for the location of the printing head in the given time. They control the head and the nozzle to pour the material based on the digital

3D model. It is not specified how much cable should be mounted for this 3D printer to work but form the studies it is set a minimum amount of 4 cables that can move the printing head in x, y, and z directions and a standard of 8 cables to make the head more stable [37].

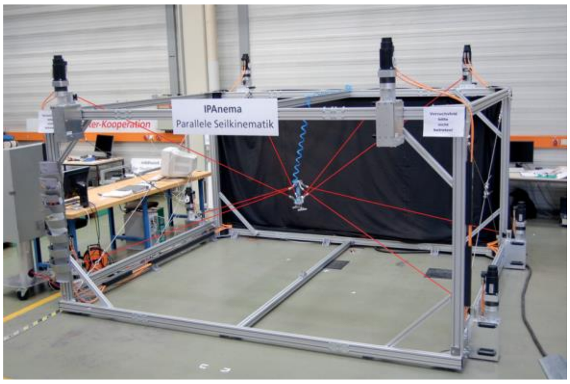

Figure 21. Cable 3D printer example, image source [37]

Furthermore, cable 3D printers are not produced as much as gantry or robotic arm because they are still experimental. One example of a cable 3D printer for buildings is BigDelta WASP 12MT (Fig.22) from the company WASP based in Italy [38]. A key feature of this cable 3D printer is that it uses on site materials like soil and mix it with long fibers such as straw that can come out easily through the printing head. Also, this printer is known as the highest 3D printer in the world because it is at 12 m heigh (structure) and has a width of 7 m (structure) which means it can print up to 2 or 3 floors [39]. It has a hexagonal plane structure shape which means can produce a 23.4 m^2 footprint and due to its height 280.8 m^3 maximum volume (these dimensions include the structure, because the company did not mention the maximum printing space dimensions). Thus, BigDelta is a fixed cable 3D printer that can print in the specified area (Fig.23). It can print with a speed up to 40 cm/sec and can be operated by 2 to 4 people. The cost of this cable 3D printer for construction is not displayed due to its status as an experimental project.

Figure 22. BigDelta WASP 12MT, image source [38]

Figure 23. BigDelta WASP 12MT printing a prototype, image source [39]

Even though this kind of technology for massive 3D printers is not developed as the other technologies it still has potential to be one of the best solutions to solve the need for low-cost housing. Also, it is safe to say that the cable 3D printing technology is at it first steps in the construction sector and as seen from BigDelta WASP 12MT it can produce buildings up to 2 or 3 floors and has the possibility for the structure to become much higher than it is right now, thus making it even capable of building high rise buildings.

2.1.7. Mixed 3D printer

Gantry, robotic arm, and cable technology for 3D printing are not the only technologies that are used but there are other ones that combine them or even discovering a new one. The reason for this is the limitations that those technologies have. That's why it is needed to create new ideas and technologies. One example comes from WASP based in Italy. It is called DeltaWASP Crane and it is fixed in one spot by 4 structure elements where one is in the center and holds the robotic arm which pours the material [40]. Its structural footprint is a triangle and the building it produces has a circular shape due to the robotic arm radius which limits to print near the center structural element where the robot is placed (Fig.24). From this triangular structure WASP created a modular 3D printer which is a series of DeltaWASP Crane printer connected with each other to create a larger hexagon pattern 3D printer (Fig.25) which can print in a larger area [41]. WASP company states that it is more efficient than other 3D printers in terms of building speed. Thus, the base 3D printer DeltaWASP Crane has a maximum printing radius 3.15 m and the maximum height 3 m (1 floor height), which means that for the width and length is considered the diameter of printing which is 6.3 m. Also, it can print a maximum area of 31.2 m^2 and a maximum volume of 93.5 m^3. This printer can not move autonomously but it can only "multiply" the printing heads and like the others it need additional equipment such as material mixing machine. The material it uses is the local clay which can be found almost everywhere which is why the Italian architect Mario Cucinella states that this is the future solution for vernacular architecture because of the material it uses [42]. It has a printing speed up to 30 cm/s and a nozzle diameter from 18 to 30 mm. The software it uses is custom from the company WASP and the slicing software is Grasshopper both available for desktop and laptop. DeltaWASP Crane costs 132,000 € the base model and to add other modules it is needed a request to the company official website which price can be multiplied.

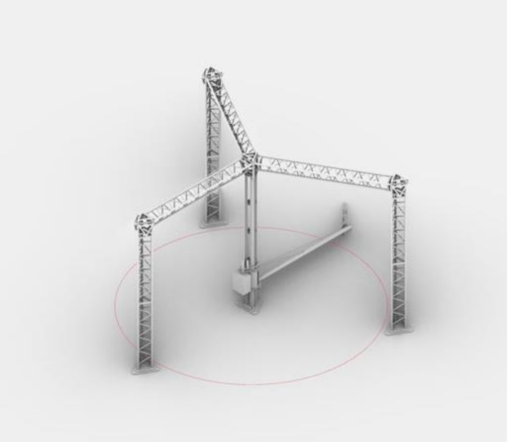

Figure 24. DeltaWASP Crane, image source [40]

Figure 25. DeltaWASP Crane hexagonal pattern, image source [41]

Furthermore, another mixed 3D printer comes from TU Dresden in Germany and it is called CONPrint3D and one of the main features is that this printer isn't made for parametric buildings and also it uses reinforcement between 2 of the concrete layers [13]. After the building is done there is the need to overlay it because the steel bars that are used for reinforcement are exposed (Fig.26). Main benefits are that this printer is cheap, can use same concrete mixture as the traditional building, precise placement of the layers and can be modified in the future even being able to control it with a laptop device. For now, CONPrint3D is treated as a gantry technology printing prototype walls in the lab, because it is still at an experimental phase, but later on it will be applied using a modified crane (Fig.27). They state that this printer can print a floor with an approximate area of 130 m^2 in about 1 day [43]. CONPrint3D has a unique printing head (Fig.28) which is like a big box with an area of 4.5 m^2 [44]. It also uses a tachymeter to for the accuracy of the printing which is less than 5 mm. Thus, this mixed 3D printer dimensions are not shown because it is still in the experimental phase and it is also mounted in a crane, but it is stated that it can print multistorey buildings. The printing speed is 15 cm/s and nozzle diameter are from 30 mm to 50 mm. Also, the accuracy of CONPrint3D is 5 mm which is directed from the tachymeter. It uses Cura as a slicing software and the price is not shown yet.

Figure 26. CONPrint3D layers and the printer, image source [13]

Figure 27. CONPrint3D crane, image source [44]

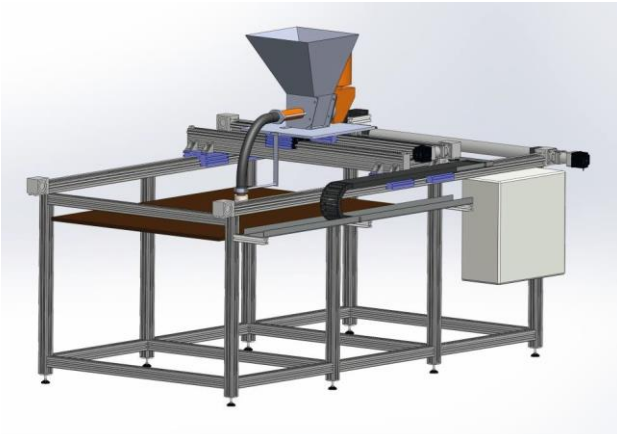

Figure 28. CONPrint3D printing head, image source [44]

2.1.8. Comparison between the 4 types of 3D printers

Table 1. General information and price of 3D Printers

Nr.	3D Printer	Company	Location	Tech. Type	Price €
1	Vulcan II	Icon	United States	Gantry	409,230
2	BOD2	COBOD	Denmark	Gantry	272,820
3	BetAbram P1	Betabram	Slovenia	Gantry	32,000
4	MAXI Printer	Constructions-3D	France	Robotic Arm	495,168
5	CyBe RC 3Dp	CyBe	Netherlands	Robotic Arm	186,427
6	Apis Cor 3D Printer	Apis Cor	United States	Robotic Arm	Leasing
7	BigDelta WASP 12MT	WASP	Italy	Cable	Experimenal
8	CONPrint3D	TU Dresden	Germany	Mixed	Experimenal
9	DeltaWASP Crane	WASP	Italy	Mixed	132,000

Shown above are general information about all 3D Printers for construction described in literature review precisely 2.1.4. – 2.1.7. where 3 main technologies and a combination of them show which 3D Printers for construction are available and their improvements so far. For the comparison between 3D printers (Table.1) location and price are taken into consideration. Starting with location, to fulfil one crucial objective of this thesis "…this innovation in Albania specifically in Tirana is possible and it is the most efficient solution for affordable housing for low-income families." it is needed to find the closest place to Albania where 3D printers are produced and later transported. As it is seen above the closest ones are first BetAbram P1 located in Slovenia, second BigDelta WASP 12MT and DeltaWASP Crane which are located in northern Italy, third CONPrint3D located in Germany, fourth CyBe RC 3Dp located in Netherlands, BOD2 located in Denmark and MAXI Printer located in France, and the fifth Vulcan II & Apis Cor 3D Printer both located in United States. Regarding the cost the cheapest printer is BetAbram P1 at 32,000 €, the medium cost printers are DeltaWASP Crane at 132,000 € and CyBe RC 3Dp at 186,427 €, for higher than medium cost printer is BOD2 at 272,820 €, expensive printers are Vulcan II at 409,230 € & MAXI Printer at 495,168 € and 3 printers don't have information about the price which are Apis Cor 3D Printer, BigDelta WASP 12MT, and CONPrint3D.

Table 2. 3D Printers Dimensions and maximum Number of Floors

Nr.	3D Printer	Width, m	Length, m	Height, m	Radius, m	Footprint area, m^2	Building Volume, m^3	Nr. Floors
1	Vulcan II	11.1	∞	3.2	-	∞	∞	1
2	BOD2	14.6	50.52	8.1	-	737.6	6012	2
3	BetAbram P1	9	16	2.5	-	144	328	1
4	MAXI Printer	9.5	9.5	3.3	6.1	116.8	385	1
5	CyBe RC 3Dp	∞	∞	3.5	3.2	32.2	112.5	1
6	Apis Cor 3D Printer	∞	∞	3.1	5.5	95	295	1
7	BigDelta WASP 12MT	7	7	12	-	23.4	280.8	3
8	CONPrint3D	-	-	-	-	-	-	>2
9	DeltaWASP Crane	6.3	6.3	3	3.15	31.2	93.5	1

Moving to the second table (Table.2) where there are shown printing dimensions, area, volume, and number of floors. To find the best 3D printer in this case it is needed to compare the volume and number of floors for each 3D printer for construction shown in the table above. As it is seen, for the volume the best 3D printer is Vulcan II which can print infinite m^3, following is BOD2 which can print 6012 m^3, next are MAXI Printer that prints 385 m^3, BetAbram P1 328 m^3, Apis Cor 3D Printer 295 m^3, and BigDelta WASP 12MT 280.8 m^3, going with the 3D printers that can print less volume which are CyBe RC 3Dp which can print 112.5 m^3, and DeltaWASP Crane that prints 93.5 m^3, and the last 3D printer does not have any information about the volume. Moving with the maximum number of floors were CONPrint3D and BigDelta WASP 12MT can build up to 3 floors and more in the case of CONPrint3D, after them the only one that can print 2 floors is BOD2, and all the rest can print only 1 floor high with the given specifications from each company.

Table 3. Materials and Specifications of 3D Printers

Nr.	3D Printer	Material	Printing Speed, cm/sec	Nozzle Diameter, mm	Accuracy, mm	Nr. Of Axis
1	Vulcan II	Lavacrete	12.7 - 25.4	50	-	3
2	BOD2	Concrete	100	20 - 50	-	3
3	BetAbram P1	Concrete	50	40	-	3
4	MAXI Printer	Concrete	30	20 - 50	10	5
5	CyBe RC 3Dp	CyBe Mortar	50	25.4	0.15	6
6	Apis Cor 3D Printer	Concrete	16.7	-	0.2	5
7	BigDelta WASP 12MT	Long Fiber mix.	40	-	-	4
8	CONPrint3D	Concrete	15	30 - 50	5	5
9	DeltaWASP Crane	Clay	30	18 - 30	-	3

In the next table above (Table.3) there are shown information about the material used from each 3D printer, printing speed in cm per sec, nozzle diameter in mm, printing accuracy in mm and number of axis. For better results for 3D printers study material and printing speed are compared. Starting with the materials the best materials are those who are ecological where BigDelta WASP 12MT and DeltaWASP Crane use respectively long fiber mixture and clay, next is Vulcan II which uses lavacrete, following we have CyBe RC 3Dp which uses its custom mortar and all the rest use concrete. For the printing speed the fastest one so far is BOD2 at 100 cm/sec, following is BetAbram P1 and CyBe RC 3Dp at 50 cm/sec, next is BigDelta WASP at 40 cm/sec, after that are MAXI Printer & DeltaWASP Crane at 30 cm/sec, in the end the slowest are Vulcan II at 25.4 cm/sec, Apis Cor 3D Printer at 16.7 cm/sec and CONPrint3D at 15 cm/sec.

Table 4. Number of operators and Software for 3D Printers

Nr.	3D Printer	Nr. Of Operators	Autonomous Movement	Additional Equipment	Software	Device
1	Vulcan II	4 - 6	YES	YES	BuildOS	Smartphone
2	BOD2	2	NO	YES	COBOD Slice	Laptop
3	BetAbram P1	2	NO	YES	Betabram	Laptop
4	MAXI Printer	2	NO	YES	C3D Slicer	Laptop
5	CyBe RC 3Dp	2	YES	YES	CyBe Artysan	Laptop
6	Apis Cor 3D Printer	2	YES	YES	Apis Cor	Custom Tabl.
7	BigDelta WASP 12MT	2 - 4	NO	NO	-	-
8	CONPrint3D	2 - 4	YES	YES	Cura	Laptop
9	DeltaWASP Crane	2 - 4	NO	YES	WASP	Laptop

In the last table (Table.4) there are shown information about the required number of operators, if the 3D printer has autonomous movement or not, if it has additional elements or not, what software it uses and in what device is this software used. To have better analysis for 3D printer comparison number of operators is chosen. As it is seen form the table above BOD2, BetAbram P1, MAXI Printer, CyBe RC 3Dp, and Apis Cor 3D Printer require 2 people to operate during the printing process, BigDelta WASP 12MT, CONPrint3D, and DeltaWASP Crane require 2 to 4 people to operate, and Vulcan II requires 4-6 people to operate.

2.2. Case studies

There are numerous projects that are finished in the world now. A few of them made up to the headlines of the best world journals like ArchDaily. They are vast in terms of shape, idea, structure, number of floors, technique used, type of 3D printer, materials, and time it took to finish them. For the purpose of this thesis the case studies will be separated in subchapters based on the 3D printing technology.

2.2.1 Buildings done with gantry 3D printer

- Case study 1: *3D-Printed Neighborhood for low budget residents*

To begin with, a whole neighborhood is being built in Tabasco, Mexico. It is a series of the same typology houses measured at 46.5 m^2 for each unit [45]. Its purpose is to help low-income dwellers in this area to have an affordable place to live, costing only 18.5 € a month which are collected to improve the neighborhood. These small houses are 1 floor height and are being built in 24 hours each [46]. They have some additional elements like porch roof (Fig.29). The 3D printer they use is ICON Vulcan II, a gantry technology printer which allows to print an unlimited length and has a specific material lavacrete. The walls are curved in the corners and in both sides of the door (Fig.30). After the 3D printing is done a terrace is constructed in the traditional way. The company have estimated that the total construction cost was about 3700 € for each unit.

Figure 29. Two house units already finished, image source [46]

Figure 30. 3D-Printed walls, image source [46]

- Case study 2: *Micro-Cabin 3D-Printed with bioplastics*

Another unique building printed with a gantry 3D printer is located in Amsterdam, Netherlands. It is printed from XL 3D Printer and DUS Architects with a bioplastic material that can be reused again to print another building. This building is not at a house scale rather it is considered a mini cabin (Fig.31) because of its small scale 8 m^2 [47]. All it includes is a bed and a bathtub (Fig.32) printed outside the cabin [48]. The shape of this mini cabin is all organic and the walls are wide and stable due to the additional material poured in a shape of "X" between two layers of the wall (Fig.33) that of the exterior and interior [49]. Not much information is given for the printing speed or the time it was needed to be constructed, but DUS Architects vision is to implement this in larger projects like residences.

Figure 31. Micro-Cabin, image source [47]

Figure 32. Micro-Cabin Bathtub, image source [47]

Figure 33. Bioplastic Wall section, image source [49]

- Case study 3: Modern *2-storey house 3D-Printed*

A 2-storey house was built by BOD 2 3D printer in Westerlo, Belgium (Fig.34). It is printed in one volume from the footprint to the roof in 504 hours or 3 weeks [50]. The total area of this house is 90 m^2. For the first-floor slab and the roof it is not used a 3D printer but it is constructed in a traditional way with steel and wood (Fig.35). The shape of the building is not organic but rather with conventional and it looks like any other contemporary 2-storey high house. The material used is concrete a common material that BOD 2 3D printer uses in its buildings. Also, it is stated that in the future this kind of house will be printed in not more than 48 hours or 2 days and it will not be only 2 floors maximum.

Figure 34. Westerlo 3D printed 2-storey high house, image source [50]

Figure 35. Floor slab, image source [50]

- Case study 4: *3D-Printed Neighborhood for homeless*

Next project from ICON Vulcan II is still for a neighborhood but now located in

Austin, Texas, United States. It is composed of small 46.5 m^2 1 floor houses that are available for homeless people [51]. The speed in which each house was printed is 27 hours. The houses are conventional and composed of additional roof made after the printing process is done (Fig.36). Due to Vulcan II restricted printing width but unlimited printing length, these buildings are placed in series in a rectangular concrete footing platform which creates some private spaces in between houses (Fig.37). The material it was used is lavacrete which is unique for Vulcan II 3D printer [52]. The cost of each building to be constructed is 3700 € same as Mexico neighborhood.

Figure 36. Flat roof house, image source [51]

Figure 37. Series of houses, image source [52]

- Case study 5: *Contemporary 2-storey 3D-Printed house*

First 2-storey house in Germany is 3D printed by BOD 2 (Fig.38) for a total 100 hours of printing time spread in 10 months of total construction time [53]. The material used is concrete and the total area of this building is 160 m^2 which is impressive compared to the 2-storey house 90 m^2 built in Westerlo, Belgium. It has a slab and a flat roof which are completed after the printing is done with a traditional method of construction with concrete and steel. This house is fully functional with all equipment and in some cases the 3D printer gave shape to furniture like the bathtub (Fig.39). It is stated from the company that it took 5 minutes to print 1 m^2 of the double skin wall [54]. Also, it has become famous around the world because of the design like a compact contemporary house and the technology involved to construct this building.

Figure 38. 3D printed house in Germany, image source [55]

Figure 39. 3D printed house in Germany interior, image source [54]

- Case study 6: *A* 3D-*Printed Typical American house*

Most of BOD 2 buildings have an astonishing printing time but a house built in Virginia, United States was completed in 12 hours. This speed is for the 3D printing only because the additional elements such as the roof and porch were completed after the printing was finished (Fig.40). It is 1-storey high and have an area of 111.5 m^2 [56]. It is made from concrete mixture which is stated that withstands harsh climate conditions like tornadoes (Fig.41). This house has a conventional design and it looks like most common American houses.

Figure 40. 3D printed house in Virginia, image source [57]

Figure 41. Virginia house wall material, image source [56]

- Case study 7: *First 3D*-Printed *School in the World*

Another building printed by BOD 2 is first ever 3D printed school in the world which is located in Malawi. It is composed of a volume 1-storey high conventional design (Fig.42) and its area is not more than 56 m^2 [58]. Area of this school is small compared with most of the schools out there but in Africa they usually conduct lesion outside the building which in this case the surface of one of the outer walls was painted and later on there was placed a blackboard for kids to be able to have a class outside the building (Fig.43). An additional element or structure is the roof which is constructed after the printing is done [59]. Also, it is said that the printing was finished after 18 hours which is less than a day. As for the material they used a mixture of concrete.

Figure 42. School interior, image source [59]

Figure 43. School outside class, image source [59]

- Case study 8: *Largest 3D-Printed building with traditional concrete*

Most of the 3D printed buildings use a custom mixture of concrete but in Muscat, Omani BOD 2 has printed 1 floor heigh house using real concrete with no additives added (Fig.44). It is a big house counting 190 m^2 which includes 3 bedrooms and bathrooms, kitchen, living room and a space for guests [60]. This building was built in 120 hours or 5 days which is the time needed for printing to finish. After that a roof slab was added as an additional structure because the shape of this building is not organic but rather composed of conventional like most BOD 2 buildings [61].

Figure 44. School outside class, image source [60]

- Case study 9: *3D*-Printed *3-story residential unit*

A new 3-storey residential unit is planned to be constructed in Dublin, Ireland. It has a total area of 430 m^2 and it has a conventional design [62]. As for the material it is same as other BOD 2 buildings that of concrete mixture. Also, it is though that the printing time for this building will be 288 hours or 12 days. There will be additional elements or structures like third floor façade tiles and a roof (Fig.45).

Figure 45. Residence render, image source [62]

2.2.2 Buildings done with robotic arm 3D printer

- Case study 10: *3D-Printed house rented by a couple*

Such as gantry technology have many projects done and may more to come even robotic arm technology for 3D printers has great and innovative projects. Starting with the first located in Eindhoven, Netherlands which is 1-storey high [63]. It is constructed by combining building elements of walls which were 3D printed by Weber Beamix in place near the site [64]. These pieces were transported and mounted in the already constructed foundations. Its shape came to be an organic boulder (Fig.46). The total area of this house is 94 m^2. It took 120 hours or 5 days to print all the pieces [65]. After the printed elements are settled then the roof slab is constructed separately in a traditional way. This house is given for rent to a retired couple.

Figure 46. Eindhoven 3D printed house, image source [63]

- Case study 11: *3D-Printed cabin for couples to live in during pandemic lockdown*

Pandemic times were difficult for most of the world. As a result, a question was raised, having as a main concern whether the buildings were appropriate for lock down period or not. An example came from Colorado, United States which printed 3 small cabins (Fig.47) connected to each other measuring up an area of 20.7 m^2 [66]. It was used three-axis SCARA 3D printer for this 1 floor high cabin. The material used for this organic cabin was adobe which was taken from nearby area [67]. This cabin is made for couples and has a bed, bathtub, and a fireplace in the middle where the entrance door is placed (Fig.48). It was used an inflatable roof to help during the rain which for this location is rare because yearly precipitation is 228 mm [68]. The door handle was also 3D printed using aluminum from cans found nearby.

Figure 47. Casa Covida, image source [66]

Figure 48. Casa Covida interior, image source [68]

- Case study 12: *Largest 3D-Printed building in the world*

What is considered world's largest 3D printed building is located in Dubai, United Arab Emirates. It functions as the new building for Dubai municipality and is 2-storey high [69]. The 3D printer used for this building was Apis Cor 3D Printer. The total area for this building is 640 m^2 and its design is conventional which is appropriate for the 3D printer that was used (Fig.49). To reinforce the concrete printed walls there are used steel bars (Fig.50) [70]. The 3D printer was moved in different spots to pour the concrete because to its maximum radius. They made the 1st floor slab and roof slab using the traditional method.

Figure 49. Dubai municipality, image source [70]

Figure 50. Dubai municipality reinforcement, image source [70]

- Case study 13: *3D-Printed Laboratory*

A 3D printed Laboratory (Fig.51) for drones was constructed in Dubai, United Arab Emirates a state which is promoting 3D printing for buildings. This organic building is made of concrete mixture and it is 1 floor high [71]. The area is 168 m^2 and the walls were printed separately and then mounted on site (Fig.52). It was constructed by CyBe RC 3Dp robotic arm 3D printer in 504 hours or 3 weeks but the time required to print all the pieces is 48 hours or 2 days. They built the roof slab in a traditional construction way. Also, they used the CyBe custom software to help during design and construction [72].

Figure 51. Dubai drone laboratory, image source [71]

Figure 52. Dubai drone laboratory building pieces, image source [71]

- Case study 14: *3D-Printed Toilet units*

Another building printed form CyBe RC 3Dp is located in Japan. It is made of 2 separate small toilet units which total area is 16 m^2 [73]. They are 1 floor high and the time it took to print them is 60 hours. They shape is organic (Fig.53) and are equipped with all necessary equipment for their purpose. Also, as an additional element or structure there is constructed a roof slab for both buildings. They also have reinforcement with steel bars connected to the foundation slab (Fig.54).

Figure 53. Toilet units, image source [73]

Figure 54. Toilet units steel bars, image source [73]

- Case study 15: *Organic 3D-Printed building*

A commercial building which is planned to be built in 240 hours or 10 days is located in Netherlands [74]. It will have an area of 100 m^2 and it will be 1 floor high (Fig.55). The shape will be totally organic which means that there will not be any additional structure element such as the roof slab. The printer that will 3D print this building is CyBe RC 3Dp [75]. The roof elements will be printed after the walls are done (Fig.56).

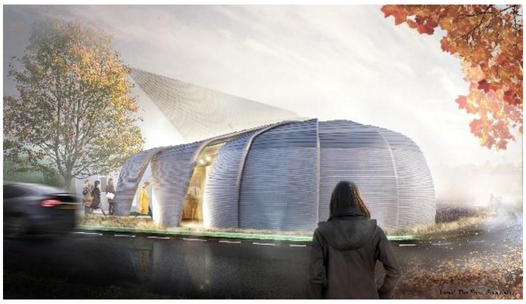

Figure 55. Building Render, image source [74]

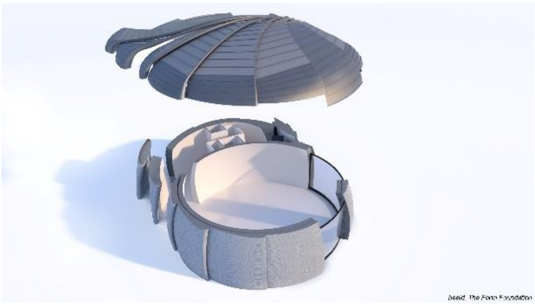

Figure 56. Building Construction Diagram, image source [74]

- Case study 16: *Efficient 3D*-Printed *normal house*

Furthermore, CyBe RC 3Dp printed another building, a house located in Saudi Arabia (Fig.57). It has a total area of 80 m^2, 1 floor high and it was printed in 168 hours or 1 week [76]. In this case the roof slab is not 3D printed but made after the printing is done. This building walls are modular which means that each wall piece is printed separately (Fig.58).

Figure 57. Saudi Arabia House, image source [76]

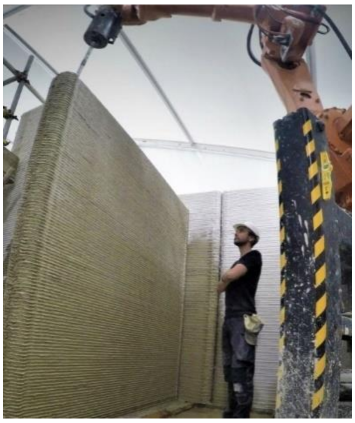

Figure 58. Saudi Arabia House walls, image source [76]

- Case study 17: Affordable *3D-Printed small house*

The first fully functional 3D printed house that was made by Apis Cor 3D Printer is located in Russia. For which is stated that it can resist up to 175 years not damaged [77]. The total area is 37.2 m^2 and it is 1 floor high (Fig.59). It has a conventional design. The speed that it was printed is 24 hour or 1 day. Also, a cost is estimated for this building with the value of 10,150 € that is more affordable than traditional houses for the same specifications. Roof slab is constructed after the printing is done.

Figure 59. Apis Cor 1st 3D printed house, image source [77]

2.2.3 Buildings done with cable 3D printer

- Case study 18: EREMO *3D-Printed nature house*

Buildings printed by cable technology 3D printers are still in an experimental phase because even 3D printers of this technology are in an empirical development. That so there is one building in experimental phase which is constructed by BigDelta WASP 12MT in Italy [78]. It is made from a material that is a mixture of lime, sand, dirt, and straw which is durable and strong. This organic house is small with an area of 50 m^2 and 1 floor high (Fig.60). This building is printed in 24 hours or 1 day. It has a custom roof composed of glazing and wooden roof [79].

Figure 60. Small House in Italy, image source [79]

2.2.4 Buildings done with mixed 3D printer

- Case study 19: TECLA *3D-Printed clay house prototype*

A promising 3D printing technology is that of mixed 3D printers where

DeltaWASP Crane is responsible for many buildings around the world. Starting with, a prototype house which was called TECLA located in Italy. Its shape is fully organic which means that there was not build any additional structural element like roof slab but rather a circular glazing panel for skylight. TECLA is composed of 2 volumes at 1 floor high which are connected to each other (Fig.61). The total area is 60 m^2 and it took 200 hours or little more than a week [80]. This house is an innovative project because of the material it used, clay (Fig.62) which was taken from the nearby area and reinforcements such as straw. It is stated by the architect who designed this building Mario Cucinella that the aim is to build the future using ancient materials and ways of building.

Figure 61. TECLA, image source [80]

Figure 62. TECLA material, image source [80]

- Case study 20: *GAIA 3D-Printed ecological house*

Another project done by DeltaWASP Crane is also located in Italy. It is called Gaia, (Fig.63) because it's a small house built with clay mixed with other biomaterials and timber for the additional elements such as the roof slab [81]. That so this house is considered ecological where straw is also used as an insulation material placed in the wall voids (Fig.64). The area is 30 m^2 and the time it took to print it is 100 hours or less than 5 days. It has an organic shape to its walls and a circular footprint [82]. It is mentioned that its construction cost is estimated to be 900 € which means that 30 € per m^2.

Figure 63. Gaia, image source [81]

Figure 64. Gaia material and insulation, image source [81]

- Case study 21: *Dior 3D-Printed store*

Furthermore, Dior has chosen DeltaWASP Crane to 3D print its pop-up fashion store located in Dubai, United Arab Emirates. It is composed of 2 volumes 1 floor high unconnected with each other and elevated from the ground by a wooden platform (Fig.65). As for additional structural element they have a roof slab. The design is modern and conventional. Their total area is 80 m^2 and the total printing time is 120 hours or 5 days [83]. The material used is also ecological.

Figure 65. Dior store, image source [83]

- Case study 22: *3D-Printed sculpture with earth mixture*

Next building 3D printed by DeltaWASP Crane is located in Germany [84]. It is small and it functions as a sculpture for 75th anniversary of the land of Hesse [85]. It has an organic shape and an area of 16 m^2 (Fig.66). The additional elemens that were used for this building are wooden support for roof slab and the wooden roof slab which has a circular cut used for skylight. This sculpture was 3D printed in 50 hours or 2 days and 2 hours. As for the material there are also used biomaterial (Fig.67) because the ecological policy that WASP have.

Figure 66. Hesse Sculpture, image source [84]

Figure 67. Hesse Sculpture material, image source [85]

2.2.5 Comparison between the case studies

Table 5. Building specifications for Case Studies

Case Study	Function	Area, m^2	Nr. Of Floors	Design Feature	Material	Additional Structures and Elements
1	Residential	46.5	1	Conventional	Lavacrete	Porch Roof / Roof Slab
2	Micro Cabin	8	1	Organic	Bio-Plastic	-
3	Residential	90	2	Conventional	Concrete	Steel Slab & Roof
4	Residential	46.5	1	Conventional	Lavacrete	Roof Slab
5	Residential	160	2	Conventional	Concrete	Steel Slab & Roof Slab
6	Residential	111.5	1	Conventional	Concrete	Porch / Roof
7	School	56	1	Conventional	Concrete	Roof
8	Residential	190	1	Conventional	Concrete	Roof Slab
9	Residential	430	3	Conventional	Concrete	Façade Tiles / Roof
10	Residential	94	1	Organic	Concrete	Roof Slab
11	Small Cabin	20.7	1	Organic	Adobe	-
12	Municipality	640	2	Conventional	Concrete	Steel Slab & Roof Slab
13	Laboratory	168	1	Organic	Concrete	Roof Slab
14	Toilet Units	16	1	Organic	Concrete	Roof Slab
15	Commercial	100	1	Organic	Concrete	Roofing
16	Residential	80	1	Conventional	Concrete	Roof Slab
17	Residential	37.2	1	Conventional	Concrete	Façade Stucco / Roof Slab
18	Residential	50	1	Organic	Natural	Roof Glazing / Roof
19	Residential	60	1	Organic	Clay	-
20	Residential	30	1	Organic	Mud mixture	Roof Slab
21	Store	80	1	Conventional	Natural	Deck / Roof Slab
22	Sculpture	16	1	Organic	Natural	Wood Support for Roof Slab / Wood Roof Slab

In the case studies section 22 buildings around the world that were printed by a 3D printer were described. In the table above (Table.5) are shown information such as building function, area in m^2, number of floors, design feature, material, and additional structures and elements for each building. As it is seen from the table 13 buildings are residential, 2 are cabins, 1 is school, 1 is municipality, 1 is a drone laboratory, 1 is toilet units, 1 is commercial, 1 is store and the last one is a sculpture. The buildings with the largest area are case study number 12 at 640 m^2 and case study number 9 at 430 m^2. Most of them are one floor high, but case number 9 is the highest at 3 floor high, followed by case studies number 3,5,12 at 2 floor high. Also, for the design feature it is seen that 12 of are conventional which means that there is not given any angle in z direction of the walls but they are rather straight and sometimes with a curved footprint in the corners, 10 other buildings are organic which means that the walls are not straight in the z direction thus they have a specified angle and in some cases the whole building is organic which looks like a shell structure. As for the material 13 buildings use concrete, 2 use lavacrete, 1 uses bioplastics and the others use natural materials such as clay, adobe, and mud. Buildings which don't have any additional structures or elements are those which have an organic design and are totally 3D printed without a roof or roof slab made after the printing is done.

Table 6. Case Studies General Information

Case Study	Stage of Construction	Construction Time, hours	Building Speed, m^2/hr	3D Printer Type	3D Printer Name	Location
1	Under Construction	24	1.9	Gantry	Vulcan II	Mexico
2	Completed	-	-	Gantry	XL 3D Printer	Netherlands
3	Completed	504	0.2	Gantry	BOD2	Belgium
4	Completed	27	1.7	Gantry	Vulcan II	US
5	Completed	100	1.6	Gantry	BOD2	Germany
6	Completed	12	9.3	Gantry	BOD2	US
7	Completed	18	3.1	Gantry	BOD2	Malawi
8	Completed	120	1.6	Gantry	BOD2	Oman
9	Planned	288	1.5	Gantry	BOD2	Ireland
10	Completed	120	0.8	Robotic Arm	Weber Beamix	Netherlands
11	Completed	-	-	Robotic Arm	three-axis SCARA	US
12	Completed	-	-	Robotic Arm	Apis Cor 3D Printer	UAE
13	Completed	504	0.3	Robotic Arm	CyBe RC 3Dp	UAE

14	Completed	60	0.3	Robotic Arm	CyBe RC 3Dp	Japan
15	Planned	10	10.0	Robotic Arm	CyBe RC 3Dp	Netherlands
16	Completed	168	0.5	Robotic Arm	CyBe RC 3Dp	Saudi Arabia
17	Completed	24	1.6	Robotic Arm	Apis Cor 3D Printer	Russia
18	Experimental	24	2.1	Cable	BigDelta WASP 12MT	Italy
19	Completed	200	0.3	Mixed	DeltaWASP Crane	Italy
20	Completed	100	0.3	Mixed	DeltaWASP Crane	Italy
21	Completed	120	0.7	Mixed	DeltaWASP Crane	UAE
22	Completed	50	0.3	Mixed	DeltaWASP Crane	Germany

In the up following table (Table.6) other important information like stage of construction, construction time in hours, building speed m2/hour (which is calculated from area dividing the time of construction), 3D printer type, 3D printer name, and the location of each building. For the purpose of this study "…this innovation in Albania specifically in Tirana is possible and it is the most efficient solution for affordable housing for low-income families" 3 columns are considered that of stage of construction, building speed and the 3D printer used. Starting with stage of construction where most of the buildings are completed but case number 1 is under construction, case study number 9 and 15 are planned to be constructed in following years, and case study number 18 is an experimental building, this means that only buildings that are completed will be analyzed. To achieve better results 2 columns information will be merged which means that there will be analyzed the average building speed for each 3D printer. There are 3 3D printers which didn't have information and specifications, thus case study number 2, 10 and 11 will not be considered along with 1,9,15, and 18 which were mentioned earlier. Starting with BOD2 3D printer it is calculated that the average speed of its buildings is 3.16 m2/hour, Vulcan II at 1.7 m2/hour, Apis Cor 3D Printer at 1.6 m2/hour, CyBe RC 3Dp at 0.4 m2/hour, and DeltaWASP Crane at the same as the previous 3D printer 0.4 m2/hour. This means that the fastest 3D printer proved by the completed buildings around the world is BOD2 followed by Vulcan II, Apis Cor 3D Printer, CyBe RC 3Dp and DeltaWASP Crane.

2.3. Summary

In order to find the best 3D printer for construction that fulfils some basic requirements for this thesis objective "…this innovation in Albania specifically in Tirana is possible and it is the most efficient solution for affordable housing for low-income families" seven information and specifications for 3D printers were compared. To make the comparison more accurate, a system of points from 1 to 5 was given to each 3D printer in the specified information or specification which were price (in euro), volume that it can print (in m^2), number of floors, material, speed, and operators. After the theoretical comparison of this information a table was generated that showed information about each 3D printer's points (Table.7). As it is seen form the table below the 3D printer which have the most points is BOD2 (28 points), after that are 5 other 3D printers Vulcan II, BetAbram P1, CyBe RC 3Dp, BigDelta WASP 12MT and Delta WASP Crane (22 points), followed by Apis Cor 3D Printer (18 points), continuing with Maxi Printer (17 points) and in the end is CONPrint 3D (15 points). As a result of it is seen that the concluding order of appropriate and not appropriate 3D printers for construction is as follows, 1st one is BOD 2, 2nd is Vulcan II, BetAbram P1, CyBe RC 3Dp, BigDelta WASP 12MT and Delta WASP Crane, 3rd is Apis Cor 3D Printer, 4th is Maxi Printer, and 5th is CONPrint3D. But this classification is not final because some of the printers are not available to buy such as BigDelta WASP 12MT and CONPrint3D because they are still in an experimental phase. To conclude a more appropriate classification there is needed to be analyzed the case studies specifically the 3D printers which were used. Thus, from the results gathered in (Table.6) for the 3D printers that didn't have any constructed building it was given 0 points and for those which had constructed buildings around the world compared by the building speed the list is as follows BOD2 has 5 points, Vulcan II 4 points, Apis Cor 3D Printer 3 points, and CyBe RC 3Dp along with DeltaWASP Crane 2 points each. This leads to a final result that the most efficient 3D printer for this study is BOD2 followed by Vulcan II, BetAbram P1, CyBe RC 3Dp, BigDelta WASP 12MT and Delta WASP Crane. If we add the information from (Table.5) about the design it is seen that BetAbram P1 doesn't have any buildings completed which automatically removes this option and for the two other 3D printers the difference is the design feature which BOD2 and Vulcan II have a conventional design not organic building, CyBe RC 3Dp has a conventional design but the building constructed by it is made of small modules and BigDelta WASP 12MT along with DeltaWASP Crane which have only organic buildings also it uses natural materials which can drastically lower the cost of construction but the downside is that it can print more than 1 floor high (in case of DeltaWASP Crane). As it is represented in the (Fig.68) a bar chart was generated from 3D printer's total points column. In this case which 3D printer is the most appropriate is found easily and first 3D printer as mentioned above is chosen to be BOD2 and DeltaWASP Crane is chosen to be the second choice for prototype development because different from other 3D printers with the same points the buildings it produces are with an organic shape.

Table 7. 3D printer comparison

Nr.	3D Printer	Price €	Volume m^3	Floors	Material	Speed	Operators	Buildings Done	Total Points
1	Vulcan II	2	5	3	4	1	3	4	**22**
2	BOD2	3	4	4	2	5	5	5	**28**
3	BetAbram P1	5	3	3	2	4	5	0	**22**
4	MAXI Printer	2	3	3	2	2	5	0	**17**
5	CyBe RC 3Dp	3	2	3	3	4	5	2	**22**
6	Apis Cor 3D Printer	1	3	3	2	1	5	3	**18**
7	BigDelta WASP 12MT	1	3	5	5	3	4	1	**22**
8	CONPrint3D	1	1	5	2	1	4	1	**15**
9	DeltaWASP Crane	4	2	3	5	2	4	2	**22**

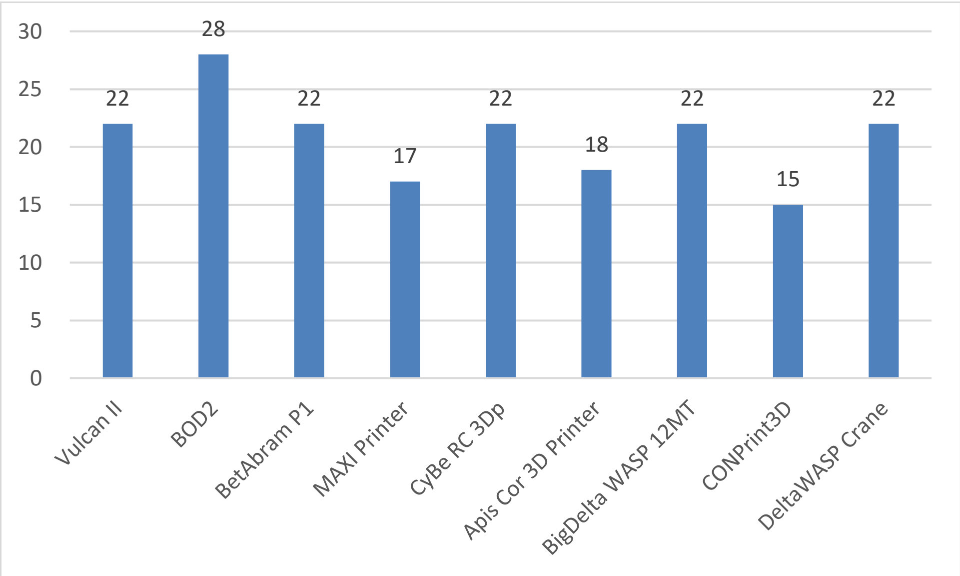

Figure 68. 3D printers scores

To have a better understanding of what design parameters do in each 3D printer it is needed to combine all the information from table 1 to table 6 based on the optimal parameters of the design. Thus, another table (Table.8) that describes optimal design parameters is generated. It explains following parameters for the chosen 3D printers maximum building footprint in meters, building area in m^2, common number of floors, building material, construction time in hours, design features, additional structures and elements, reinforcement, wall type, and roof type. Starting with the maximum building footprint BOD2 has larger dimensions while Delta WASP Crane is less large which leads to 2 limits of building prototypes that are to be designed in this thesis. Moving to the building area which is taken from the already built buildings that were described previously in case studies, BOD 2 has larger buildings compared to Delta WASP Crane. Following is the common number of floors which in both of them the preferred one was 1 floor high. About the material used Delta WASP Crane is more ecological which means it can be cheaper while constructing because it uses natural materials that can be found anywhere. Continuing with the construction time where BOD2 has better results than Delta WASP Crane from the buildings finished by each. About the design feature it is seen that BOD2 buildings are conventional while Delta WASP Crane buildings are organic. From the case studies all the buildings that were 3D printed with BOD2 had additional structures and elements while Delta WASP Crane doesn't add anymore additional structures or elements after the printing is done. They both use reinforcement BOD2 uses steel bars and Delta WASP Crane uses straw as an old way of reinforcement because of their ecological way of building. Wall types in BOD2 are straight but in Delta WASP Crane they are curved. About the roof type BOD2 has a flat roof while Delta WASP Crane has a dome roof. From all these parameters it is seen that both printers are good in what they can build which are very different from each other. Thus, prototypes will be generated based on this results and design features.

Table 8. Optimal Design Prameters

Optimal Design Parameters		
Parameter	**BOD2**	**Delta WASP Crane**
Maximum Building Footprint, m	Rectangle 14.6x50.52	Circle diameter 6.3
Building Area, m^2	56-190	30-80*
Number of Floors	1	1
Building Material	Concrete	Clay, adobe, mud, straw, etc
Construction Time, hours	12-120	100-200
Design Features	Conventional	Organic
Additional Structures and Elements	Roof slab	NO
Reinforcement	YES	YES
Wall Type	Straight	Curved
Roof Type	Flat	Dome
**** The area can be enlarged with the repositioning of the 3D printer***		

CHAPTER 3

SITE SELECTION

3.1. Location

Site is located in Kashar (Fig.69) which is next to the border of Tirana. As a municipality Kashar is part of Tirana. It is in the west side of the city. There are 2 different maps the one in the left to identify the landscaping of that region and the one in the right to show the main roads and waterways. For the site analysis maps QGis software is used.

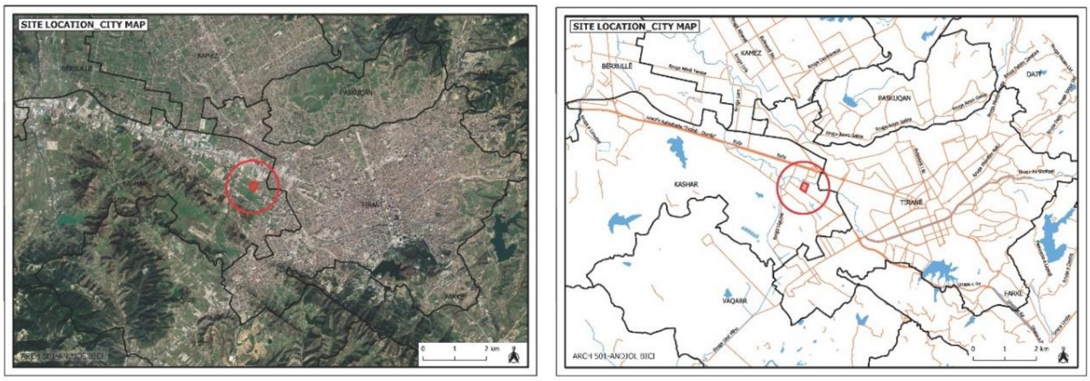

Figure 69. Site location in a large scale

In the next map (Fig.70) is shown the site in relation to the surroundings. Where the satellite map shows the buildings and one next to it shows landscape levels every 1m. The site is located at 75m above the sea level.

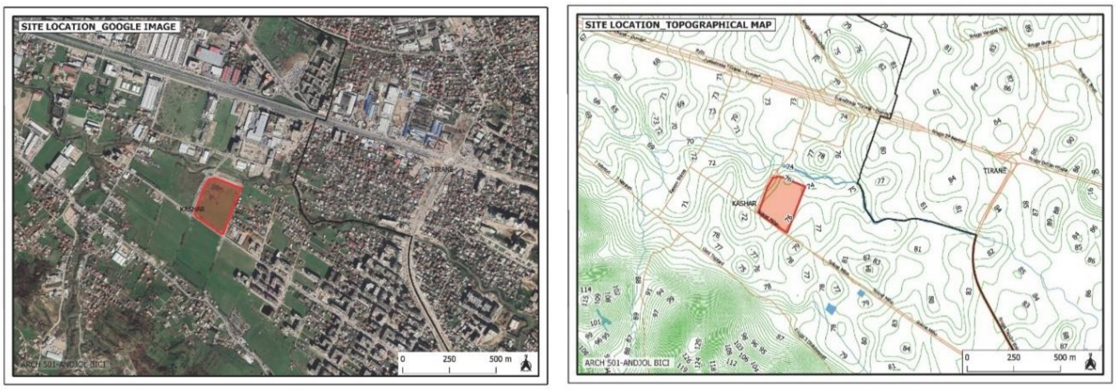

Figure 70. Site location nearby area

The following map shows a satellite image (Fig.71) of the site. As it seen in the map the biggest dimension of the site boundary is that of the length 234 m. The overall area of the site is 45,141 m^2. In the map below (Fig.72) are shown the main roads which are Rruga Karapici & Rruga Sokrat Miho. Also, there are displayed the levels of the site every 1m level. The main entrance to the site is from the highway Tiranë-Durrës (as shown with the red arrow in fig.72)

Figure 71. *Site area*

Figure 72. Site area (levels, main roads, and buildings)

3.2. Planning regulations

One crucial element for the site selection is planning regulations. These regulations are set from National Spatial Planning Agency of Albania and are free for everyone. As it is seen in the figure below (Fig.73) the site is adaptable for this project. Area code is Unit KA/184 where the total plot area in the selected sky-blue color is 9.15 ha. Also, the proposed usage of land is for residential and services at 95% of the total area which means that only 5% of the area will be used for infrastructure. The maximum height that is allowed to be constructed is 5 floors and the total height 17 m. Lastly building coverage ratio (BCR) is 1.6 and floor area ratio (FAR) is 45%. As a conclusion this site has all the settings that are needed to design and built with just a few limitations.

Figure 73. Planning regulations

3.3. Circulation

Circulation analysis of this site is conducted in 4 separate maps. Starting with the first map (Fig.74) which shows the accessibility of the selected site from the closest city of Durres which is located in the west and Tirana International Airport which is located in the north-west referring to the site. There are needed 32 minutes ride from Durres to the selected area using Tirana-Durres Highway. Also, 17 minutes are required to travel by vehicle from site to Tirana International Airport. Other close places to the selected site are Shijak in the west, Fush-Kruje, Manez, Vore and Kamez in the north-west.

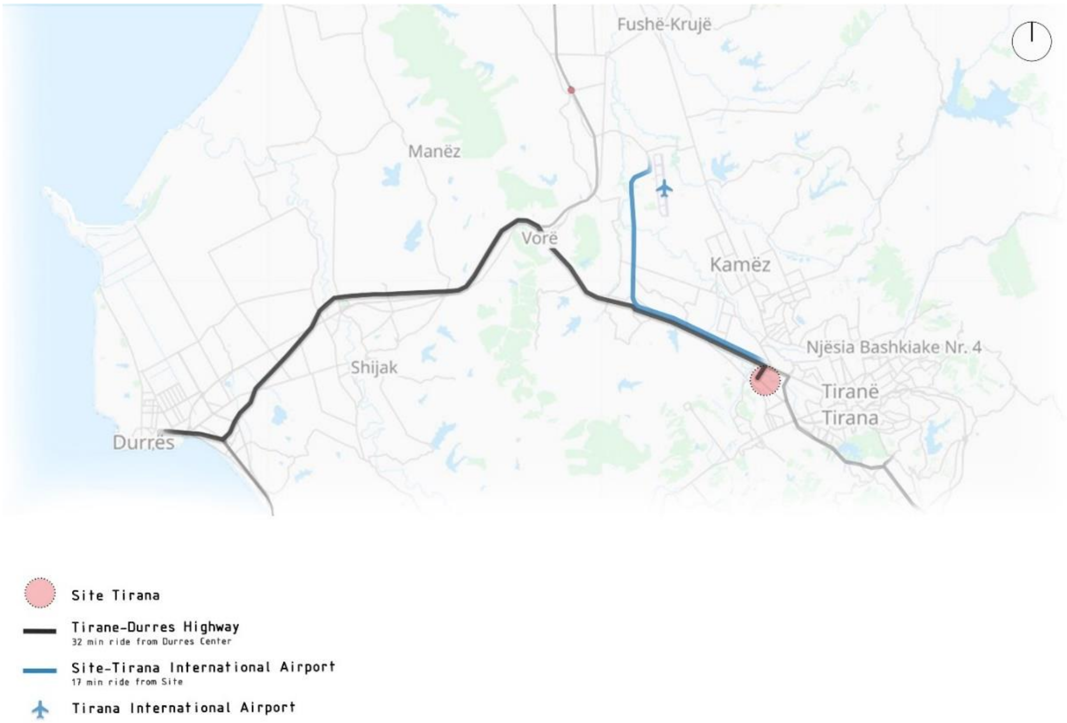

Figure 74. Site access in a macro scale

The next map (Fig.75) shows a closer view of the site and the accessibility in the city of Tirana. The site is located in Fushe (Mezes) which is part of Kashar and Mezez neighborhood. The main roads are classified in highway (black bold) and main artery (red bold). There are needed 18 minutes to ride from the site to Tirana city center (Sheshi Skënderbej) which is shown in an orange bold line and the city center with a red icon. There is one river that passes to this site Lana River (blue bold). Also, for the pedestrians this site can be accessed from the well-known place in Tirana "Casa Italia Overpass" and it is shown with a red bold dashed line. There is a bus line that passes through this area Line 3 [86] which connects Kashar, Yzberisht and the center of Tirana. Neighborhoods to the site are Mezez in the west, Laprake in the north-east, Astir in east and Yzberisht in south-east.

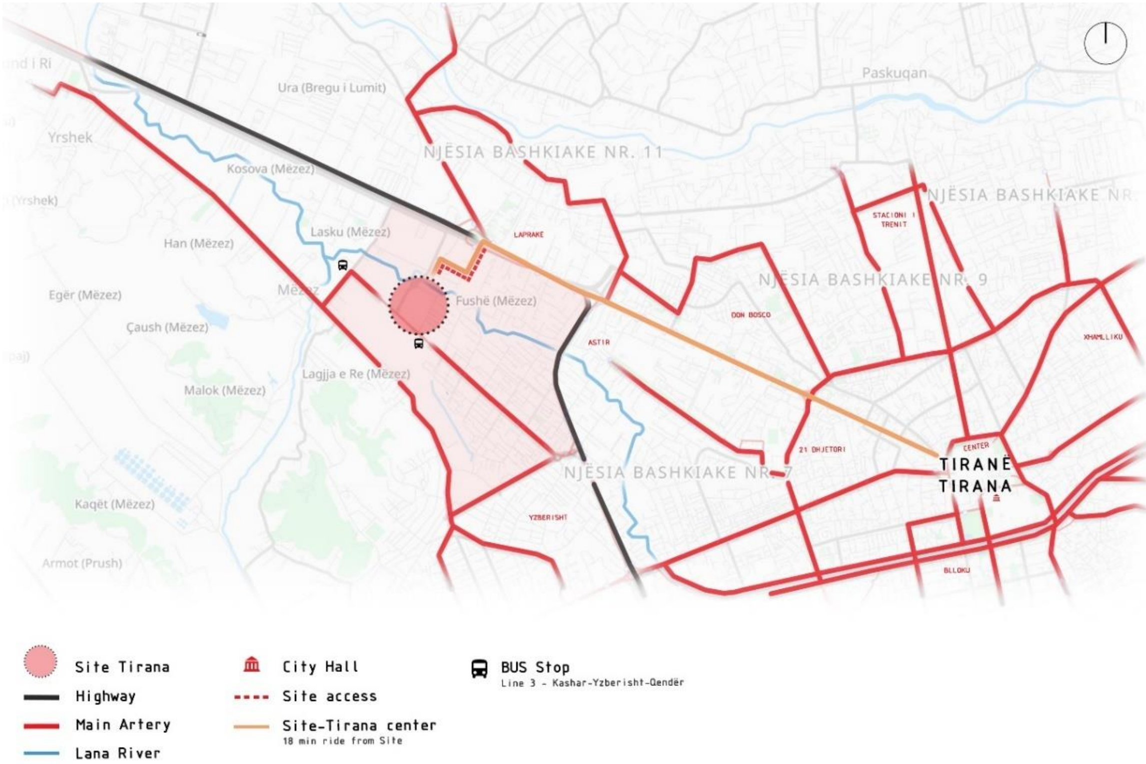

Figure 75. Site access in a city scale

In the following map (Fig.76) is shown a closer view to the site and 4 photos showing some parts of the area condition and infrastructure. There are shown with a red bold line all main roads and with a dark gray line all secondary roads. With a pink line are shown all informal roads. With a red bold dotted line, it is shown the access to this site for the pedestrians. In a blue bold line, it is shown the river that passes through this site, that of Lana River. As it is seen from the photos starting from the first one which is taken in the north-west part of the site, the infrastructure is already finished with an asphalted road and a sidewalk which is decorated with trees. The second photo is captured in the corner which is located in the south part of this selected area, and it shows end of the sidewalk. In the third photo (south-east) is shown an area covered with mud which is part of the site. Going with the last photo which is taken in the north-east part of this site and shows the vegetation of this area.

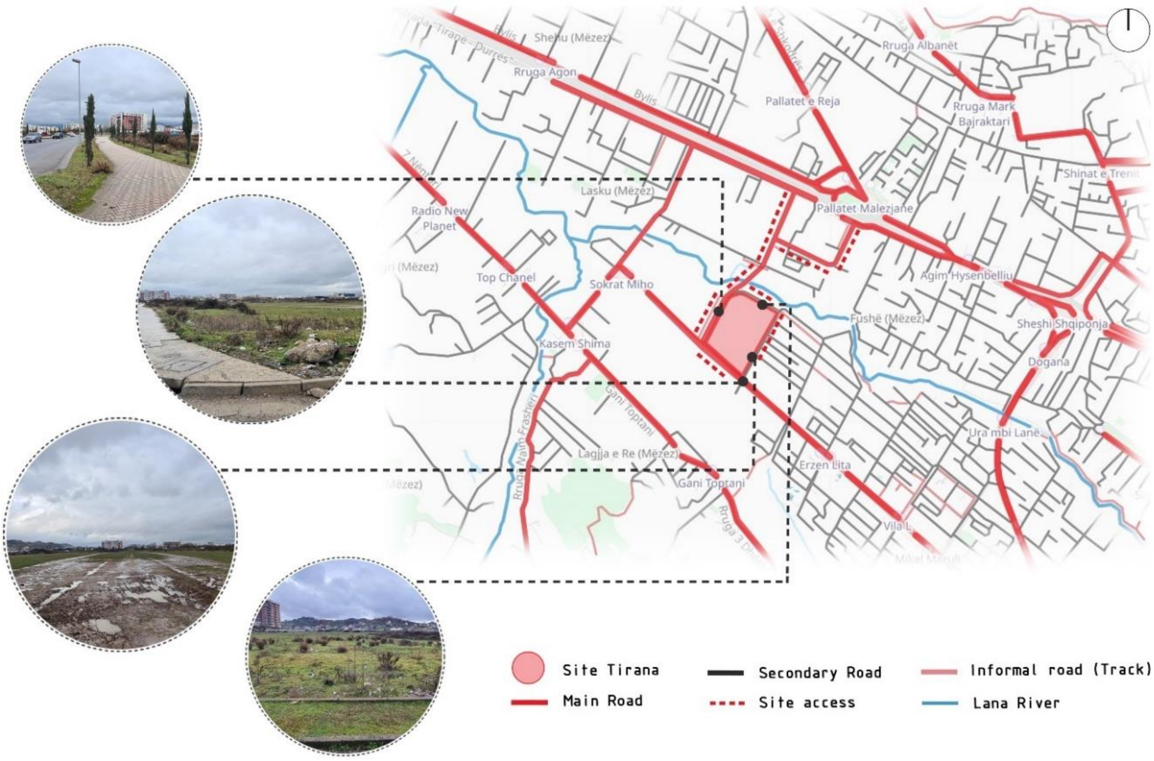

Figure 76. Site main roads and photos

Furthermore, in the last map (Fig.77) is shown the circulation of the area and a close map of the site. In the larger map two lane streets are shown with a dark gray bold line and pedestrian flow with a dark gray line. Above those roads are placed arrows to show the direction of vehicular movement. A yellow line represents the line where informal parking is located. Going at the zoomed map, where the main roads are shown in a red bold line and secondary ones same as in the larger map. Informal roads are shown with a pink line and sidewalks are shown with a brown-gray line. There is shown the main entrance to the site with a big triangle and with smaller ones are shown the entrances of each building nearby. Other potential entrances to this site are shown with a diagonal line hatch.

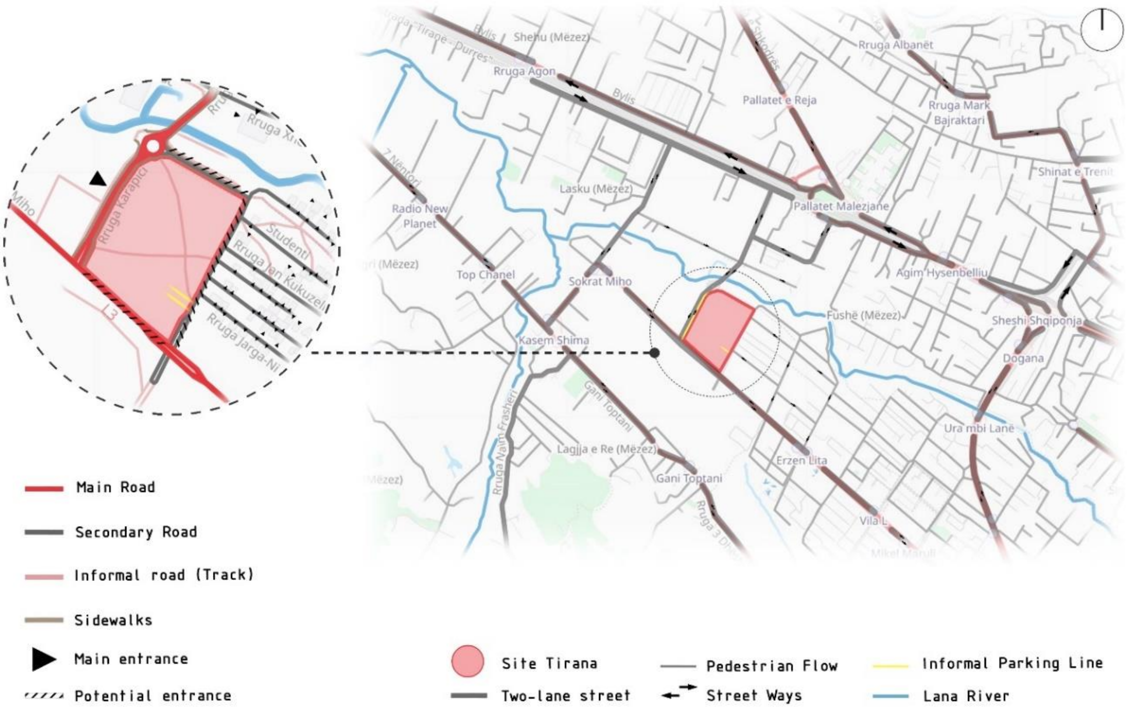

Figure 77. Site circulation maps

3.4. Building heights

The site does not have many buildings near except north, east and south-east direction (Fig.78). In the north part it has buildings mostly 1 to 3 floors which function mostly as warehouses. There is only one high rise building in this part which is more than 9 floor height which function is residential. Then in east and south-east direction there are mostly residential composed with houses 1-3 floors and some of them 4-5 floors. There is a group of high-rise buildings 9+ floors which function is residential. All high-rise buildings ground and first floor are dedicated to the services and entertainment businesses. West and south parts of this area are not developed yet, but from the planning regulations (Fig.73) there can be built residential and commercial units up to 5 floors. More and more buildings are already being constructed in this area so the buildings height map may change in a short time.

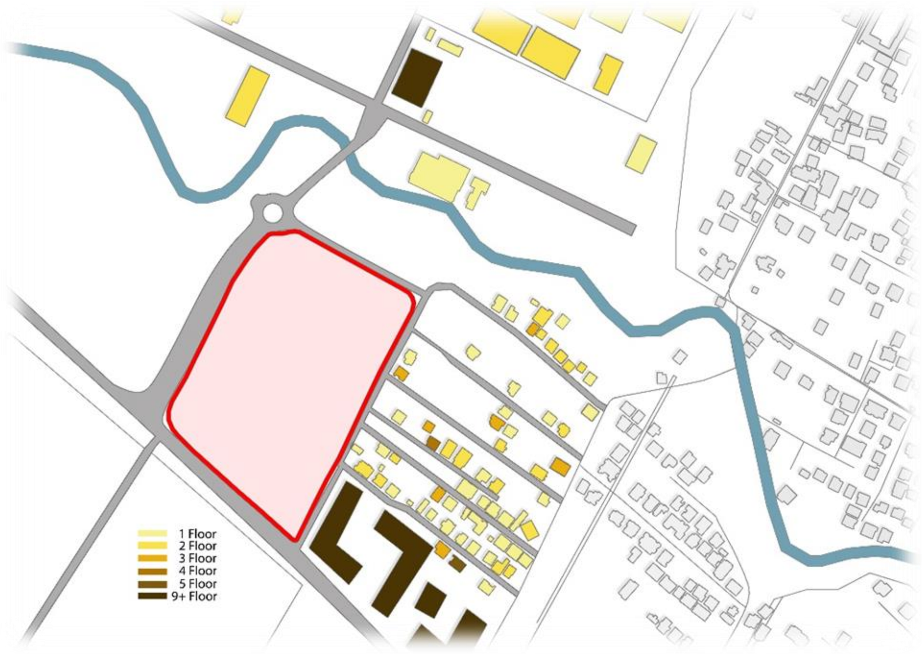

Figure 78. Building heights

3.5. Climate conditions

This site is located in Kashar so the climatic conditions will be analyzed for that area. In the figures below (Fig.8-13) are shown charts of average temperatures and precipitation, cloudy, sunny, and precipitation days, maximum temperatures, precipitation amounts, wind speed and wind rose. Where in the first graph (Fig.8) the highest temperatures are at 31ºC (July and August) and the lowest at 2ºC (January and February).

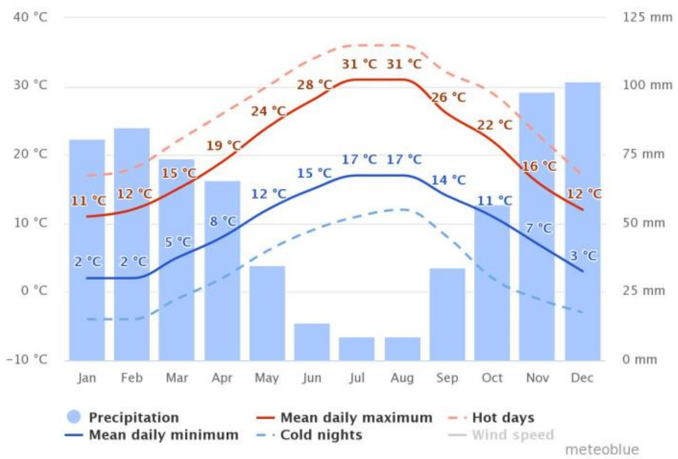

Figure 79. Average temperatures and precipitation graph

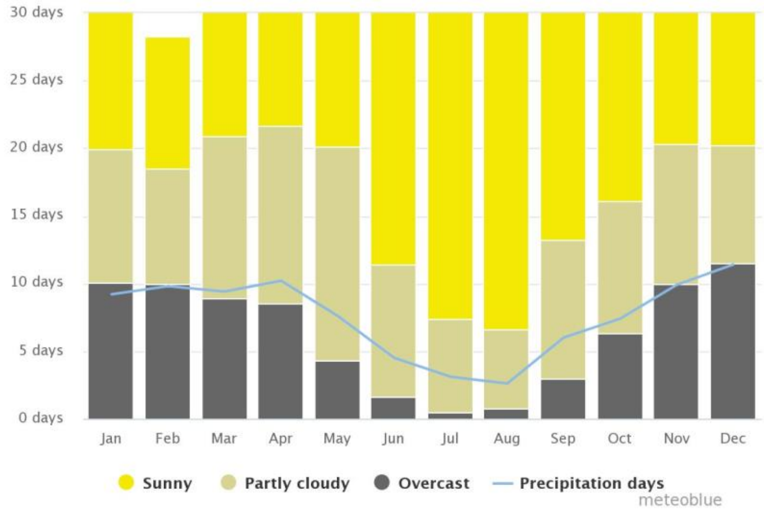

Figure 80. Cloudy, sunny, and precipitation days

In the second chart (Fig.80) is seen the same trend as the previous one where the sunniest days are in July and August at around 24 days and the days with the least are from November to January at 10 days. As for precipitation days from November to April are the highest values at around 10 days but for July and August there are the lowest values at around 3 days.

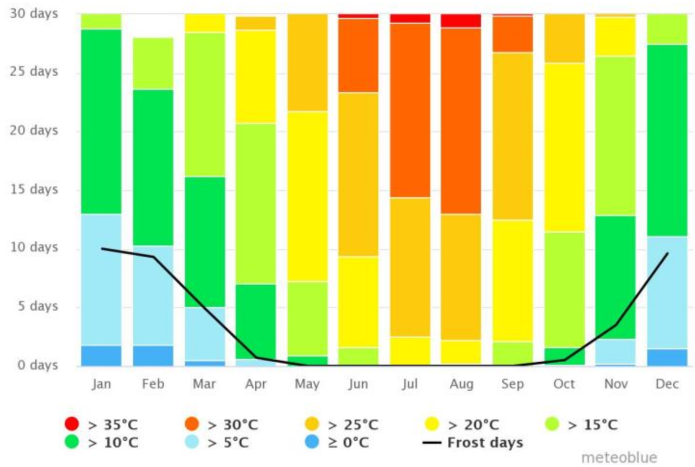

Figure 81. Maximum temperatures

The next chart (Fig.81) shows maximum temperatures for each month in 30 days period. It is seen that the hottest days are during Summer from June to August at above 35 ºC and also in September with around 1 day. The lowest values are from November to April where in January are the lowest values for around 3 days at below 0 ºC.

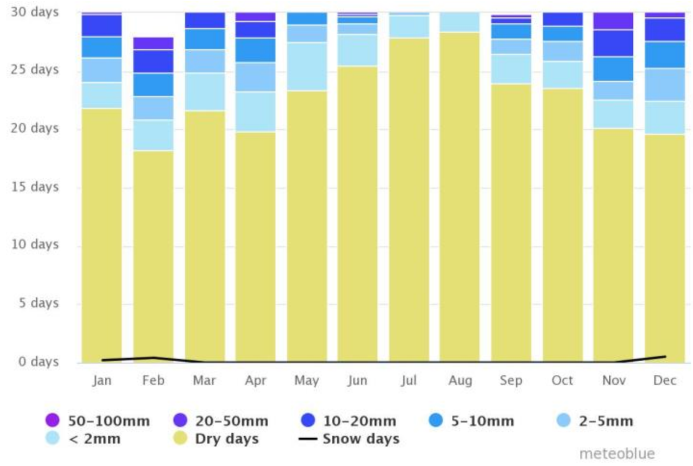

Figure 82. Precipitation amounts

The precipitation levels are now shown with amounts in mm (Fig.82). It is seen that most of the months are dry where lowest values are in July and August at around 3 days over 2 mm and the highest are in November at around 3 days about 20-50 mm. There are not values above 50 mm also there is shown only 1 day in February and 1 day in December that might snow for this area.

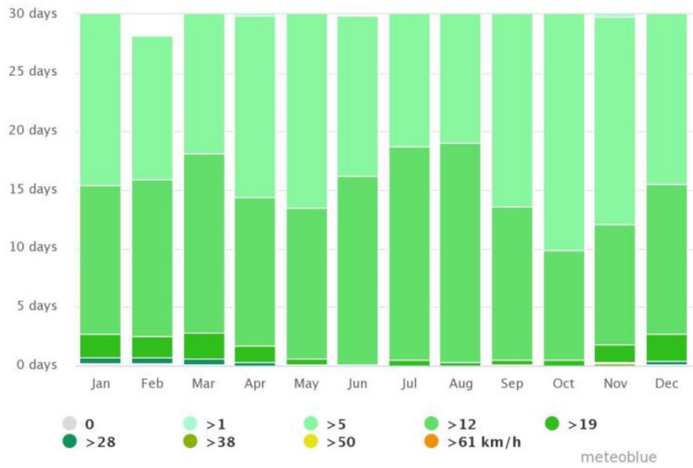

Figure 83. Wind speed

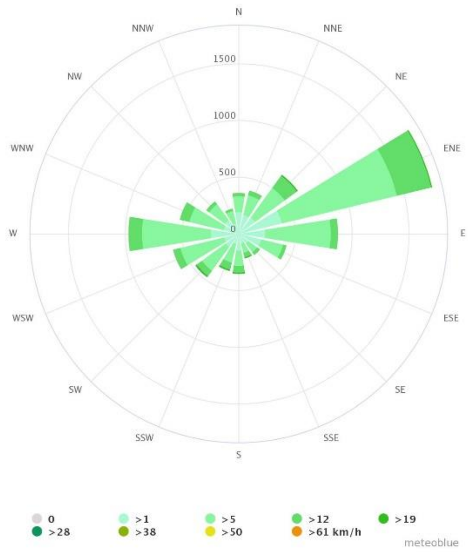

Figure 84. Wind rose

In the last graphs are shown wind speed (Fig.83) and wind rose (Fig.84). Wind speeds are about the same and slow in this area for each month where in June are the lowest values above12 km/hr for around 1 day and from December to March are the highest values above 28 km/hr for around 1 day. In the next graph it is seen that winds rise mostly from East Northeast.

3.6. Vegetation

The site is composed of hardscape, softscape and waterscape (Fig.85). In the hardscape there are included the sidewalks and the roads which are found in all 4 sides of the site. Following is the softscape that includes different types of vegetation such as trees, bushes, and grass. In this site are located cypress trees, hemlock bush, blackberry bush, and helxine grass. Also, in the waterscape there is included Lana River which passes along the north-east side of the selected are.

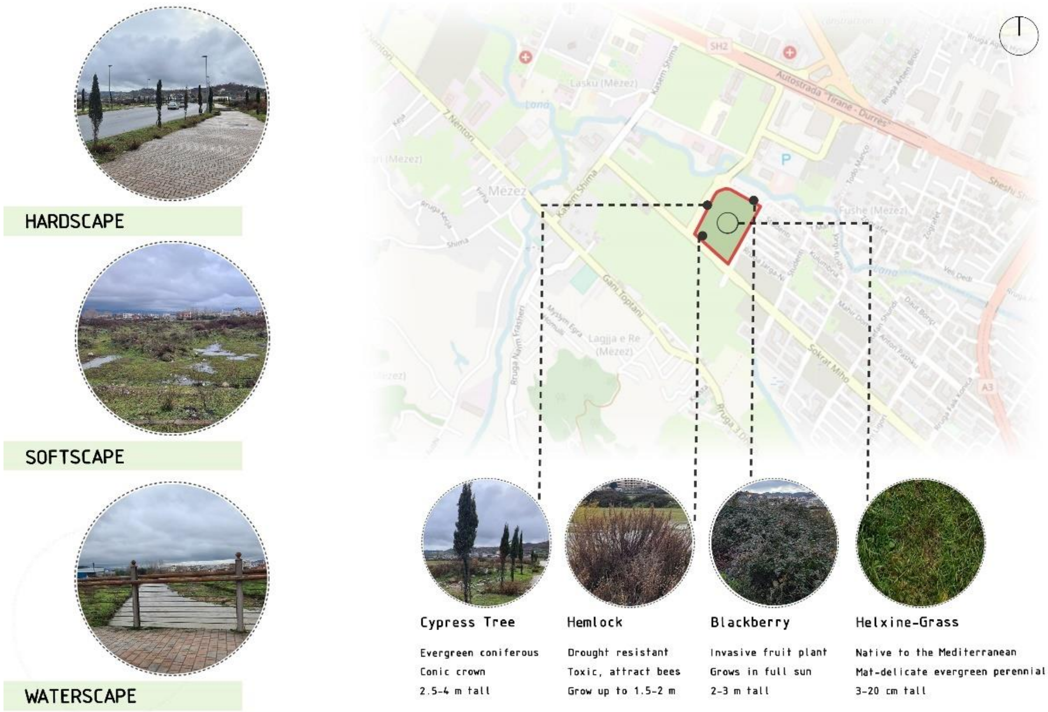

Figure 85. Vegetation analysis

3.7. Photos

Below are 4 panoramas of the site (Fig.86-89) from each side. In (Fig.86) it is shown a view from the north-east part of the site. The site is filled with bushes and grass and plastic/other waste in some parts. There is a sidewalk and an already built road that functions as an informal parking space for vehicles and mostly there are seen students at driving school practicing.

Figure 86. Site north-east panorama

Below (Fig.87) is shown a site view from the north-west. As it is seen the site in this part is filled with waste. The sidewalk is in both sides of the road and in the sides are placed some decorative trees. This road is the main road which means that cars pass by in any given moment. Also, it is observed that few people use this sidewalk due to lack of buildings or services in this particular area.

Figure 87. Site north-west panorama

In the next panorama (Fig.88) a view forms the south-west part of the site is shown. This part is also filled with waste mostly plastic bags and bottles. The road as well as the previous one functions as a main road and it is crowded with cars and sometimes traffic. Pedestrians in this part are seen passing more often.

Figure 88. Site south-west panorama

The last panorama (Fig.89) shows the south-east part of this site. It is observed that this part is used as an informal parking space by the locals. Also, a high-rise building is in the final phase of construction which will bring numerous services to this area. In the other part (right side of the picture) there is a neighborhood filled with low rise buildings but with unimproved roads. Due to the inhabitants of this area the road in this part is used mostly by pedestrians.

Figure 89. Site south-east panorama

CHAPTER 4

DEVELOPMENT OF THE PROTOTYPES

4.1. Set of criteria of 3D printed house which can be realized in Albania

A crucial part of this design is a set of criteria for the housing typologies that will be designed. In this case a book from Albanian Ministry of Urban Development [87] shows housing standards in terms of space, method of construction, materials used etc. In chapter 4 of this book are displayed with tables all areas and number of spaces required in a house. So, for a 1+1 house it is required a minimum of 1 living space 12 m^2 and if it is combined with a kitchen it needs to be 14.52 m^2, the bedroom must be 12 m^2, for the kitchen there are shown 2 options that of kitchen integrated with dining area 6.16 m^2 and with no dining area 4.2 m^2, there is needed 1 bathroom with an area ranging from 3.6 to 4.2 m^2, there is included also a storage space with an area from 1 to 1.5 m^2, to the circulation space it is given an area ranging from 4 to 5 m^2, for the balcony or loggia an area of 0.6 m^2 is required, the last space included is the vertical circulation (stairs) space which ranges from 5.3 to 5.5 m^2, so in total the area of a 1+1 unit should not be less than 50 m^2.

Going with the 2+1 module the living space should be 13 m^2 of if the kitchen is included goes up to 15.52 m^2, one bedroom should be 12 m^2 and the other 8 m^2, the area for kitchen + dining is 6.8 m^2 and without dining is 4.2 m^2, the bathroom should be 3.6 to 4.2 m^2, for the storage the area required is 1 to 1.5 m^2, the circulation area should be 6 to 7 m^2, the loggia or balcony is required to be 0.6 m^2, the vertical circulation is needed to be 5.3 to 5.5 m^2 and the total area of 2+1 unit should not be less than 60 m^2.

Furthermore the 3+1 house requires the living space area 14 m^2 and with a kitchen included 16.52 m^2, two bedrooms should be 12 m^2 and the third one should be 8 m^2, the kitchen of it is combined with a dining is needed to be 8 m^2 and without it 4.2 m^2, there are needed a minimum of two bathrooms with an area that varies from 3.6 to 4.2 m^2, the storage area should be 1 to 1.5 m^2, for the circulation it is required an area of 6 to 7 m^2, loggia or balcony should be 0.6 m^2, vertical circulation is needed to be 5.3 to 5.5 m^2 and the total area for the 3+1 house should not be less than 75 m^2.

To conclude, the minimum area for 1+1 is 50 m^2, for 2+1 is 60 m^2 and for 3+1 is 75 m^2. These values are just the minimum area required for a given house typology thus the area may be larger than that due to 3D printers properties.

4.2. Design of series of prototypes

- Prototype 1 House Typologies

In the previous chapter are chosen 2 3D printers for construction BOD2 and Delta WASP Crane. To have a better understanding of BOD2 limitations and possibilities there are taken information from BOD2 specifications report [88] which is a detailed report about its structure, additional equipment, and materials it can use. it is found that the printer structure is made out of steel modules with a 2.5 m length (Fig.90). For the height (z) there are connected 4 modules with a total height of 10 m and for the width (x) 6 modules with a total width of 15 m which is given as a dimension because there isn't any element mounted in that direction except the module which holds the printing head. The length (y) is infinite so there can be mounted infinite number of elements. There are 2 kinds of ways to fix this 3D printer structure in the ground. Starting with the first way which is fixing the raw structure with modules in an already finished building foundation. Then, the second way is to put reinforced concrete footings in each 3D printer's column. These footings can be built below and above the ground. If the footings are placed above the ground then the printer can print up to 10-meter height (z) from 8.1 meters of maximum height that is without the footings.

Figure 90. BOD 2 3D printer, source [88]

Furthermore, all the information taken from the report is translated into a plan (Fig.91) where are shown 2 methods of printing that includes extreme printing border, grid, reinforced concrete feet of the 3D printer, 2.5 m modules as beams in view and as columns in section, also the printing head structure. Firsly, the extreme printing border is set and it is shown with a garnet dashed line. The width of this border is same as given in the report 14.6 m and unchanged in both methods while the length in the first method is 9.6 m (4 modules 2.5 m) and in the second one it is 49.6 m (20 modules 2.5m). Apart from the extreme printing border there is added the chosen design border which is a grid composed with 3 x 3 m squares. Thus, the maximum area that is chosen to print in the first one is 108 m^2 and in the second one it is 576 m^2. The difference between these two methods is the time it will take to mount (from the report 4-6 hours) and dismount (from the report 2-3 hours) these structures and the way the printer will print the houses where in the second case it can print more than 1 house in one mount which and sound good but it will take longer in time and may include some errors during the process. So, there should be a proper plan from the specialists of BOD2 printer that which way is the most appropriate to be followed.

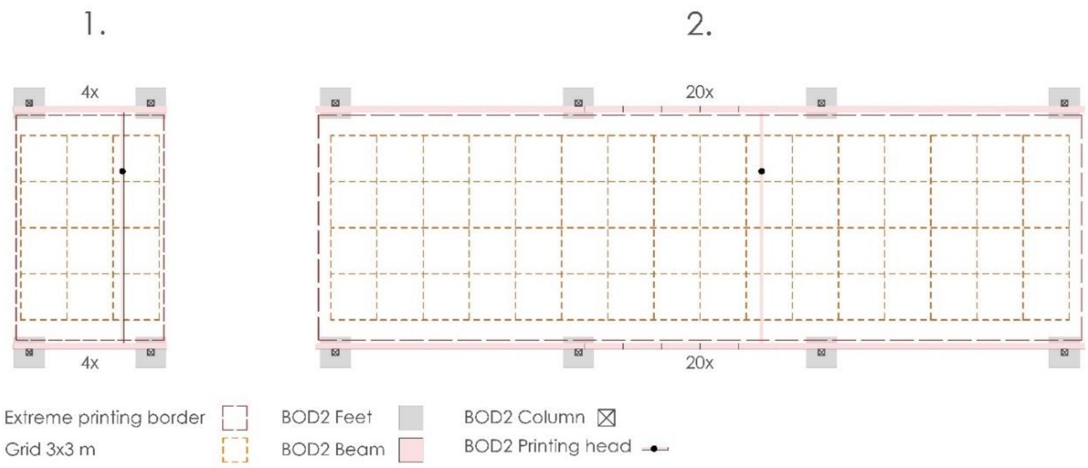

Figure 91. BOD 2 3D printer plan scheme

Following with, the design of the prototypes based in the information from BOD2 printer plan scheme. As mentioned above a grid was generated using 3 x 3 m square connected with each other (Fig.92) with the maximum extension of 12 m wide and 48 m long. These dimensions are also based on the literature review "3D Printers

Dimensions and maximum Number of Floors" table (Table.7) where the maximum printing area is 14.6 x 50.52 m. After the grid is set, 3 housing units footprint are set. The first one on the left is a 1+1 typology with a maximum area of 72 m^2, the second one is a 2+1 volume with an area of 81 m^2 and the last one is a 3+1 house 108 m^2.

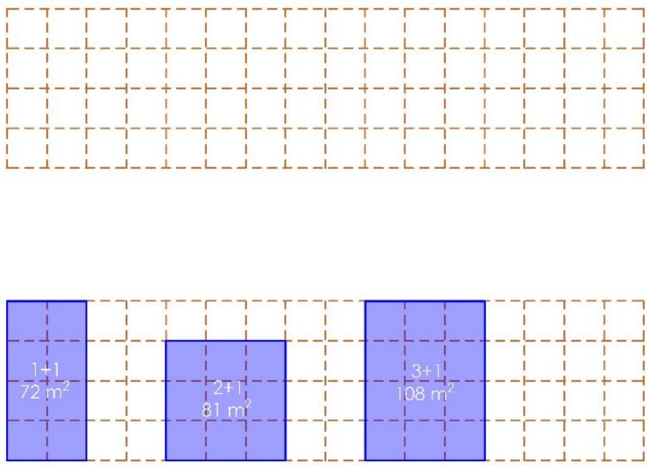

Figure 92. Grid 3x3 m (top) and House standard areas (bottom)

Moreover, in the figure below (Fig.93) it is shown the spatial composition of the typologies. Placed in the grid alongside with the printing structure that were described in the previous paragraphs, are shown the housing typologies. There is done a shift of 1 m for all volumes to leave a necessary space for 1 vehicle to be able to park in that area. In the next part there is shown the spatial organization of these modules. The buildings are shown, property area for each house, public space and all properties which are next to the given combined with an arrow that shows their spread direction. The property area for 1+1 house typology is 228 m^2 and the distance of the house from its borders are 2 m north & west, 4 m east and 5 m south. Going with the 2+1 property area which is 285 m^2 where the distance of the building form the borders is 4 m north & east, 6 m south and 2 m west. Furthermore, 3+1 property is the same with 2+1 and the distance of the building from its borders is 2 m north & east, 5 m south and 4 m west. Also, the height of each module will be 1 floor and the names for each of the Prototype 1 typologies are A1 (1+1), A2 (2+1) and A3 (3+1).

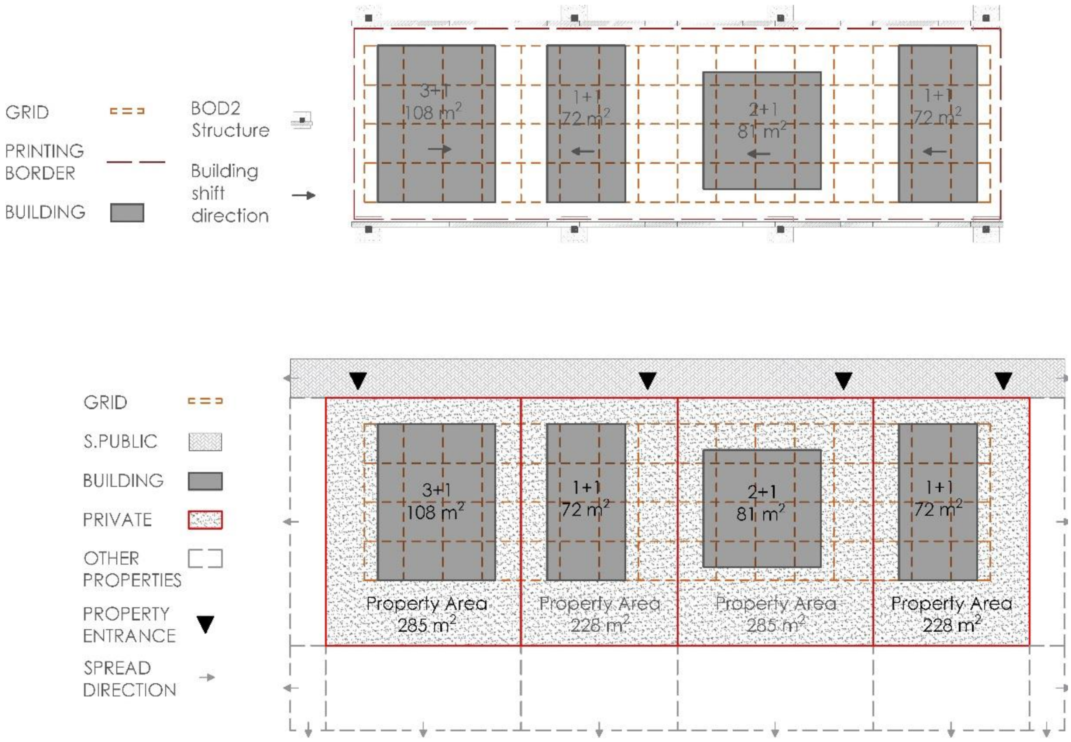

Figure 93. House modules combined (top) and Spatial organization (bottom)

In the next picture (Fig.94) there are shown plans for each house in ground floor and top view. As it is seen A1 module is composed of a common living space (living, kitchen, and dining) with an area of 28.6 m^2, a bedroom 12 m^2, a bathroom 4.8 m^2 and circulation 17 m^2. In the A2 module there is planned to be again a common living space 21.4 m^2, 2 bedrooms the one on the left is 12.3 m^2 and the one in the right 11.6 m^2, the bathroom is 7.5 m^2 and the circulation area is 14 m^2. The A3 house includes a common living space 35 m^2, a master bedroom + bathroom 15.5 m^2 where the bedroom is 12 m^2 and the bathroom 3.5 m^2, 2 other bedrooms are 8.6 m^2 (top left) and 8.8 m^2 (top right), the bathroom is 5.7 m^2 and the circulation area is 15.5 m^2. There are also put windows in various spaces to add more sun light to these houses. The roof is going to be with a slope where A1 and A3 have the same slope of 8% and the A2 has a slope of 10%. Also, the corner of outer and inner walls is not straight but with curves. That’s because it can be printed faster than the straight corners. This curve is not only in the corners of the walls but even in the openings such as doors and windows.

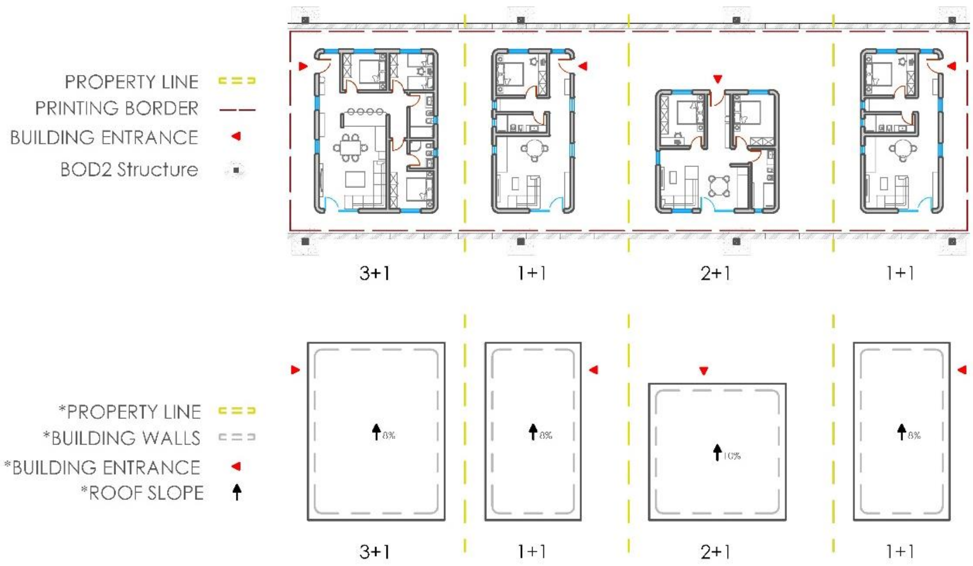

Figure 94. Ground floor plan (top) and Top view (bottom)

For a better understanding of the houses, digital 3D models of each of them are generated (Fig.95). The views are in isometry. On top there are placed the views with shadows of the full houses (walls + roof). The bottom views have the roofs removed to understand better the inside of these volumes.

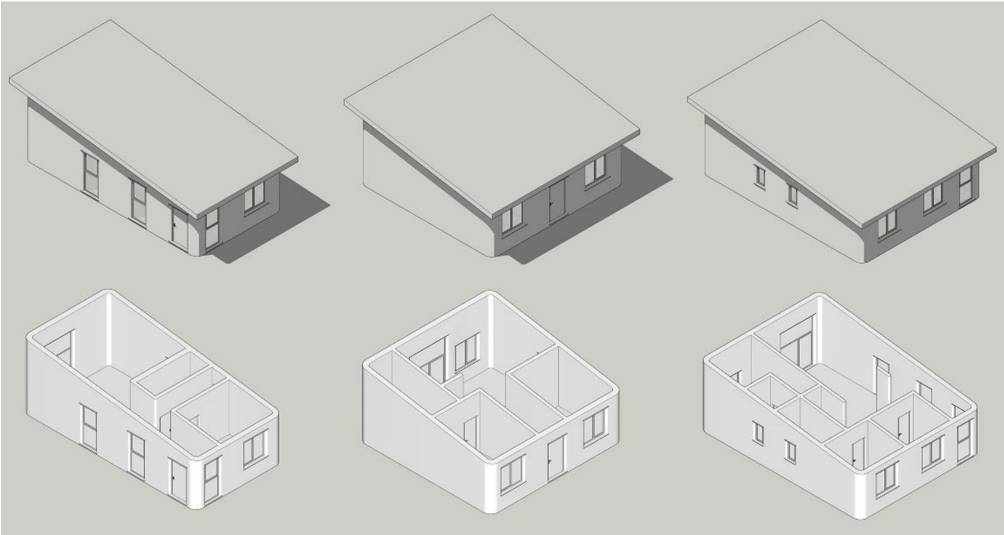

Figure 95. *ISO 3D views of the modules: full structure (top) and opened (bottom)*

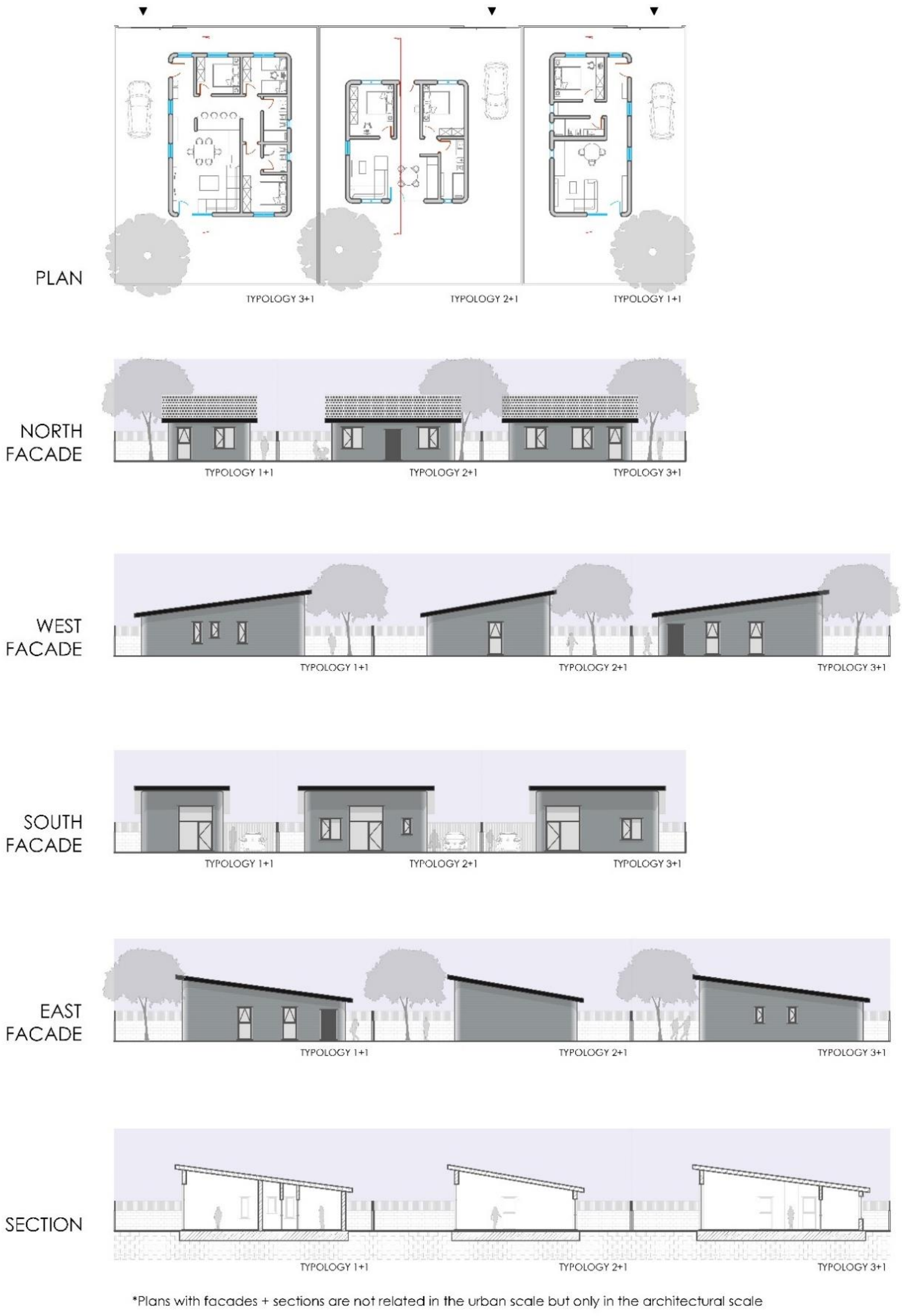

Figure 96. Plans, facades, and sections of Prototype 1, A1, A2 & A3 typologies

Following, in the figure above (Fig.96) are displayed the plans, facades and sections of each house along with the property border. There are proposed 4 different kinds of windows, 1 glazed wall, 1 entrance door and 1 type of interior doors. This is done because of the cost. If doors and windows were different for each house then the price would become much higher, thus for all units there are thought to be same modules of windows and doors. The distance from the floor to the roof in the lowest part is 2.8 m and at the highest part it is 4.3 m. This kind of roof was chosen for these houses to differentiate the spaces both in exterior and interior. Where the lowest part is reserved for the entrance of the house and bedrooms while the highest part is for the living area and also in the A3 typology master bedroom.

- Prototype 2 House Typologies

Starting with, same as for the Prototype 1 design process there is needed a proper study for Delta WASP Crane 3D printer itself. It stated from the company [40] that the diameter extreme border that can be printed is 6.6 m and the maximum height is 3 m. Compared to BOD2 this printing area is significantly smaller (Fig.97), but there is a benefit with this 3D printer that it is modular not just as structural elements but also as a whole.

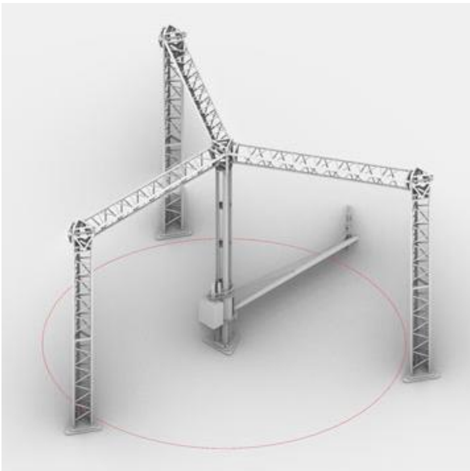

Figure 97. Delta WASP Crane 3D printer, source [40]

In the diagram below (Fig.98) it is shown the bigger version of Delta WASP Crane. There are in total 2 printers that WASP company offers as a Delta WASP Crane, for 50 m^2 buildings and for more than100 m^2 buildings. For the design of the prototypes the second 3D printer model is chosen. It is composed of a hexagonal base supported by triangular truss both in columns and as beams. Another important information that is displayed in the diagram is the overlap of printing areas which are shown as circles. Two robotic arms work separately but without colliding with each other during the process.

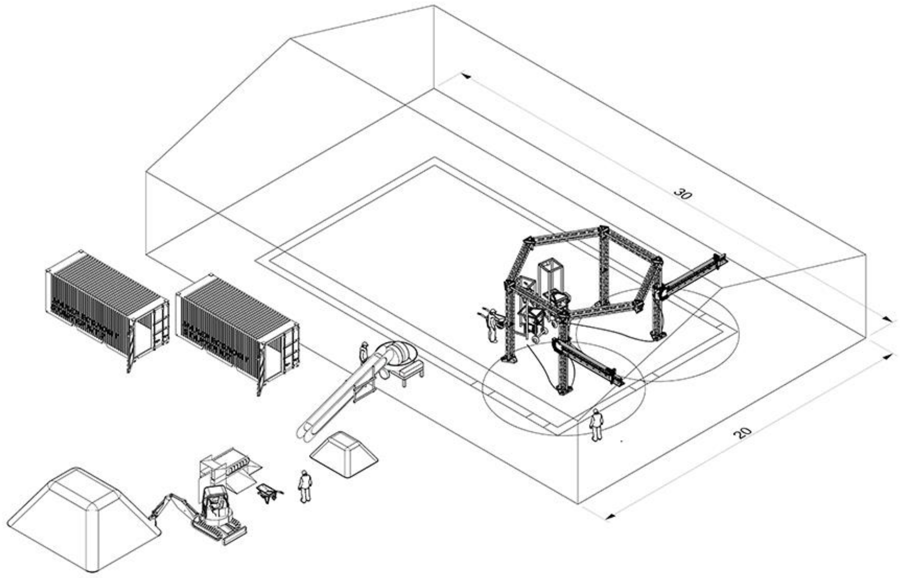

Figure 98. Delta WASP Crane 3D printer modular diagram, source [40]

Thus, a plan was generated (Fig.99) to understand better the specifications and limitations of this 3D printer. Firstly, 2 circles were generated with 3.2 m radius where one of them is shifted 1.9 m to the next circle. Then, the structure of DWC (Delta WASP Crane) 3D printer which as mentioned above +100 m^2 model was chosen. The structure is made of a hexagonal base which is fixed in the ground with steel feet. It is composed of triangular trusses both in columns and in the top where all columns are connected with each other. The DWC printing arm is also a truss system but different from other ones it is thin and connected to the columns using a circular section steel element which allows the arm to move without any problem. Also, there is given the direction in which the arms move.

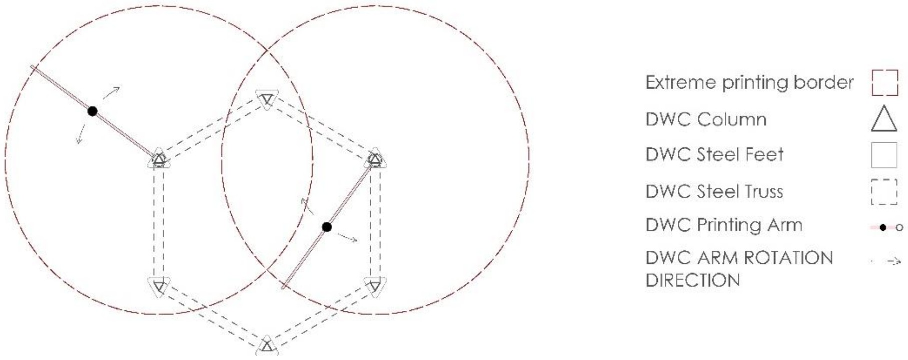

Figure 99. Delta WASP Crane 3D printer plan

Following, a grid is generated from 2 circles. As mentioned above 2 circles with the radius 3.2 m are combined together by shifting one circle 1.9m in the direction of the other circle. This resulted in an appropriate space for a human to pass through the overlapping of 2 volumes (Fig.100). Thus, the grid is generated using the same shift measure and direction and it is composed of 45º rotated squares (rhombus).

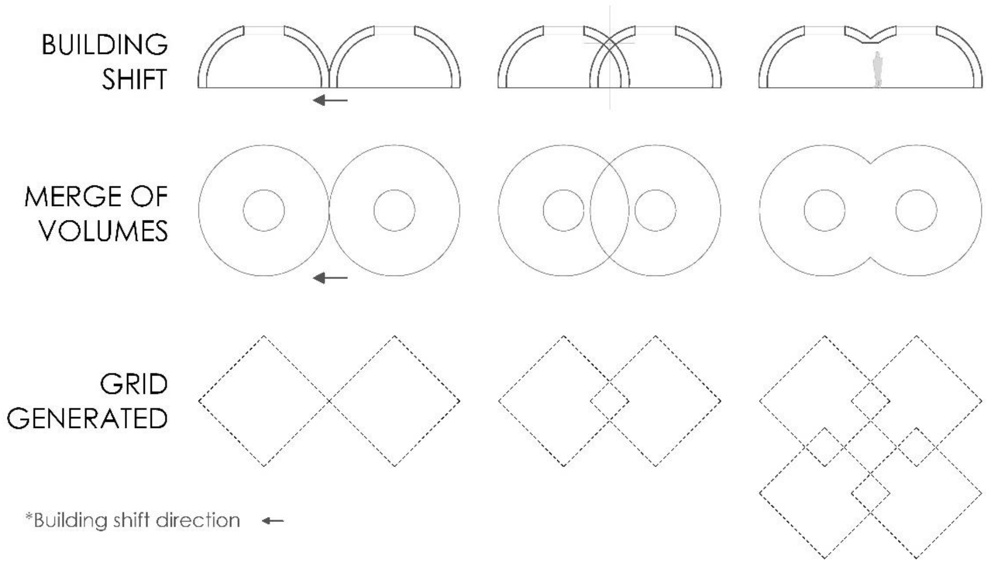

Figure 100. Grid generation diagram

After the grid is generated then the following is the development of the typologies (Fig.101). It started by combining circles with a radius of 3.2 m placed above the grid. After that, the result came to be that 1+1 house (B1) is 131 m^2, 2+1 house (B2) 151 m^2, and 3+1 (B3) typology 198 m^2. These spaces seem to be out of scale and far from the set of criteria mentioned in previous subchapter. The reason for that is the shape of the dome structure that does not allow free movement of a human close to the walls and corners due to the height of the structure from the ground. If that space is removed from the total area then the area will be closer to the standard.

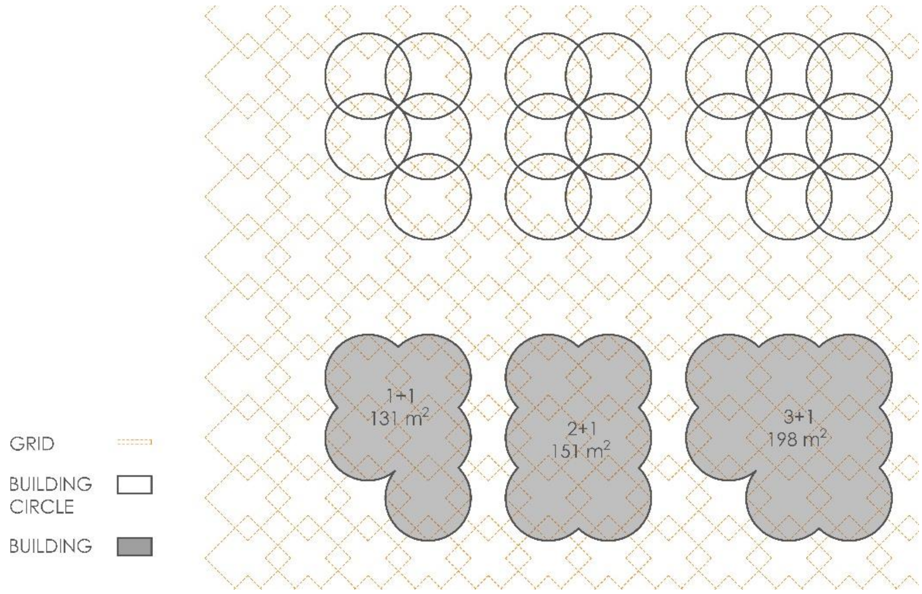

Figure 101. House modules

Furthermore, the modules are developed into furnished plans. In the figure below are shown ground floor plan and the top view (Fig.102). Footprint of these modules are thought to be composed of curves, thus, to create a parametric feeling of the domes from the outside. Each dome has an oculus with a radius of 3.2 m. The B1 volume is on the left and has a living room 18.5 m^2, bedroom 25 m^2, kitchen + entrance 21 m^2, dining room 17.5 m^2, a bathroom 16 m^2 and circulation 5 m^2. Next house B2 is the one in the middle and it is composed of a living room 18.5 m^2, 2 bedroom one 25 m^2 (on top right of the volume) and 24 m^2 (on bottom right of the volume), a kitchen + entrance 18.5 m^2, a dining room 17.5 m^2, a bathroom 10 m^2 and circulation 6 m^2. The room areas for the volume B3 starting with the living room 21 m^2 and dining room 17 m^2, a master bedroom (+ bathroom) 24.5 m^2, 2 other bedrooms 20 m^2, a kitchen 15 m^2, a main bathroom 12 m^2 and circulation 7 m^2. As described before functional room areas are smaller.

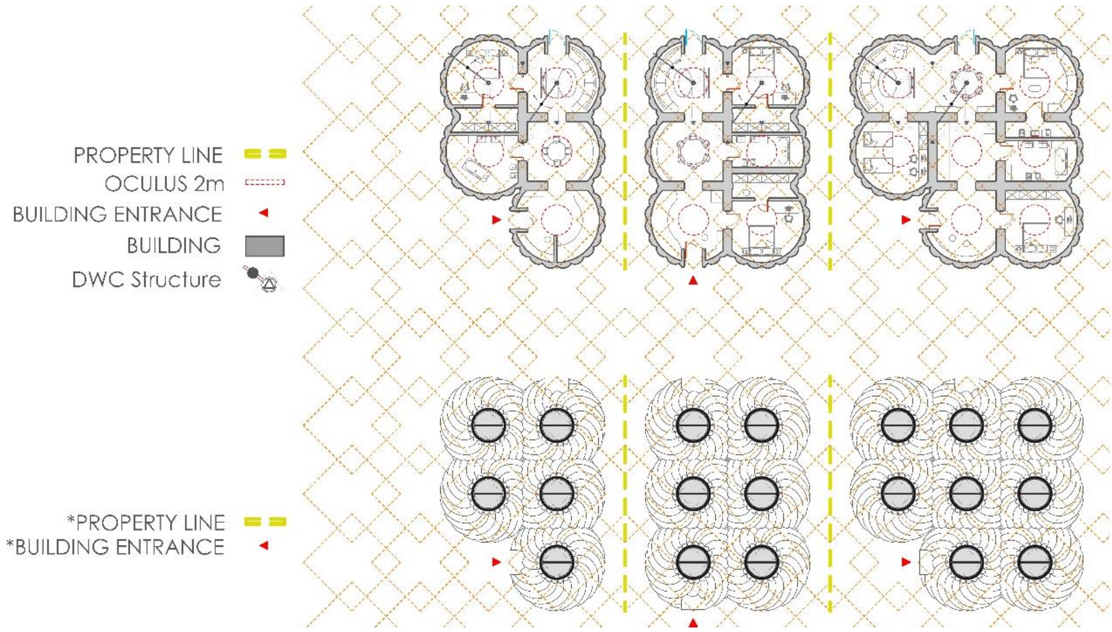

Figure 102. Ground floor plan (top) and Top view (bottom)

In the next image (Fig.103) it is shown the spatial organization of the property. As it is seen the entrance is from the south (public part). There is enough space in the entrance to park 1-2 cars in B1 module and 3+ cars in the B2 and B3 module. Also, B1 property has an area of 300 m^2, B2 property area is 365 m^2 and area of the property B3 is 486 m^2. There is enough space outdoors for daily routine and activities of the families that will live there.

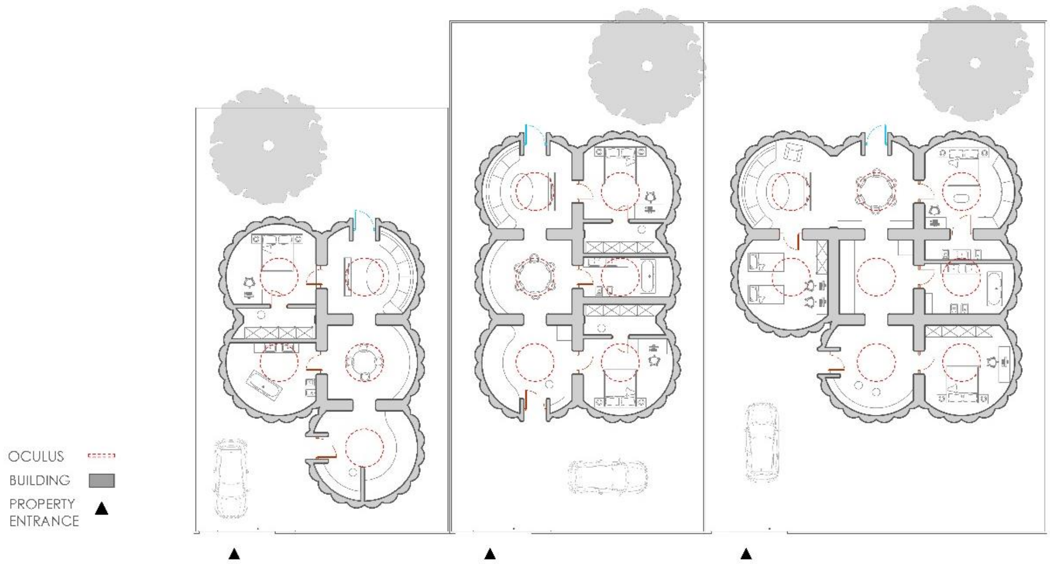

Figure 103. Spatial organization of the property

In the end, there are shown plans, facades, sections for each volume (Fig.104) and isometrical views (Fig.105). There is chosen to be a parametric shape of the building. The doors both exterior and interior which count up to 4 different door and window modules are repeated in every module. This is done to lower the cost of the project. Also, the material which will be used for these buildings will be a mud mixture with other bio reinforcement materials.

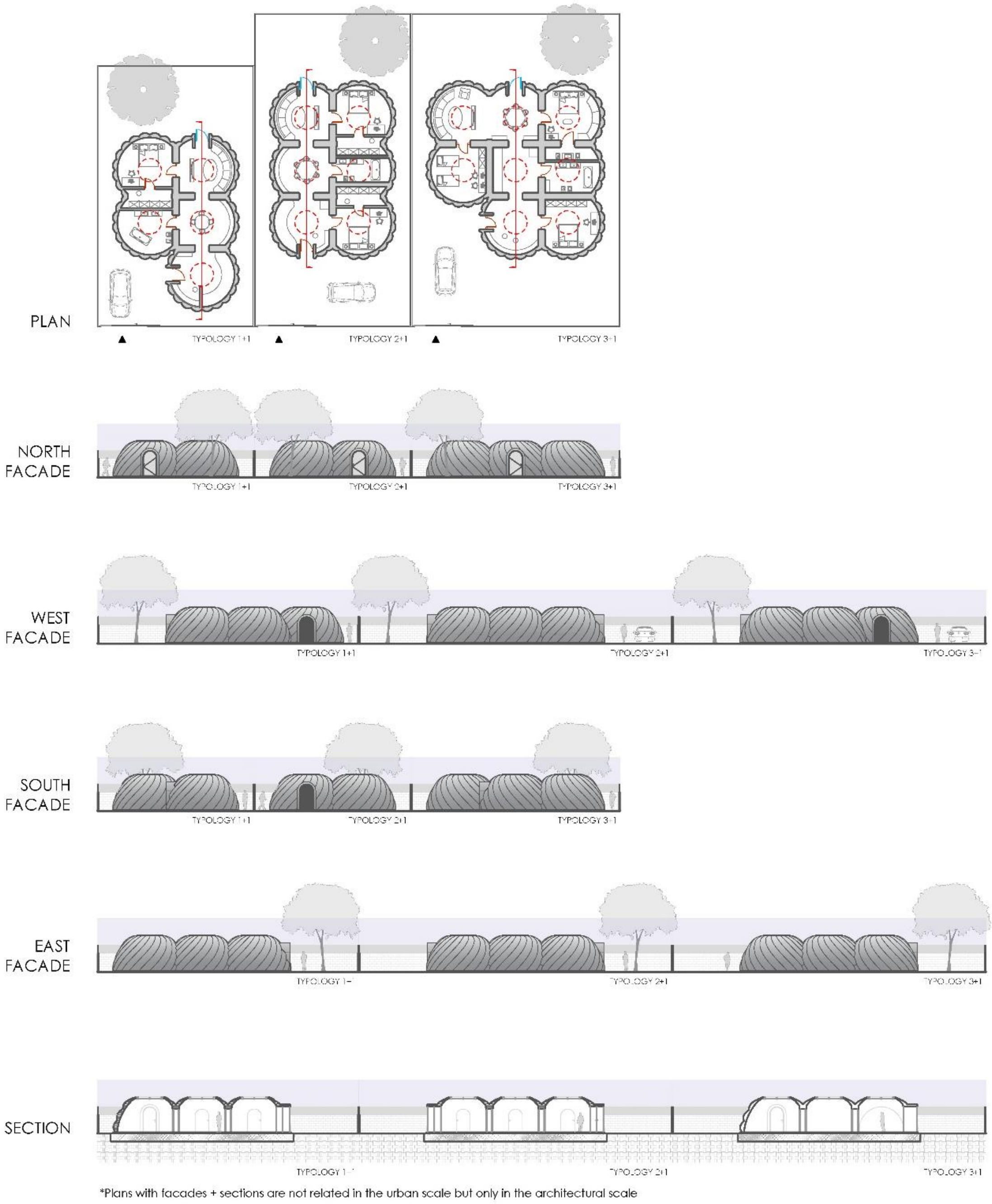

Figure 104. Plans, facades, and sections of Prototype 2 B1, B2 & B3 typologies

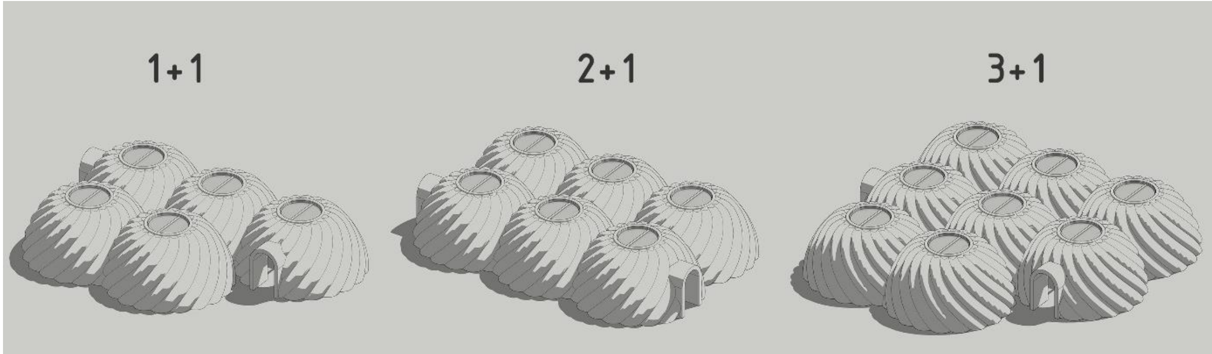

Figure 105. 3D views of the Prototype 2 houses

4.3. Realization via scaled 3D printer models

After the design of the prototypes is done, then follows the 3D print of these models. The software that is used to prepare models to print in 3D (small scale) is called Repetier Host. Starting with the first chosen 3D printer modules Prototype 1. In The pictures below are shown 3 models of different typologies A1 (Fig.106), A2 (Fig.107) and A3 (Fig.108) along with the information about printing time and filament needed. The volumes that are going to be 3D printed are in a small scale 1:100. There are added for all volumes support layers for the printer to be able to complete the model from start to finish. Thus, the time required for A1 volume to be printed is 3 h and 12 min and if it was to be printed on site it will need about 3 to 5 hours of BOD2 printing time. For A2 model there is shown that it needs 3 h and 36 min to be printed and with BOD2 that time would be 4 to 6 hours. The last model A3 needs 4 h 38 min to be completed in a small scale and 5 to 7 hours in a real scale by BOD2.

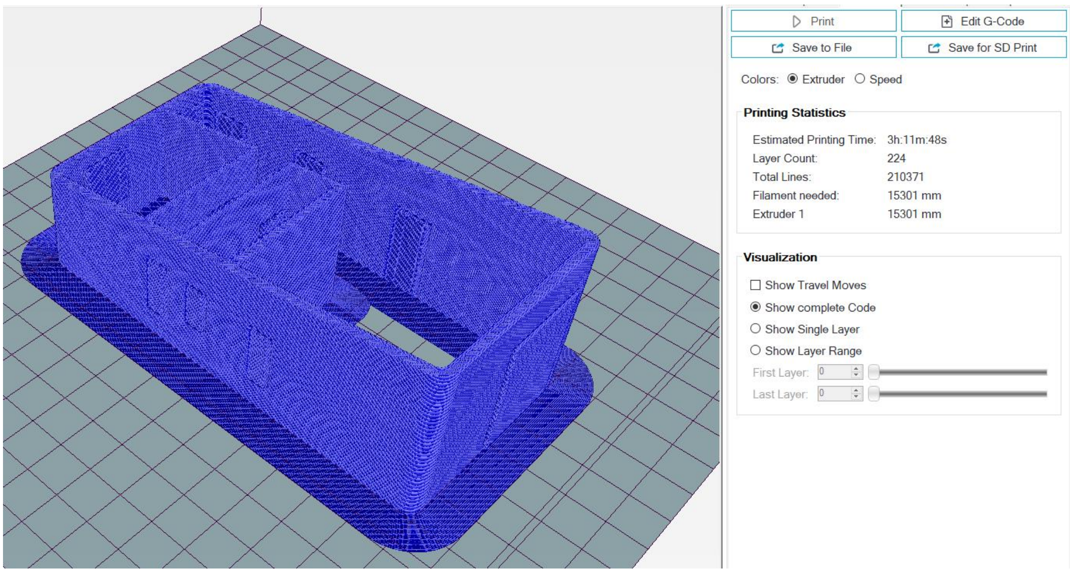

Figure 106. Prototype 1, A1 volume 3D printing preparation

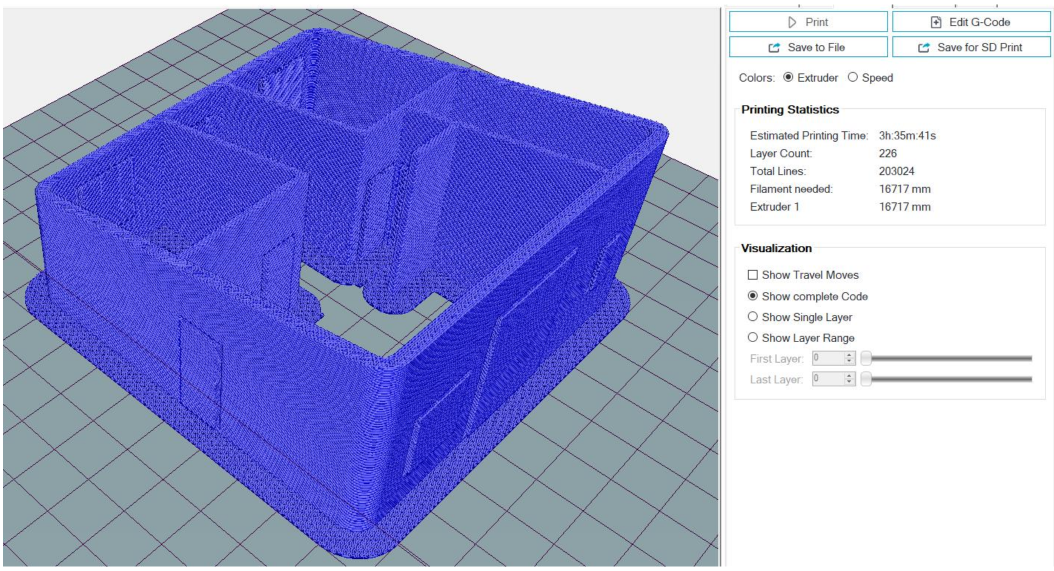

Figure 107. Prototype 1, A2 volume 3D printing preparation

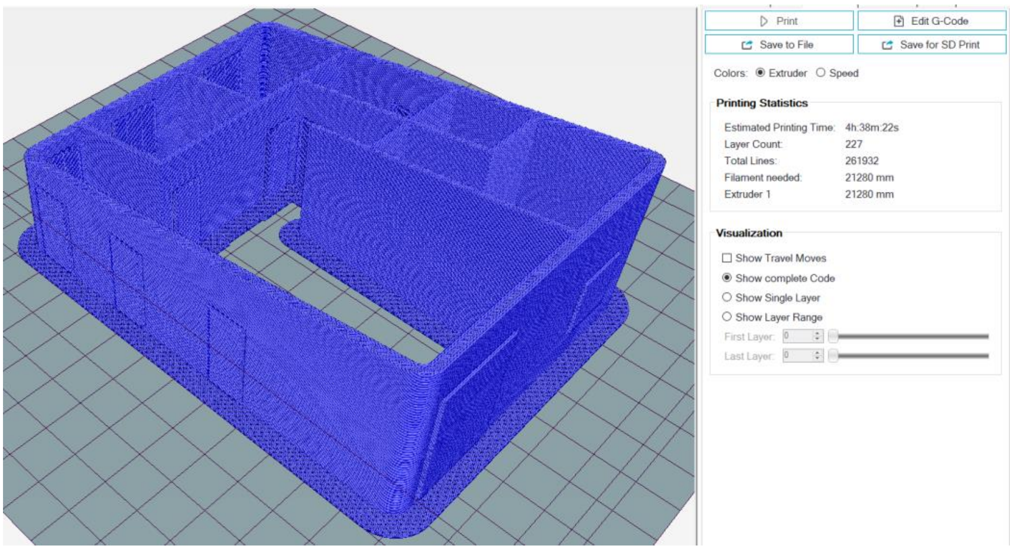

Figure 108. Prototype 1, A3 volume 3D printing preparation

Following, Prototype 2 whom models are shown in the pictures below for B1 (Fig.109), B2 (Fig.110) and B3 (Fig.111). In this case there is needed no support because the structure will hold itself while 3D printing. So, the time required for B1 model to be printed in a small scale is 4 h and 17 min and with DWC 3D printer in real scale about 19 to 21 hours. For the B2 volume is needed 4 hours and 3 min (without the inner walls) with a simple 3D printer and 21 to 23 hours with DWC. The B3 volume can be printed in 5 h and 18 min (without the inner walls) with a small-scale 3D printer and 26 to 28 hours to print in the site with DWC. Time required for DWC buildings to be printed in real scale is more than that of BOD2 because of the printing speed each printer has.

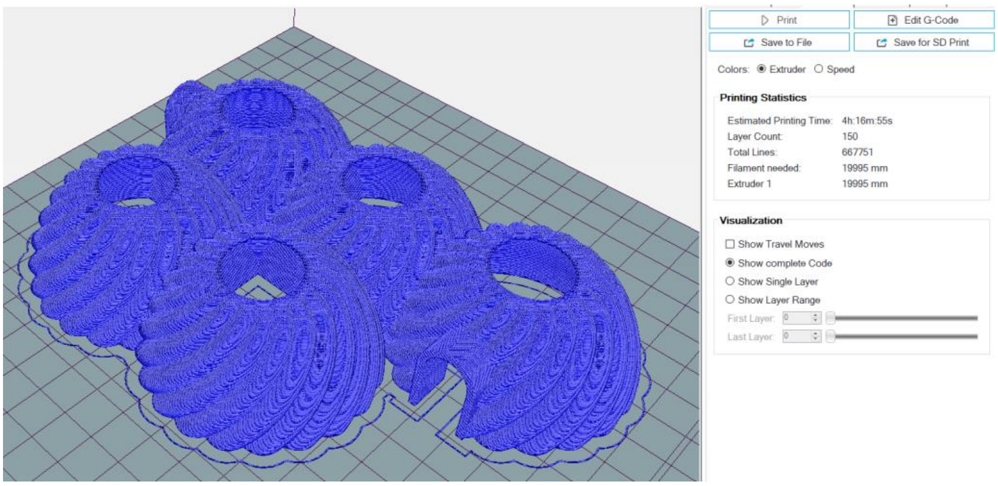

Figure 109. Prototype 2, B1 volume 3D printing preparation

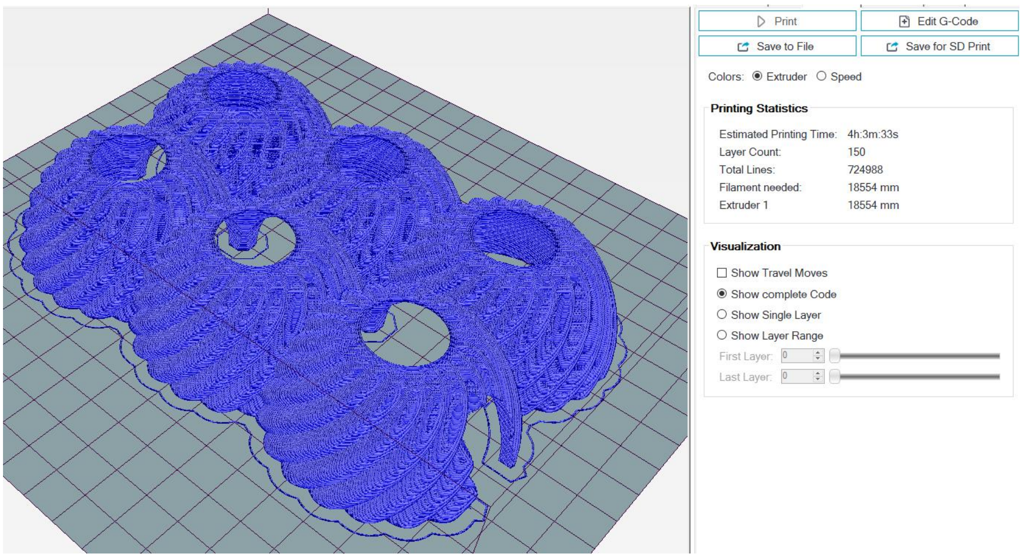

Figure 110. Prototype 2, B2 volume 3D printing preparation

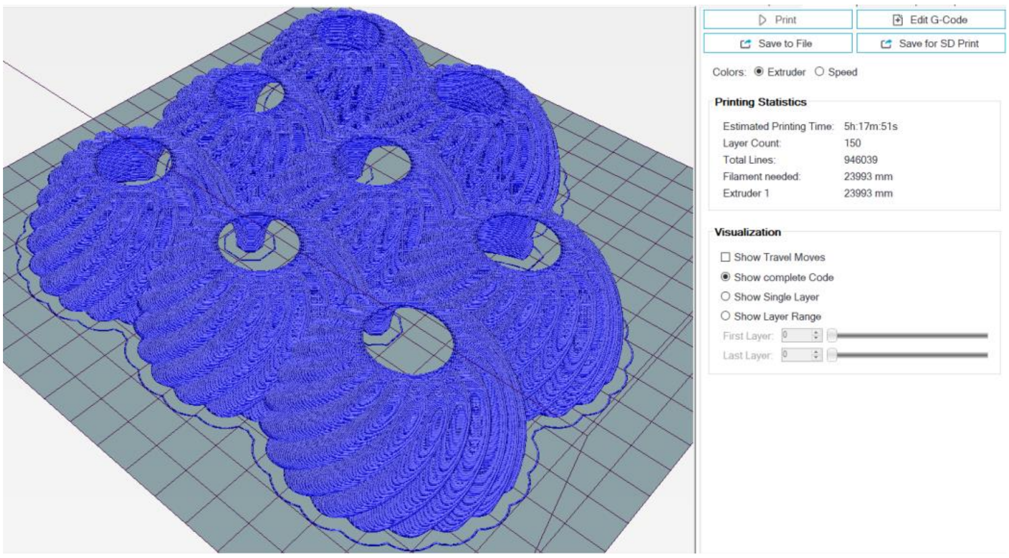

Figure 111. Prototype 2, B3 volume 3D printing preparation

Furthermore, the first model A1 of Prototype 1 has been printed in Epoka University printer’s lab (Fig.112). It took in total more than 4 hours to print which is more than what was shown in Repetier Host result (Fig.106).

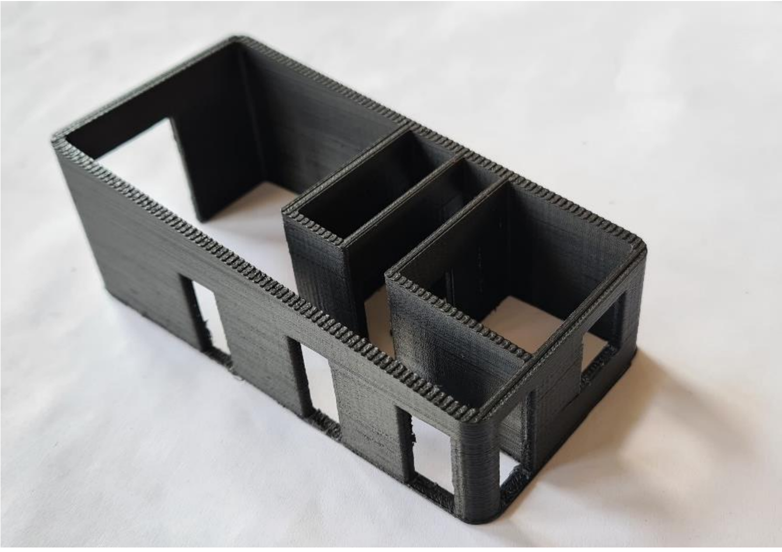

Figure 112. 3D Printed A1 house of Prototype 1

In the end, the next model that was printed in the digital fabrication lab is B1 of Prototype 2 (Fig.113). It took in total 7 hour of waiting time or about 2 hours and 45 minutes more than the given time from Repetier Host (Fig.109). This issue is mostly due to 3D printer speed. As mentioned before in this case there isn't use any support by the 3D printer. The reason for this was to prove that this structure can be 3D printed without the need for additional supporting elements while building. Different from A1 module this prototype is more stable and compact.

Figure 113. 3D Printed B1 house of Prototype 2

CHAPTER 5

DISCUSSION

5.1. Evaluation of prototypes

5.1.1. Spatial properties

The table below (Table.9) shows the area of each room and the total area for Prototype 1 and Prototype 2 typologies. The areas of Prototype 1 rooms are smaller than Prototype 2 due to the shape of the Prototype 2 houses. Also, the circulation in Prototype 1 houses is larger than the second one. The reason for that is the shape of the buildings, the design of the inner spaces and the need for more light. Most of the rooms in Prototype 2 have approximately the same area, because of the overlapping circles explained in chapter 4. The spaces in Prototype 1 are merged such as living room with kitchen and dining while in Prototype 2 there are all separated.

Table 9. Room areas for each prototype

ROOM AREAS			
TYPOLOGIES	**BUILDINGS / ROOMS**	**PROTOTYPE 1, area (m^2)**	**PROTOTYPE 2, area (m^2)**
1+1	LIVING ROOM	14	18.5
	BEDROOM	12	25
	KITCHEN	8.6	21
	DINING	6	17.5
	BATHROOM	4.8	16
	CIRCULATION	17	5
	TOTAL AREA	**72**	**131**
2+1	LIVING ROOM	13	18.5
	MASTER BEDROOM	12.3	25
	BEDROOM	11.6	24
	KITCHEN	4.7	18.5
	DINING	3.7	17.5
	BATHROOM	7.5	10
	CIRCULATION	14	6

	TOTAL AREA	81	151
3+1	LIVING ROOM	17.6	21
	MASTER BEDROOM	12	21
	BEDROOM 1	8.8	20
	BEDROOM 2	8.6	20
	KITCHEN	12.2	15
	DINING	5.9	17
	BATHROOM MAIN	5.7	12
	BATHROOM	3.5	3.5
	CIRCULATION	15.5	7
	TOTAL AREA	**108**	**198**

There is also needed a plan of how many of this housing units can the selected site include. For this there are designed some simple site plans (Fig.114). In the Prototype 1 site plan there are calculated to be placed in as simple way 106 housing units from these 43 A1, 37 A2 and 26 A3. For the Prototype 2 there are calculated to be 71 housing units in which 29 B1, 18 B2 and 24 B3. This is not a definitive design because this neighborhood needs some services like markets and small parks. Also, the roads are an important part of the site where in this design are calculated to be 3 m wide sidewalks and 6 m wide roads.

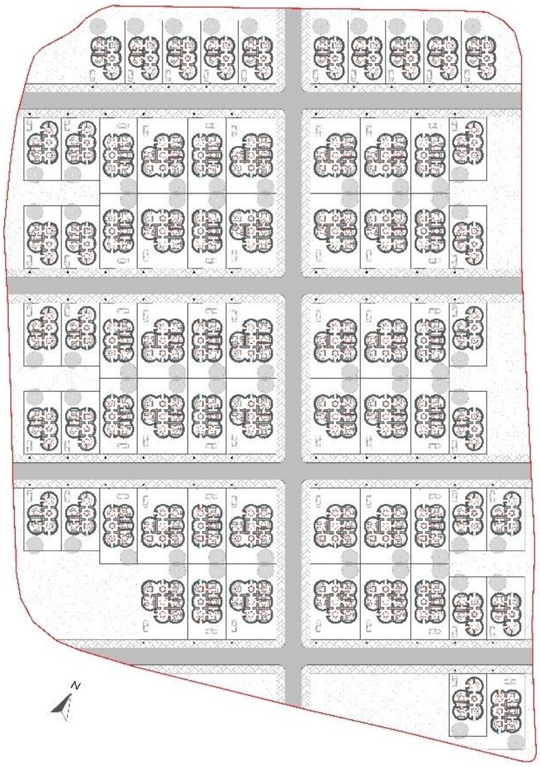

Figure 114. Prototype 1 (left) and Prototype 2 (right) house units placed on site

5.1.2. Building materials and structural properties

In the table below are shown building structural properties (Table.10). There are shown information about total area of each typology for each prototype (m^2), height (m), volume (m^3), property area (m^3), additional materials and structural elements. Starting with the first column it is seen that the area of Prototype 1 typologies is smaller than those of Prototype 2, because of the 3D printer limitations which were mentioned in previous chapter. Next is the maximum height of the building where in case of Prototype 1 the height is less than what BOD2 3D printer offers (10 m) and in the Prototype 2 there is the maximum height offered by Delta WASP Crane (3 m). Following is volume where Prototype 2 modules have the largest volume of walls. The volume is calculated using Rhino software. Prototype 1 is modelled with SketchUp and later exported to an appropriate file for Rhino to calculate the volume of the walls. For Prototype 2 the models are modelled using Grasshopper and Rhino, that's why the calculation of the volumes was much easier in this case. In the next column is shown the area of the property where in case of Prototype 2 is much larger due to the larger area of each house typology. As for additional materials, in Prototype 1 there can be used any kind of insulation material where in Prototype 2 there are used ecologic materials such as straw. The last column of structural elements shows that in case of Prototype 1 there are used steel bars for reinforcement while in Prototype 2 there is needed no additional structural element due to the shell shape of this structure. Other additional materials that can be used are the stucco of the walls and for structural elements there is required a wooden roof in the Prototype 1 which is required due to the limitations of the 3D printer accessed for those typologies.

Table 10. Table of building structural properties

BUILDING STRUCTURAL PROPERTIES							
TYPOLOGIES		TOTAL AREA (m^2)	HEIGHT (m)	VOLUME (m^3)	PROPERTY AREA (m^2)	ADDITIONAL MATERIALS	STRUCTURAL ELEMENTS
PROTOTYPE 1	A1	72	4.5	42.5	228	INSULATION MATERIAL	STEEL BARS FOR REINFORCEMENT
	A2	81		44.7	285		
	A3	108		56.3	285		
PROTOTYPE 2	B1	131	3	66.35	300	STRAW FOR THERMAL INSULATION	NONE
	B2	151		79.1	365		
	B3	198		104.4	486		

5.1.3. Production time

The table below is generated showing the 3D printed prototypes information (Table.11). The table includes specifications about each prototype typologies in scale 1:100 and in scale 1:1 (real scale printed with the specified 3D printer). Starting with printing time in 1:100 scale where in the case of Prototype 1 there is needed less time to print each volume compared to Prototype 2, because of the volume that each model has as seen in the (Table.10). Next, there is shown the number of layers which come from the Repetier Host software as shown in the previous chapter screenshots for each module (Fig.106-111). There are needed supports for Prototype 1 because of the doors and windows which are with a rectangular shape while Prototype 2 does not require any support. In Repetier Host software some settings are changed for each prototype. For Prototype 1 all models are firstly scaled down with 0.1 in object placement tab, then in the slicer tab as a slicer it is set to be CuraEngine by default. As for the printing settings print configuration is set to default, for adhesion type there is chosen raft, quality is set to 0.2 mm, support type is chosen to be everywhere, speed is set to normal, infill density is 20% and cooling is enabled. In filament settings extruder 1 is set to default. There are the same settings for Prototype 2 typologies, except for adhesion type which is set to none and support type which is also set to none. The last column is about printing time in scale 1:1 using specified 3D printers for each prototype. To calculate the time needed for this process there is taken average measures firstly from Repetier Host filament needed in printing statistics. For Prototype 1 models there are needed for them to be sliced with no support to make the results more accurate. After that this filament needed value is divided with printing speed of each 3D printer where for BOD2 is 1 m/s and for Delta WASP Crane is 0.3 m/s. Thus, the value that comes after is divided by 60 to find the minutes needed and later is also divided by 60 to find the hours needed. So, the values found represent that the time needed for Prototype 1 houses is less than the time needed for Prototype 2 houses. To better represent the results of (Table.11) a graph is generated showing the time needed for each module to print in 1:100 and 1:1 scale (Fig.115).

Table 11. Table of 3D printed prototypes

3D PRINTED PROTOTYPES					
TYPOLOGIES		**1:100 PRINTING TIME (hours)**	**NUMBER OF LAYERS (1:100)**	**SUPPORTS**	**1:1 PRINTING TIME (hours)**
PROTOTYPE 1	A1	3.2	224	REQUIRED	3.5 - 5
	A2	3.6	226		3.7 - 6
	A3	4.6	227		4.7 - 7
PROTOTYPE 2	B1	4.3	150	NOT REQUIRED	19 - 21
	B2	5	150		21.5 - 23
	B3	6.6	150		28 - 31
**The height of one layer in 1:100 scale is 0.2 mm and in scale 1:1 it is set to be 2 cm for both prototypes*					

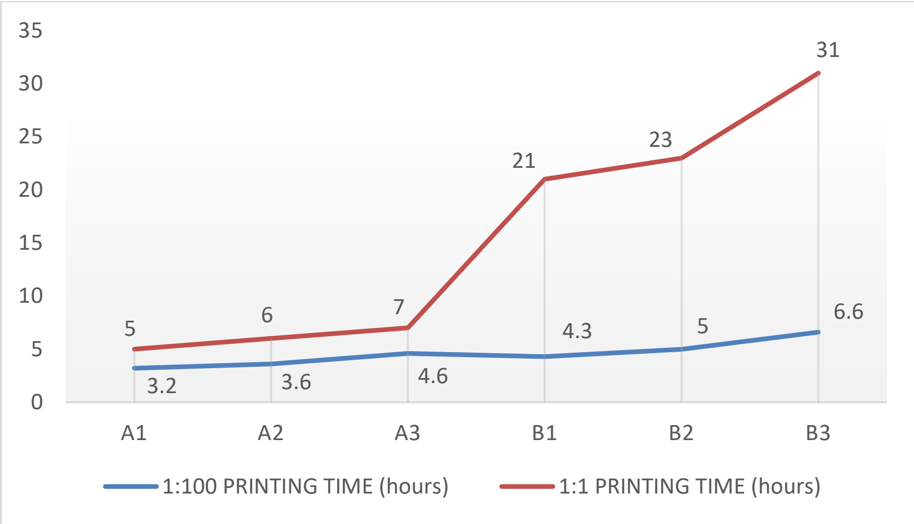

Figure 115. Time needed to print in 1:100 and 1:1 scale

In the next table there is shown the construction time for both traditional and 3D printed technology (Table.12). The calculation for the traditional time is done through a common construction time estimation. For the best values the way that these buildings are constructed in traditional way is the intensive method in which the workers work every day for 8 hours and more. As seen from the case studies in chapter 2 all buildings have a slab foundation above which the building is constructed. Starting with the Prototype 1. The first calculation is about the foundation which takes around 5 days to be completed. For this prototype buildings there is chosen to be constructed with reinforced columns, bricks for exterior walls, gypsum boards for inner walls and a wooden roof because this is the cheapest and fastest method to construct in traditional way. Thus, for the columns there are needed 5 days, for the roof reinforced beams there are needed 4 days and for the roof 10 days. Then for the finishing parts like stucco, hydraulic installations, electrical installations, furnishing and more, also for the increased building size there are needed 11 days for A1, 16 days for A2 and 21 days for A3. So, the total days are as follows 35 days to complete A1, 40 days to complete A2 and 45 days to complete A3 (this time is an approximate number of days). In the next column is shown the time needed for the same building to be constructed with a 3D printer which is almost half the time required for the traditional way. For this construction method there are calculated the foundation slab (5 days), printing time (around 1 day), roof 10 days and other things 3 days because the stucco is not needed and the installation time is reduced. Moving with Prototype 2 where the time required for this structure to be build is around 6 months for the A1 module, 7 months for A2 and 8 months for A3. Thus, this time is not efficient compared to Prototype 1. But, in the 3D printing time this prototype has better results than the previous one. That's because this design doesn't require a roof. There are needed 5 days for the slab foundation, around 2 days for the printing process, and 3 days for other executions. For the other houses there are added 2 more days. From this table there is generated a graph (Fig.116) which shows in the left the number of days and in the bottom all typologies. There is seen that the time of construction using 3D printing is less than traditional method where the difference is highlighted in Prototype 2 typologies. Also, the Prototype 2 has the lowest values in 3D printing time.

Table 12. Construction Time

CONSTRUCTION TIME			
Prototypes	**Buildings typologies**	**Traditional Construction Time (days)**	**3D printed time (days)**
Prototype 1	**A1**	35	19
	A2	40	20
	A3	45	21
Prototype 2	**B1**	180	10
	B2	210	12
	B3	240	14

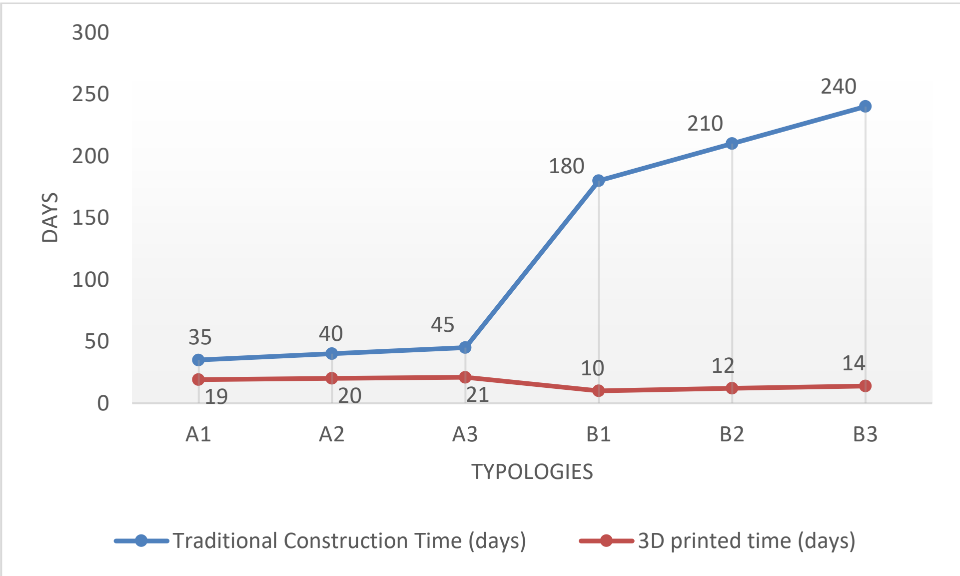

Figure 116. Construction Time Graph

CHAPTER 6

CONCLUSION

The main purpose of this thesis is to show that the 3D printing technology for construction is appropriate and efficient to build low-cost houses for the families that cannot afford to buy a house in the city of Tirana. In the second chapter it seen that 3D printers for construction are improved day by day, taken for example BOD2 which is the 2nd version of COBOD company and other 3D printers which are in the same way to offer the best settings for any construction company or individual who want to print a building. After that in the case studies part it is seen that the information and what each 3D printer offers is already experimented in the world where some 3D printers have built permanent shelters like Vulcan II, BOD2, ApisCor 3D printer and CyBe RC. Where the others have only built experimental buildings to prove that their technology is efficient. The site that is chosen for this study functions as an orientation for the housing units that are placed there. It is appropriate for this kind of neighborhood both in terms of space and accessibility.

There are chosen 2 3D printers BOD2 and Delta WASP Crane where the 1st one has the best settings compared to all other 3D printers and the other one setting are close to other 3D printers such as Vulcan II. But the main purpose that Delta WASP Crane is chosen is because of the case studies where this 3D printer has completed in total 3 buildings and distinguishes from other 3D printers for its parametric design. Both 3D printers have advantages and disadvantages in terms of technology and efficiency. The BOD2 3D printer has the largest printable area which can be increased infinitely adding more elements which can add up the cost for this 3D printer (272,820 € +) while Delta WASP Crane has a small printable area which can be increased adding more 3D printers and elements, thus adding the value of Delta WASP Crane 3D printer (132,000 € +) much more than BOD2 for the same large area because there are to be added other printing heads not only elements. As for the maximum height of each 3D printer, again BOD2 has the highest printing height up to 10 meters if there are used footings for the structure, in the other hand Delta WASP Crane can print in a maximum heigh of 3 m which limits the design drastically. The material that BOD2 uses is a mixture of concrete while the material that the other 3D printer uses is ecological and can be found everywhere. From this it is seen that Delta WASP Crane material is inspired by old building materials that are used in buildings that even today are standing strong. Taken this to consideration, this ecological material has the lowest cost and can help to lower the cost of the building. A crucial setting for this material extrusion is the nozzle diameter where in BOD2 varies from 20 to 50 mm and for Delta WASP Crane varies from 18 to 30 mm. This means that BOD2 can use the same material that Delta WASP Crane uses. Another thing to consider is the printing speed where BOD2 is the fastest 3D printer for construction in the world (100 cm/s) and Delta WASP Crane has a lower speed (30 cm/s) which increases the time of printing. From the prototypes that are designed it is seen that Prototype 1 is the most efficient in terms of area and height but Prototype 2 is the most efficient in terms of structure, material, total construction time and the elimination of building framework. Thus, Delta WASP Crane seems to be the best 3D printer for this thesis purpose. Although, BOD2 can 3D print the same design used for Prototype 2 and improve it in the height. This will lower the printing time needed, lower the cost of the building, lower the need for more labor, decrease footprint area and allowing to design a better house with less limitations compared to Delta WASP Crane. Thus, the most efficient way to fulfil the objective of this thesis "*Next objective is to verify that this way of building is efficient in terms of time and cost, which achieves the main commitment of this thesis, as well as depicting which prototype is more efficient in terms of cost and time based on the application of printing of small-scale model.*" is to combine both prototypes and design a building which has less footprint area and doesn't need any roof slab. In this case BOD2 is the most appropriate 3D printer in terms of speed, cost and limitations (Fig.117). But there is needed for BOD2 to improve the material (ecological), construction time (eliminating the frameworks) and design feature (using parametric design).

BOD2	Specifications	Delta WASP Crane
●	Printing Area	
●	3D Printer Cost	
●	Printing Height	
	Material	●
●	Printing Speed	
	Construction Time	●

BOD2 Chosen

Things that should be Updated for the best results:

- Material
- Construction Time
- Design Feature

Figure 117. Advantages and Disadvantages between selected 3D Printers

Differences between the 2 technologies traditional construction and 3D printing technology are distinct. An important information is found in this thesis in form of a table (Table.12) in which it is seen that the 3D printing technology is the most efficient in terms of time. Reduction in construction time also means that the cost is reduced. The construction time in case of Prototype 1 is the half time required to construct the building using the traditional time, but there is needed a roof to be constructed using that method which increases the time in this case. But in Prototype 2 where the structure is different and the roof is absent, it is seen that the construction time required is the half time compared to Prototype 1 3D printing time. This means that the benefits of this kind of shape are astonishing. There is possible for a complex structure for example B3 which is a 3+1 module almost 200 m^2 to be finished in 14 days. It is a great improvement in the construction technology which reduces drastically the construction time. Thus, there is possible to build houses for emergencies like earthquakes and shelter all affected families within days after the disaster.

Furthermore, during the time of this study research, the information taken from websites and even papers are constantly updated and added new information. Another great limitation is the cost estimation analysis for each building prototype because the companies didn't show any information about the cost and also the buildings that were completed didn't show the total cost of construction. This limited the study to focus more into the time of construction. Another limitation was the 3D printer's settings information which are taken from different sources, thus increasing the number of references. Furthermore, the process is limited only in 2 different 3D printer technologies gantry and mixed while robotic arm and cable are not included in the design of the prototypes. During the writing of this study there are published numerous articles for this technology where BOD2 that is chosen as the most appropriate 3D printer for this thesis objective has proven with the newest constructions that it is possible to 3D print a complex organic shape.

To continue with, these limitations didn't allow for some crucial information to be analyzed, mostly the cost. That's why it is needed future research in which this part will be elaborated. Also, a good orientation is given for the 3D printer technology which can be used and is the most efficient, that of BOD2. So, the future research for this technology can be focused mostly in BOD2 3D printer and from this focusing more into challenging design. One of the challenges that is not yet solved is printing on a relief or on different foundation slabs, which can be a potential future research.

Thus, this technology is brand new and will be part of the next "industrial revolution" that of robotization. Plenty research and companies are investing in this technology and improving it day by day. It has a great impact in architecture. With this technology exists the possibility to build the buildings which are proven to be impossible. Also, for it being the technology of the future another architecture field of design will be invented that of "planetary design" (Fig.118). Which designs the buildings that will build in other planets such as Mars [89].

Figure 118. Mars Buildings Idea, source [89]

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