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DESIGNING BUILDINGS FOR 3D CONCRETE PRINTING

NAČRTOVANJE ZGRADB ZA 3D TISKANJE BETONA



European Master in
Building Information Modelling

Master thesis No.:

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BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK**UDK:** 004.921:69-5-033.3(043.3)**Avtor:** Cristian Iaconi**Mentor:** Prof. Dr. Goran Turk**Somentor:****Naslov:** Načrtovanje zgradb za 3D tiskanje betona**Tip dokumenta:** Magistrsko delo**Obseg in oprema:** 50 str., 44 sl.**Ključne besede:** 3D betonski tisk, aditivna proizvodnja, in-situ tisk, predtisk, sistem gibanja, strategija oblikovanja, digitalni model, optimizacija, rezanje**Izvleček:**

Tehnologije 3D tiskanja betona dobivajo zagon v gradbenem sektorju, čeprav tipični arhitekturni načrti stavb niso neposredno uporabni za 3D tiskanje. Med arhitekti je premalo znanja o tehnologiji 3D tiskanja betona, ker niso usposobljeni za projektiranje zgradb za ta specifičen način gradnje. Ugotovimo pa lahko, da je oblikovanje in priprava takih digitalnih modelov za 3D-tiskanje zaradi najsodobnejših tehnologij sodobne 3D-računalniške grafike zdaj lažje kot v preteklosti.

Magistrsko delo podaja primer načrtovanja stavbe in metodologije optimizacije za 3D tiskanje betona z vidika arhitekta. Z uporabo programske opreme, kot je Autodesk Revit, imajo sedaj arhitekti več možnosti ustvariti in prilagoditi digitalni model zgradbe, ki je primeren za 3D tiskanje betona. Cilj metode je izboljšanje oblik geometrijskih elementov z nastavitvijo konstrukcijske strategije za vsako fazo in hkrati priprava modela BIM za hitro ekstrakcijo natisljivega digitalnega modela. Nazadnje vzpostavimo povezavo med digitalnim modelom in izdelanim 3D objektom z izvozom in rezanjem modela z uporabo posebnih formatov in programske opreme za predvideni 3D tiskalnik.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

3D concrete printing technologies are gaining momentum in the construction sector, although typical architectural building designs are not directly applicable to 3D printing. There is a lack of knowledge regarding 3D concrete printing technology among architects because they are not trained in designing buildings for this specific construction method. The good news is that designing and preparing such digital models for 3D printing is now easier than ever thanks to the cutting-edge technologies of modern 3D computer graphics.

The thesis provides an example of a building design and optimization methodology for 3D concrete printing from an architect's perspective. Using BIM authoring software like Autodesk Revit, architects are now more capable of creating and adapting a building design into a digital model suitable for 3D concrete printing. The method focuses on improving the shapes of geometrical elements by setting a construction strategy for each phase and, at the same time, preparing the BIM model for quick extraction of the printable digital model. Finally, the connection between the digital model and the materialized 3D-printed object is made by exporting and slicing the model using specific formats and software for the intended 3D printing machine.

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1. Introduction

The world is going digital, electric, and urban through the fourth industrial revolution, and in the construction sector, it takes the name Construction 4.0, as provided with a comprehensive overview in the book by Marco Casini, "Construction 4.0: Advanced Technology, Tools, and Materials for the Digital Transformation of the Construction Industry" [1]. In a few words, the construction industry is rapidly transforming, becoming more or less as it was predicted at the beginning of the 19th century.

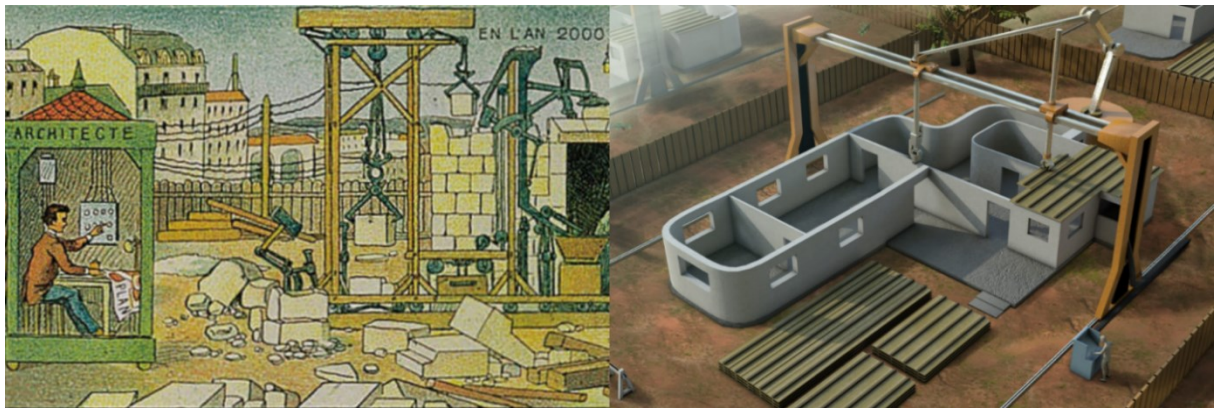


Figure 1: Similarities between what was predicted and what is developing: (left) Building Site of the Future (2000) as envisioned by Villemard in 1901; and (right) Contour Crafting as an Automated Construction Process developed by Dr. Behrokh Khoshnevis [2].

The general background of this thesis is digitization and automation in construction by using both physical and digital advancements of BIM (Building Information Modelling) tools and 3DCP (3D Concrete Printing) technologies from an architect's perspective by responding to the question: "How to design a building for 3D concrete printing"?

We know so far that 3D concrete printing allows for the creation of more personalized and better-performing buildings that can have a positive impact on the built environment. Implementation of this concept within the construction sector is considered an innovative and transformative approach to the current challenges faced by the industry [3]. However, today's advancements in computational design, simulation software, and robotics make it more feasible than ever.

The motivation behind the topic is personal development as an architect since the construction sector is expected to extensively utilize additive manufacturing for 3D printing housing, ensuring a promising future that offers sustainable and cost-effective solutions [3]. Also, it opens to us, as architects, new opportunities and challenges in creating brand-new designs by giving us more freedom in the conceptualization of the desired forms and spaces. To point this out, the technology is widely recognized as the construction method of the future [3].

1.1. Problem Statement

Traditional manufacturing and construction methods are often too expensive for custom-made solutions and special applications. Construction materials cost and availability are huge obstacles, especially in developing countries and remote locations. Besides the fact that time means money, speed is crucial when you need to rebuild an entire village because of natural disasters or build a military base in a short period of time. Last but not least, improving material loss control and reducing human involvement are crucial for achieving better performance in construction.

The promising technology that might be the solution is 3DCP (3D Concrete Printing), but commonly used building designs are not directly applicable or compatible with 3D concrete printing technologies. We cannot just take a conventional building plan and start printing; we will face a lot of problems doing that. While this technology is in an early stage of development, there is a lack of knowledge among professionals regarding this method. It's hard to find an architect that is completely ready to design a building for 3D concrete printing without minimum preparation in advance.

Additionally, it is essential to develop new approaches around 3D concrete printing in order to harness their full potential in construction since current technologies and regulations are designed around standard methods and shapes. Moreover, the current availability and areas of application are very narrow, highlighting the urgent need for expansion and diversification.

The problem is the gap between what we can design and what we can build with 3D concrete printing!

1.2. Research Objectives

The focus of the research is on special requirements and solutions in designing buildings for real-scale 3D printing and providing novel design methodologies that would support efficient construction for 3D concrete printing.

The main aim of this thesis is to learn about designing for 3D concrete printing, especially what an architect should know about this method and how they can put that knowledge into practice. More specifically, to discover different approaches and techniques, find out their limitations and advantages, and learn how to improve the reliability of the application.

The ultimate objective of this thesis is to propose an approach to a building design system for 3D concrete printing that takes care of the most important aspects: designing and optimizing the digital

model. The new design system's aim is to be more efficient in comparison with existing projects by improving the clarity of building design and printing methods. The intended purpose of the resulting design is to serve as a learning proposal rather than being specifically intended as a final product applicable in real-life scenarios.

The main research objective is to close the gap between what we can design and what we can build with 3D concrete printing!

1.3. Structure of the Research

The research structure consists of two main parts: the theoretical knowledge part and the practical application part.

The theoretical knowledge part, which would consider research findings, will focus on extracting essential information about 3D concrete printing, like available technologies, materials, special requirements, design limitations, workflow, and so on. This part will finish with brief presentations on some real case studies from different locations with unique approaches and methods.

The practical application part, which will start with the actual building design, will be done using the collected theoretical information and BIM software for modeling. Then the model will be adapted and prepared for the real-scale printing process. The final part will consist of results, a BIM model of the entire project, and digital models of the printable elements. Additionally, a small-scale 3D-printed model will be made for demonstration purposes.

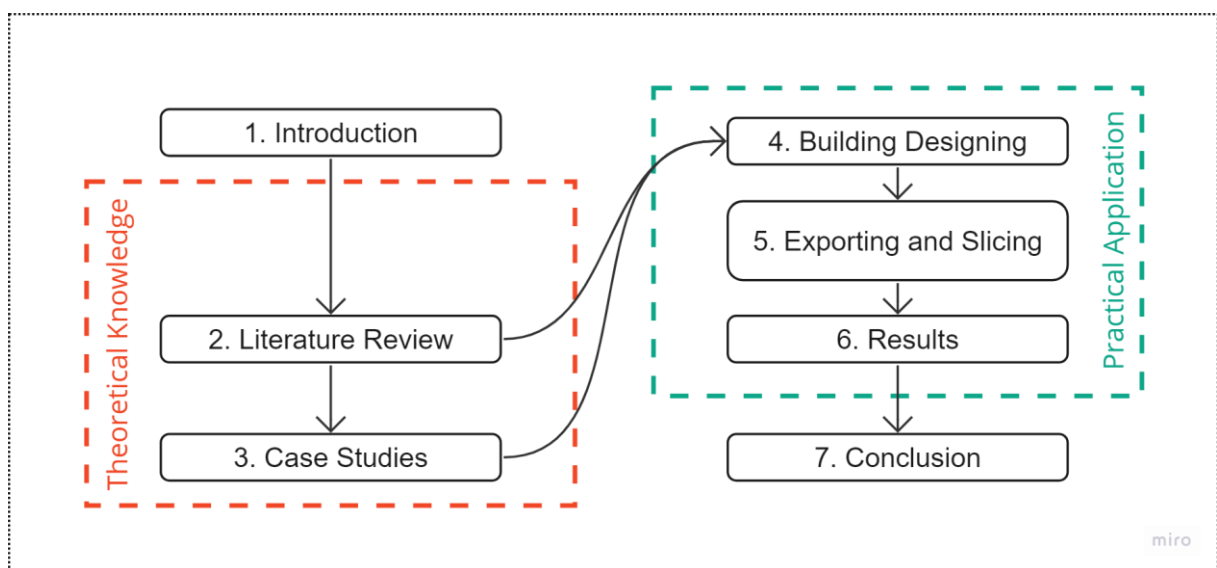


Figure 2: Thesis structure by author

2. Literature Review

An overarching examination of the technological advancements and applications of 3D concrete printing has been undertaken to trace its development and usage. Despite the fact that there are several techniques and technologies, the events mentioned were a crucial turning point in the development of the concept of 3D concrete printing. As a result, this milestone illustrates the development of 3D concrete printing as a technology as well as its various applications.

For a better understanding, a brief explanation of the 3DCP's key characteristics was done based on the literature review. The quick overview starts with the scale of application, moves on to the relevant technologies and their key elements, and ends with two types of printing operations: on-site and off-site printing.

2.1. 3DCP Development Overview

3D concrete printing (3DCP) or additive manufacturing (AM), as a general term defined by ASTM Committee F42, is a process for creating an element by joining materials layer upon layer by extracting data from a 3D model. It allows for printing parts with intricate and complex geometries, eliminating the need for molds and minimizing labor requirements. Moreover, it offers various benefits, such as reduced construction time and waste generation [3].

The origin of 3D concrete printing technology is generally associated with the theorization and patent presentation of contour crafting by Dr. Behrokh Khoshnevis in **1995**, where he introduced a new manufacturing system that used fluid construction material. Later in **2004**, this method was proposed by Dr. Khoshnevis to be used on a large scale as a system to print walls [4]. Since this time, there has been an upsurge of interest in this particular manufacturing system, as seen by the number of papers that have been published [5].

The true revolution of 3D concrete printing started in **2014**, when the first houses were built using elements that were printed by a massive printer. In Europe, the Dutch design firm Dus Architects constructed the first house that will be realized entirely by 3D printing technology. In the same year, WinSun, a Chinese enterprise, provided the first demonstration of a large-scale deployment of 3D concrete printing by assembling 3D printed parts to create ten homes that, according to the business, could be manufactured for about \$5,000 each. WinSun also declared in **2015** that they had completed a five-story building, making it the tallest 3D printed concrete structure [6].

In **2016**, Apis Cor, a Boston-based robotic construction startup, claimed that by working with the Dubai Municipality, they were able to 3D print the largest building, a 640 m² public structure. It is safe to assume that most of the structure was 3D printed on-site, except for the foundation, staircases, and ceilings, as the construction phases were made public [7].

The first authorized 3D printed structure in Europe was created in **2017** by COBOD, the world's leading producer of 3D concrete printing automation systems, and is a one-story office building in Copenhagen, close to the company's headquarters [8].

In **2018**, the first 3D-printed pedestrian bridge in Europe will be inaugurated as a result of a partnership between TU Eindhoven and Royal BAM, a Dutch construction company. In this instance, a number of components were printed off-site, assembled, and then posttensioned to give the structure the necessary strength and allow it to be built in Gemert, a tiny Dutch town.

A fascinating project from Austin-based ICON, a construction technology company, in **2019** helped validate the field's viability for commercial use by producing a number of 3D-printed houses with wooden roofs for the purpose of housing the homeless. Each of the 500-square-foot homes took roughly 24 hours to manufacture using their business' robotics software and the Vulcan II 3D printer, which is the first construction printer made commercially available. It was created primarily to operate under the special limitations of rural areas [9].

In **2020**, COBOD constructed the first example of a two-story building that was 3D printed in partnership with Kamp C, a center for sustainability and innovation in construction. The degree of structure refinement also demonstrates the technology's potential. The development was followed later by five residential houses finally built and rented in the Netherlands in **2021** thanks to the collaboration between PERI, a German scaffolding company, and COBOD [8].

After years of planning, permitting, and communication with the city and community, in the late summer of **2022**, the first multi-level 3D concrete home in the U.S. was printed, a two-story single-family home that integrates customized architectural design and a resilient structural system.

Finally, in **2023**, the construction of the largest 3D-printed building in Europe started in Heidelberg, southern Germany. It will eventually hold a data center and be 55 meters long, 11 meters wide, and 9 meters high. Only 140 working hours are anticipated to be required for the complete print operation. A massive robot that prints layers upon layers of concrete on top of one another performs the building labor that would typically be completed by dozens of human workers [10].

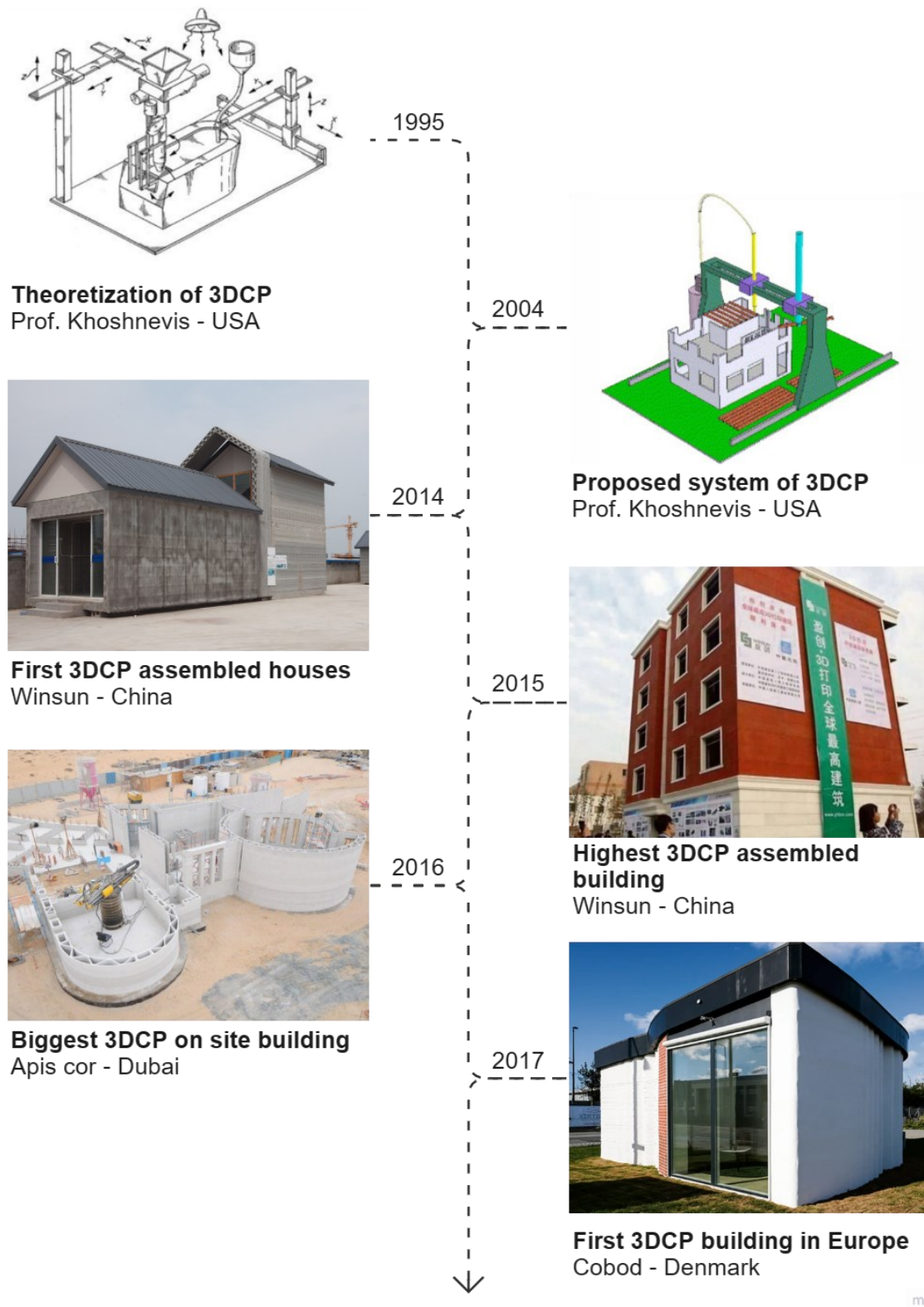


Figure 3: 3DCP development timeline 1995-2017



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Figure 4: 3DCP development timeline 2018-2023

2.2. Scale of Applications

The scale of application within 3D concrete printing is an important component that contributed to a deeper understanding of the project's design and its significance. A project's scale is a characteristic that describes and characterizes it based on its **size, scope, and accomplishment**. After examining the developed projects, three groups can be identified.

Buildings: Printing a building mostly refers to printing the walls of a building because the printer has not been involved in other operations directly on-site until now. Other components, such as the roof or the slab, are created with conventional methods or using preprinted elements, but are not limited to [11]. This category can be divided into one-story buildings, projects that are limited to just one level, and multiple-story buildings, projects that have two or more levels. The majority of the projects are residential, governmental, or military structures.

However, the majority of printed building structures nowadays are either lovely but barely usable pavilions or residences that are little more than printed boxes with traditional trinkets attached. But the promise of printed buildings has yet to manifest its full potential.

Elements: This category consists of things like columns, beams, stairways, walls, and arches, which are pre-printed parts that may be put together on-site to form a construction or can be used as components for completing a building that has just printed walls in place. Usually, the elements are pre-printed off-site in special facilities, but it can also be done right near the construction site.

In this category, we can also include printed elements used for interior design purposes, like concrete-printed vases and decorative walls. Architects and interior designers may use all of their imagination to create original ideas that were previously impossible to produce using traditional manufacturing methods [11].

Infrastructure: In this category, 3D concrete printing applications go beyond the residential and public building fields, focusing strictly on infrastructure projects. Bridges are the most known examples of using 3D concrete printing in infrastructure; however, there are several more excellent real-world practical instances of using the technology to build parapets and stairways for public areas. The use of 3D concrete printing in the infrastructure sector is rapidly expanding, thanks to the use of parametric and computational design, which helps us optimize the distribution of material and maximize structural performance while also allowing us to create intricate details of natural shapes for better integration within the built environment [11].

2.3. Technologies

The technical framework that businesses and research institutions utilize to produce their projects is defined by many components. Certain components that are often included in a configuration can be recognized in the **Figure 5**. The whole technical configuration can be reduced to three main components: the **digital model**, **material mixer**, and **motion system**.

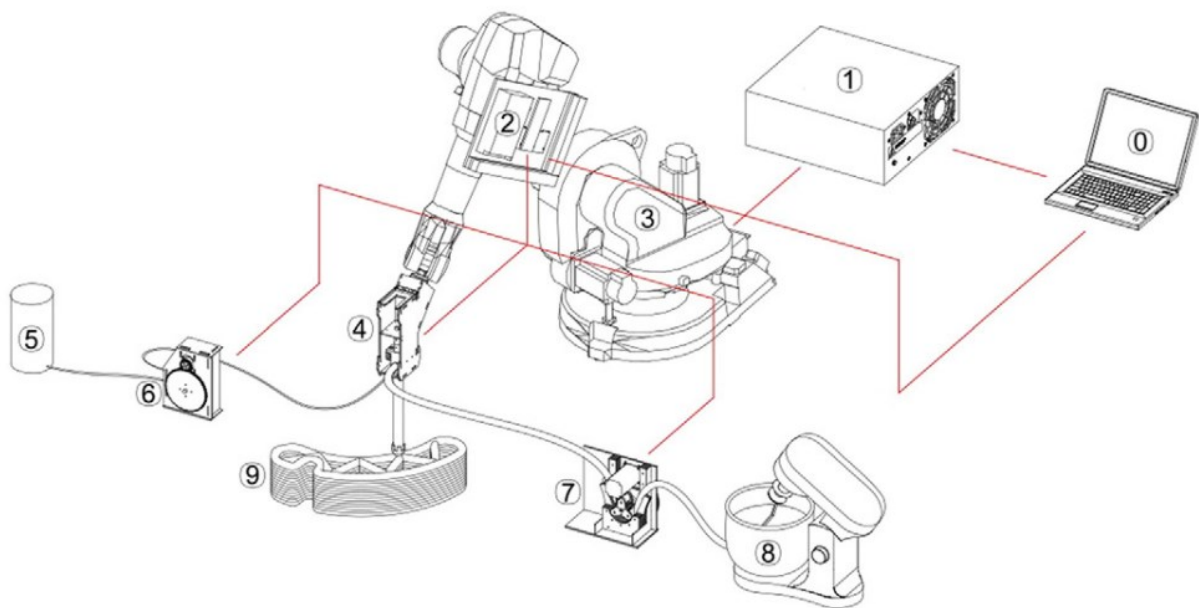


Figure 5: Example of a 3DCP setup: 0. System command; 1. Robot controller; 2. Printing controller; 3. Robotic arm; 4. Printhead; 5. Accelerating agent; 6. Peristaltic pump for accelerant agent; 7. Peristaltic pump for premix; 8. Premix mixer; 9. A 3D-printed object [12]

Based on the 3D concrete printing setup example, two main technological processes in 3D concrete printing can be concluded: the computational design used as an input and the actual printing process involving a material mixer and motion system.

Computational design: For 3D concrete printing, it is necessary to generate and model forms in accordance with a set of guidelines derived from processing limitations. Then the model should be prepared and translated into a script used for system commands.

Printing process: There are two phases to the 3D printing process. First, make a mortar premix with pump-friendly rheological behavior. Due to its thixotropic tendency, the premix is maintained in a shearing mixer to prevent setting. A peristaltic pump is then used to deliver the pre-mix to a mixing screw inside the printhead [12] A motion system is used for the spatial displacement of the printhead.

2.3.1. Digital Model

Making a computer model of the elements that will be 3D printed is a crucial component of the overall 3DCP process. Luckily, the advanced technology of today's 3D computer graphics, both in terms of software and hardware, makes it simple to create such digital models. Many commercial and open-source software programs are available for use in this regard.

To point out, the final outcome of a conventional 3D concrete printing design process is a digital model, which is then converted into a machine-readable language that runs the motion system. Three steps make up the design process for 3D concrete printing: (I) global design of building elements; (II) material distribution; and (III) toolpath planning [13].

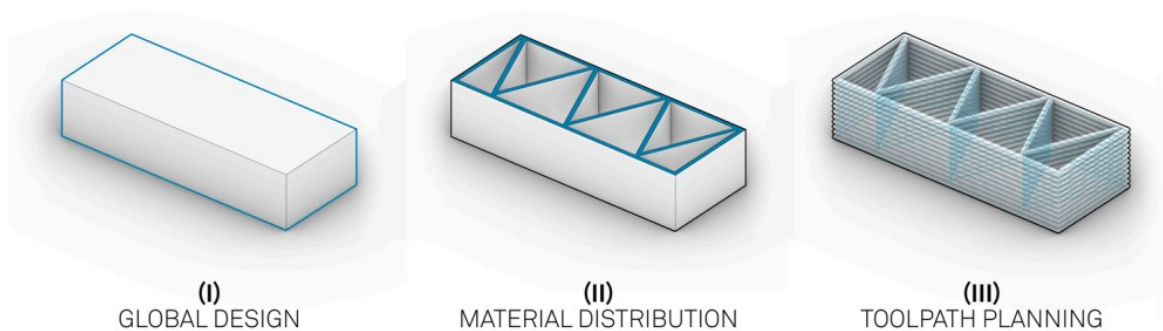


Figure 6: Development scales in a conventional 3DCP design process: (I) global design; (II) material distribution; (III) toolpath planning [13]

In commercial applications, these three steps are created by various specialists, which de facto results in a gap between the stages. The idea of these processes is disregarded in conventional structural engineering. Furthermore, the creation of AM-specific designs is not supported by modeling using the conventional Boundary Representation (BRep). This difference between the planned design geometry and the actual manufacturing results causes a significant difference. Additionally, related materials can exhibit unexpected mechanical behavior [13].

When designing, the physical nature of 3D printing and its constraints must be taken into account because they are not easily visible during computer-aided design. For instance, the design process should take into account the motion system's speed, the size of the nozzles, the thickness of the layers, the behavior of the materials, and the extrusion capacity of the pump [11]. e.g., layer thickness, product dimensions, etc., and the functional properties of the produced part, e.g., mechanical strength, thermal conductivity, etc. Both types of constraints will have to be considered synergistically at three different time and spatial scales: the material scale, the building path scale, and the global shape scale.

The 3D concrete printing is one of the few processes that actually uses the BIM model directly for the translation of building elements from the digital environment to real-life materialization.

Suggestive modeling approach:

The recommended method involves using a BIM program as the beginning point for a tightly connected method for deploying robotic 3D concrete printing in buildings. The BIM modeling program Revit is used as an example, and Rhino is used to implement this strategy, Rhino.Inside.Revit plugin. So, Rhinoceros is used to create the script for robotic printing, and Grasshopper is recommended due to its greater usage in the digital fabrication environment than Dynamo [14].

In this way, the command lines and printing simulation are created immediately. A tightly connected method for using robotic 3D concrete printing in construction is proposed, and it begins with the BIM program CON329-8 operating inside the memory area of Revit. Model exports and imports don't transmit any information because the entire procedure is prepared in a single environment [14].

The Speckle plugin, for instance, may be used to facilitate cooperation among project stakeholders. It will be used to exchange printing data and transfer geometrical data across the software it supports in real-time. Forge, BIM360, or Unity Reflect are more options for cloud-based information storage and collaboration. Fologram might be used to depict the model and the 3D concrete printing simulation in augmented reality. When integrating into construction environments, BIM technologies may be utilized for conflict detection in all BIM-related contexts, including project documentation [14].

The process's outcome is displayed in **Figure 7** to demonstrate how the created model and 3DCP simulation may be seen simultaneously. This visualization is shown in four columns, from left to right, in Rhinoceros, Revit, the Speckle online viewer, and in augmented reality with Fologram.

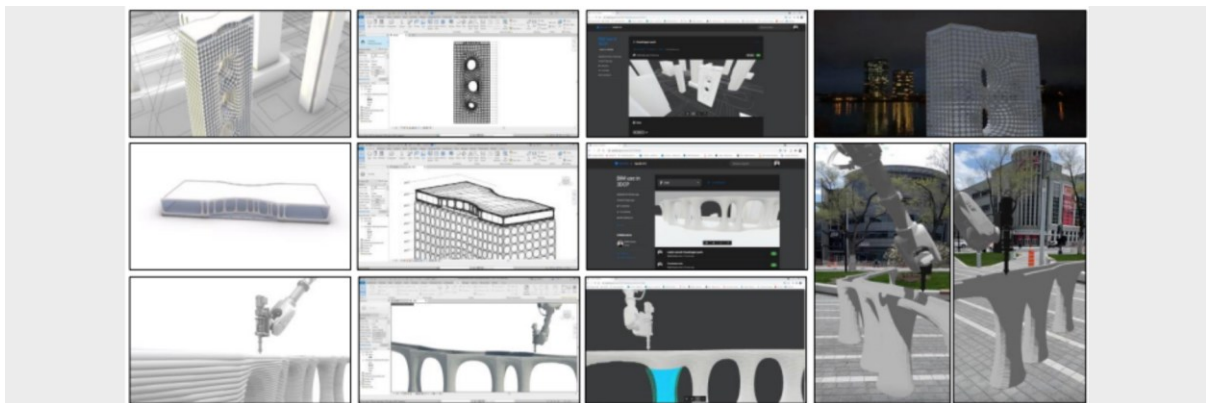


Figure 7: Visualizations of suggested processes that are available in Rhinoceros, Revit, Speckle, and Fologram [14]

2.3.2. Material Mixing

In order to print, it is necessary to pump and extrude a concrete mixture with the required rheological characteristics layer by layer. The component of the system responsible for combining the ingredients and supplying them to the nozzle in the case of 3D concrete printing is known as material mixing and supply.

There are a few ways to pump and extrude the concrete mixture, but the most popular one in use (inkjet head printing), as we see below, can be divided into three steps, each of which may vary from company to company. Generally speaking, the three steps are mixing, pumping, and printing, as shown in **Figure 8** [15].

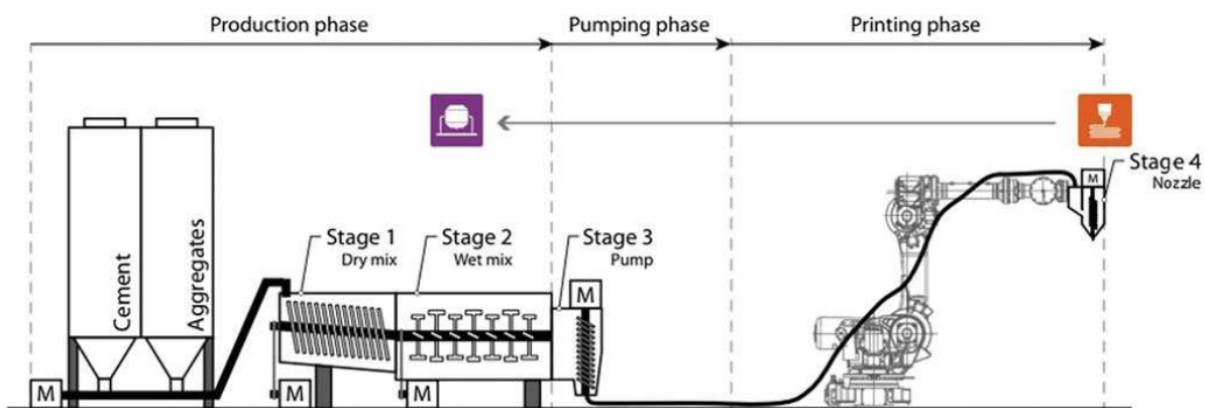


Figure 8: The phases of material mixing and supply [15]

In the production phase, all the elements are combined to create the admixture that will be used throughout the printing process. First, water is combined with the primary material. In the case of 3D concrete printing, mortar is used as the primary material and may be dry mixed with other ingredients such as aggregates and additives to enhance certain properties [15].

In the pumping phase, the homogeneous mixture is pushed to the printing, often by a pipe, since this procedure uses cementitious materials, a particular kind of pump is needed considering the unique qualities of this kind of material.

Finally, during the printing process, the mixture that was pushed via the hose reaches the printhead, where it may either be sent straight into the printing apparatus or stored in a hopper, a tank with a certain volume. In all situations, this spindle is in charge of extruding the material, regulating its flow while rotating, maintaining uniformity, and limiting the occurrence of air bubbles. Material must travel through a nozzle, which can have a variety of geometries, as a result of the spindle's rotation [15].

Two systems may be distinguished depending on the technology in use: **Batch Process** and **Continuous Mixing Process**.

Batch Process: The most basic and accessible system that can be implemented in the field. In this procedure, a typical mixer is used to combine the cement, aggregate, water, and additives. When the substance is prepared for printing, it is then transported to a concrete pump, which forces the concrete through a pipe to the nozzle to produce the designed element. The drawback of this approach is that after the printing process has started, it is impossible to adjust the mixture. As a result, it is likely that the entire batch will need to be replaced if the material properties are not sufficient [16]. Additionally, adding additives to the material before it is forced through the nozzle, such as an accelerating agent, can increase the material's quality but can also clog the hose.

Continuous Mixing Process: This technique, which was developed specifically for 3D concrete printing, uses a mechanism where cement and water are added as needed during printing. Occasionally, the additive is subsequently added to a mixing reactor right before the extrusion. The material may be continually mixed, allowing the water/cement ratio to be adjusted as necessary [16]. Additionally, the option to add additives like accelerating agents before extrusion provides the opportunity to modify the concrete's capacity to cure, for instance, if the stability of the print is compromised.

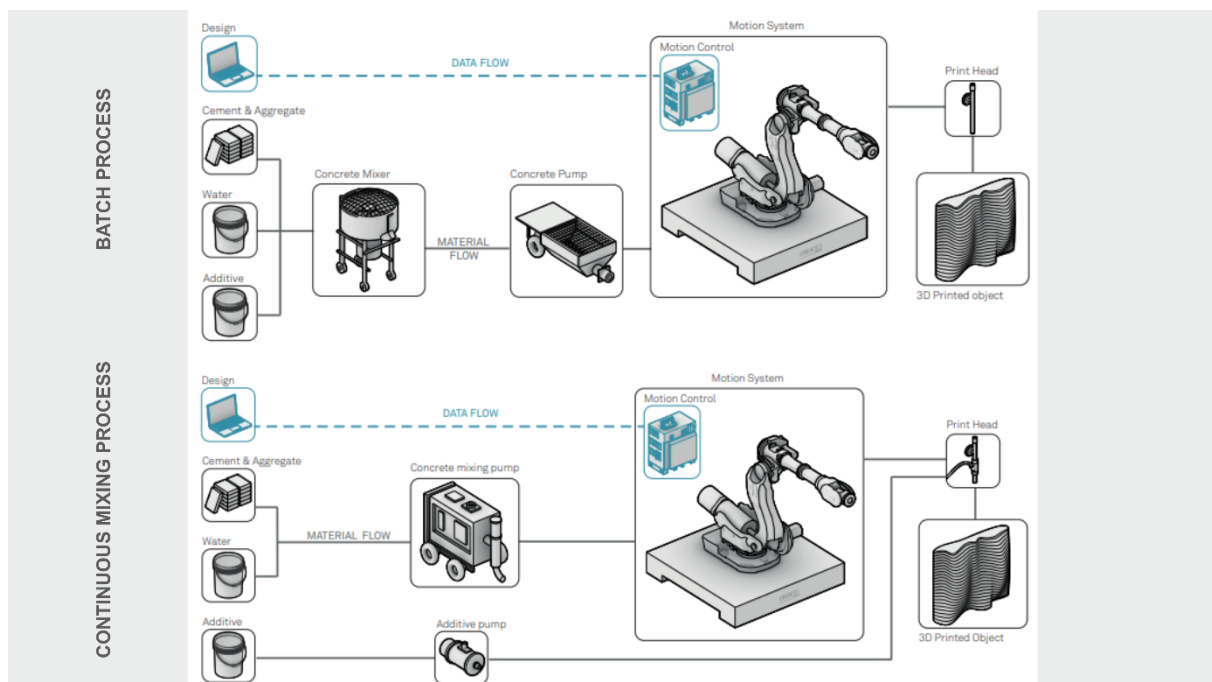


Figure 9: Diagrams of two distinct material mixing processes; batch process and continuous mixing process [16]

2.3.3. Motion System

A computer-controlled system that can move the extruder to the correct location is required to move the nozzle in accordance with the script generated by the digital model. The choice of a suitable motion system depends on the project's scope and construction strategy but is largely influenced by its size, geometry, and construction location. The most popular motion systems used in 3DCP are **gantry-based systems** and **robotic arms**.

Gantry systems are common motion systems used in the additive manufacturing (AM) construction industry that are especially connected to technologies like contour crafting. This system has a printing head that can move in the X, Y, and Z axes, like a Computer Numerical Control (CNC) machine [16].

The Gantry System's main features are as follows:

- **Stability and load-bearing capacity:** The gantry system is preferred because of its propensity to bear heavy loads, making it appropriate for building big structures.
- **Affordability and Flexibility:** It is renowned for being quite simple to produce, accessible, and adaptable to various building projects.
- **Voluminous Design:** The voluminous design of the gantry system is one of its drawbacks. Frequently, the actual gantry structure must be greater than the print area.
- **Limited adjustability:** Another issue is the printing angle's limited adjustability. The normal range of flexibility provided by gantry-based systems is between 3 and 4 degrees. This constraint may make it difficult to print intricate and curved designs.

The Gantry System's prominence in the AM building industry may be attributed to its dependability, affordability, and flexibility in meeting different construction requirements. However, in some design contexts, its size and lack of flexibility may pose problems [16].



Figure 10: Gantry system by Cobod [8]

Robotic arm: A robotic arm on wheels or an uninterrupted track makes up the mobile 3D printer. This system's high degree of flexibility allows it to print intricate structural structures since it has six or seven degrees of freedom. However, at some building sites, the mobility of the mobile robotic arm and the precision of its localization are constrained by the topographical conditions, despite the fact that using this mobile system is more advantageous than using one that is fixed. Other mobile 3D printer models lack wheels or continuous rails, and are lifted from one printing spot to another at the building site using a crane [17].

Mobile 3D printing Robotic arms are designed for portability and versatility. They can navigate construction sites or manufacturing facilities, providing flexibility for printing various parts of structures. Equipped with precise control systems, these arms ensure accurate deposition of concrete or other materials, ensuring structural integrity. They are commonly used for on-site construction, reducing the need to transport prefabricated components.

Fixed robotic printing arms are stationary setups, typically installed in manufacturing facilities or construction sites on gantries or frameworks. They excel in high-volume production and repetitive tasks, operating continuously without relocation. These arms offer a consistent printing path, making them ideal for large-scale projects with repetitive design elements. Their precision and uniformity make them suitable for applications where consistency is crucial.

Both types of robotic arms play a vital role in advancing 3D concrete printing technology, offering different advantages depending on the project's requirements. These two types of robotic arms cater to different construction needs, with mobile arms prioritizing flexibility and on-site printing, while fixed arms focus on high throughput and precision. The choice between mobile and fixed robotic arms depends on factors such as project scale, mobility needs, and production volume.



Figure 11: Robotic arm by Cybe [18]

2.4. Printing approaches

Different approaches to 3D concrete printing in construction can be outlined. Depending on the manufacturing environment, these can be classified into two main categories: **in-situ printing** and **preprinting**. The illustrations in **Figure 12** shows a difference in the construction stages and geometric complexity between the two groups.

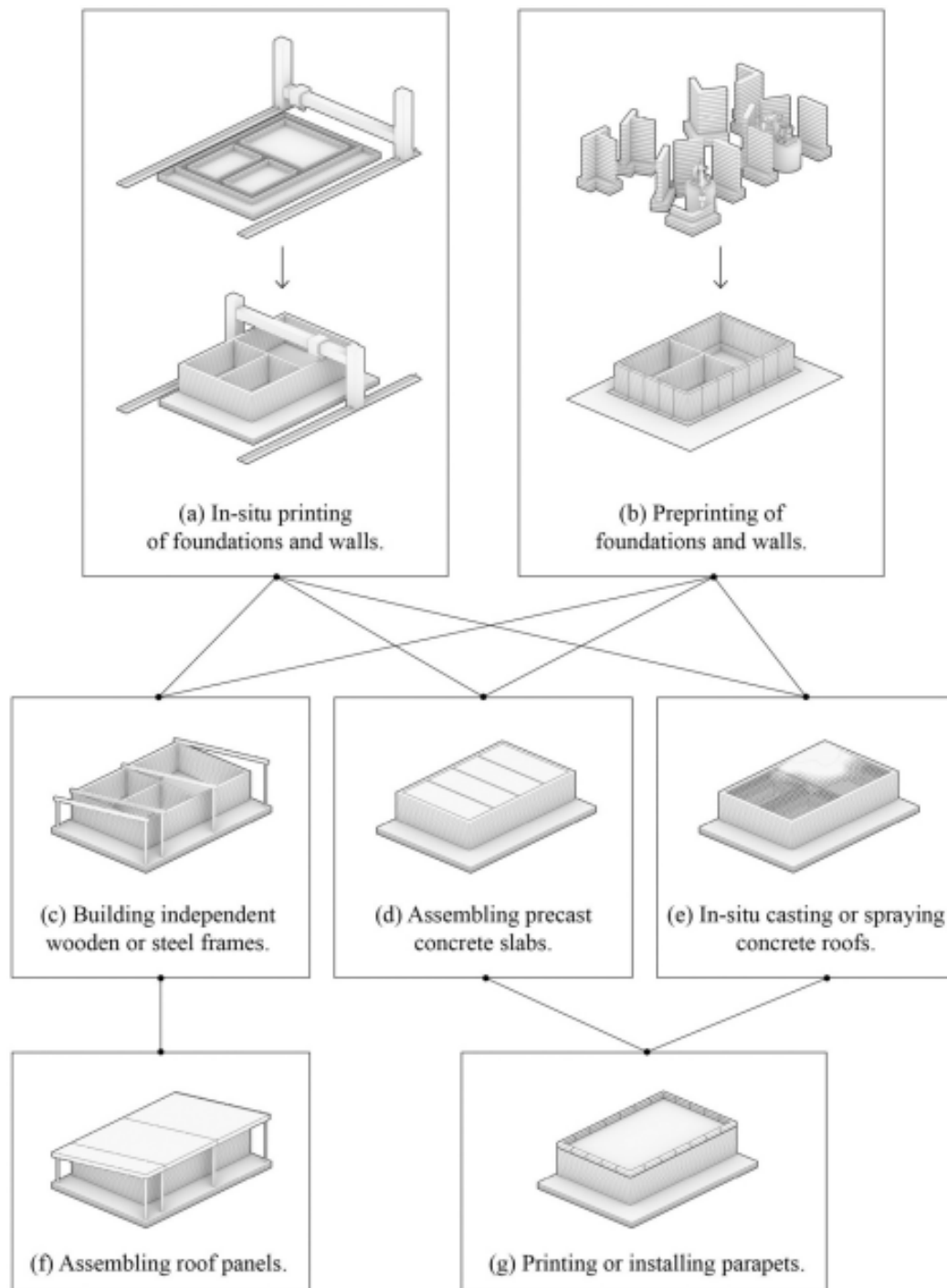


Figure 12: Common 3DCP building construction techniques [19]

2.4.1. In-situ 3DCP

Walls with straight extruded shapes are frequently created using in-situ 3D concrete printing. As a result, the single-story structure is questionable as a feasible application of the 3D concrete printing technology since it tends to concentrate on spatial divisions and the manufacture of walls that have a structural behavior comparable to masonry. Concrete is still viewed in these straightforward constructions as a readily available, affordable material, which is already the cause of its abuse [20].

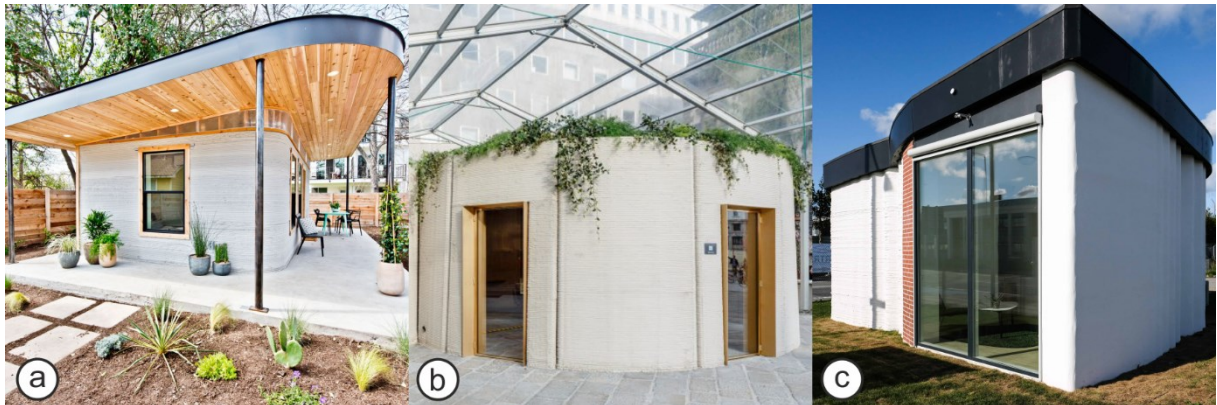


Figure 13: In-situ 3DCP: (a) house from Icon, (b) house from CyBe, and (c) office unit Cobod

2.4.2. Prefabricated 3DCP

As shown by prefabricated structural elements like columns, beams, slabs, and spatial elements such as bridges, concrete is preferred for usage as a structural material. Prefabrication provides a greater ability to produce more sustainable concrete buildings through material optimization and effective forms, as shown by the difference in shape flexibility [20].



Figure 14: Prefabricated 3DCP: (a) column from Xtree, (b) bridge from Tsinghua University, and (c) slab from TU Graz

3. Real 3DCP Case Studies

In order to better understand the application of 3D concrete printing methods and solutions on real-scale projects, three real-life case studies were analyzed and briefly presented. All three selected projects share the same function as residential buildings but used different approaches and methods in order to be built. There are different aspects between the projects in all stages of the construction process, starting from the design concept and finishing with the printing and assembly process, but the projects were mostly classified by the place where the printing process is done, as in-situ printing, preprinting, and mixed.

3.1. In-situ printing

The residential building project from Germany presented below is a good example of an in-situ printing method. It is a building with a basic architectural design and structure that has the same size and level of complexity as a typical two-story independent mansion **Figure 15**. The project mostly concentrated on optimizing today's building industry's constructional, design, and 3D concrete printing process difficulties [21].



Figure 15: The animation of the 3DCP house in Germany [21]

Construction concept: The building was designed to have a solid foundation and many layers of wall components (**Figure 17**). The interaction of the various wall shells, each with a width of 60 mm, allowed for the creation of cavities that, on the one hand, served as fill-in insulation for the thermal insulation and, on the other, served as lost formwork for locally cast unreinforced concrete for structurally highly loaded areas of the building. There was no reinforcement used in the construction of any vertical wall components.



Figure 16: The interior of the 3DCP house in Germany [21]

Motion system used: A gantry system was used for the in-situ printing of the walls. It was installed on a concrete foundation by using a mobile site crane. The motion system covered the entire printable area of the building, and by gently adjusting the water volume, printing speed, and amount of material extruded, the printing process may be modified to work under different weather and temperature conditions. This allowed the creation of an unplastered facade surface with a uniform exterior finish [21].

Construction strategy: The ground floor slab's edge formwork was created using a 3D printer in the first phase. Then the walls were printed in segments in order to adhere to the maximum layer time. The horizontal components, such as the ceilings, were traditionally strengthened using partly prefabricated concrete parts that were installed on site over printed wall panels before being covered with ready-mixed concrete (**Figure 16**). The knowledge obtained from printing the ground floor was immediately applied to the top floor of the building since updates to the 3D model are simple to accomplish and can be implemented straight on the printer [21].

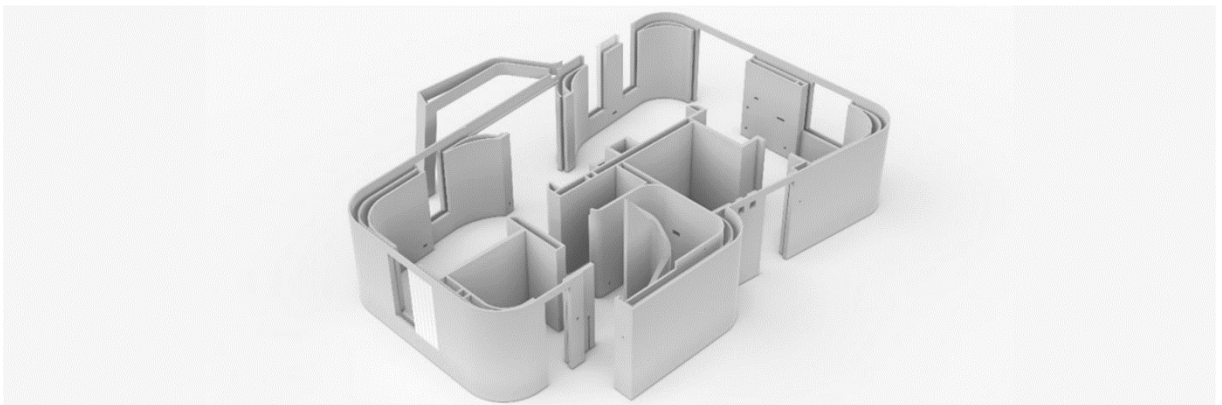


Figure 17: The BIM model of the 3DCP house in Germany [21]

3.2. Preprinting

The residential building project from the UAE presented below is a good example of the on-site assembly of preprinted elements. It is a ground-floor building that consists of an entirely load-bearing concrete printed envelope and interior walls; it also eliminates the requirement for steel reinforcement bars, as seen in **Figure 18**.



Figure 18: The image of the 3DCP house in the UAE

Construction concept: The building was designed to be easily divided into multiple printable components. Each printable component is unique in geometric form and adapted for specific needs. Only the assembly of the components was done on-site; the printing process was entirely done off-site.

Motion system used: An indoor robotic arm printer was used for preprinting the components off-site without wasting any material, achieving greater environmental control and hence better print quality by creating a flawless surface finish with great accuracy. The prints could be conducted with near-zero downtime and exceptionally high accuracy (± 0.05 mm), and modules that failed to print could easily be reprinted. As a result, production may be increased while material use and expense are significantly decreased.

Construction strategy: The digital model of the building structure is divided into printable modules or components, and each of these components is printed independently off-site. All of the information for embedding the service fixtures is converted into form when the model is rationalized into modules for printing, and this form is then directly printed to produce the final output in concrete. After indoor printing, the prefabricated modules are transported on-site and then assembled using a typical crane.

3.3. Mixed

The residential farmhouse project from China presented below is a good example of using both in-situ printing and preprinting methods. The housing project is situated in a mountain community and is inhabited by peasant residents. The impacts of site conditions are caused by the restricted construction area that is determined by the built environment, such as the congested nearby homes and narrow alleys. The second effect is brought on by the unpredictable weather, the dry alpine climate, and the significant day-to-day temperature variation, which both call for greater material stability throughout the printing process [19].

Construction concept: Because it was more appropriate to bring robotic arms to the location where in-situ printing will take place, the farmhouse was divided into two tiny bays and three large bays by an in-situ printed wall. Large bays serve as a living area; the house's bathroom and kitchen are formed by small bays that sit between larger bays. In addition to the in-situ printed walls, the majority of the preprinting components are completed in the site preprinting zone. The foundation trenches, structural walls, ornamental walls, arch roofs, and flat roofs are only a few of the several 3D concrete printing component types that make up the entire structure (**Figure 19**) [19].



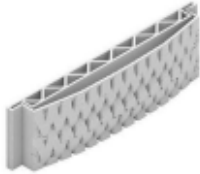


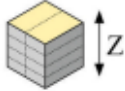
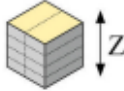
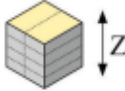
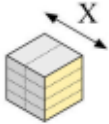
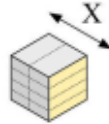
Foundation Trench	Structural Wall	Decorative Wall	Arch Roof	Flat Roof
				
Printing Direction Horizontal	Horizontal	Horizontal	Vertical	Vertical
Loading Direction 				
Printing Environment Factory preprinting	In-situ printing	Site preprinting	Site preprinting	Site preprinting

Figure 19: Component types of the 3DCP farmhouse in China [19]

Motion system used: Three robotic arm printing devices mounted on mobile platforms were used for both in-situ printing and site preprinting. Each printing system's track is essentially separated into two halves. The north section is in charge of in-situ printing, which takes days to complete for each wall, while the south part is utilized for more flexible work that can be completed in a matter of hours [19].

Construction strategy: There were four stages to the building process: foundations, walls, roofing, and the finishing (**Figure 20**). Phase one involved the 3D printing and assembly of the foundation, which took place concurrently at the manufacturing facility and the construction site. The structural walls were in-situ printed during phase two. During this phase's intermissions between various in-situ printing tasks, ornamental wall components were further produced at the preprinting zone on the site. The in-situ printing work was continued in Phase 3 along with the printing of the roof components in the preprinting zone on site. The open space's surface treatment, inside trim, and landscaping are all included in the final phase [19].

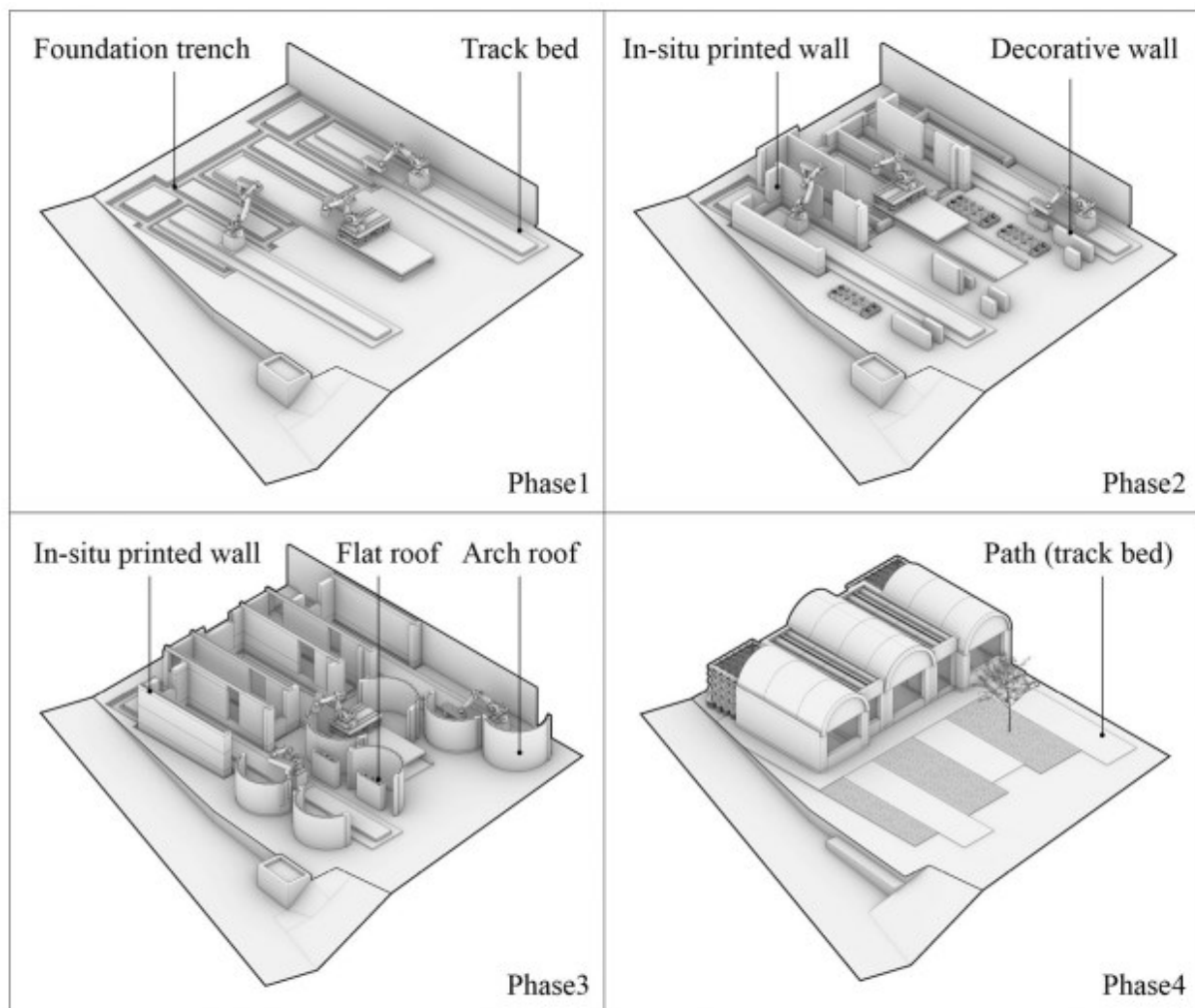


Figure 20: The construction strategy of the 3DCP farmhouse in China [19]

4. Building Designing for 3DCP (Methodology)

The practical part of the thesis consists of designing a building and adapting the BIM model for the real-scale 3D concrete printing process. The methodology combines the theoretical knowledge of 3D concrete printing requirements with the use of BIM tools. The design process is focused strictly on the architectural part of the project while also considering the overall structural aspects.

The goal of the methodology is to design a typical 2-story residential house with a maximum constructed area of 200 square meters. This kind of project is one of the most common among residential houses and is inspired by the existing 3D concrete printed projects around the world. The project should contain realistic construction solutions and explore ways to integrate 3D printing into components other than just walls. Additionally, the building design should be compatible with already existing technologies and be easily replicated in larger groups of buildings.

The design process should be done using the same BIM authoring tools used by architects for traditional architectural design activities. The general outcome of the methodology will consist of a BIM model and a small-scale 3D-printed model.

For the methodology, three main steps were concluded:

1. **Design Strategy:** A step before the design process begins that is primarily concerned with defining the BIM authoring tools and project design concept.
2. **Global Design:** An intermediate step, similar to the conventional design process, when the overall design with general proportions is completed.
3. **Design Optimization:** Final step, where the design is detailed and adapted specifically for the 3D concrete printing process.

Since the 3D concrete printing on a building doesn't have a huge impact on functionalities and the distribution of spaces, and overall design follows mostly the traditional architectural design process, the focus of the methodology is on design optimization.

4.1. Design Strategy

Before we start the design process of a building for 3D concrete printing, it's needed to establish a strategy that helps us have a clear vision of the ongoing process and desired design outcome. The design strategy consists of defining the basic requirements for the design process, starting with the authoring tools and AM technologies and continuing with the other aspects already involved in the traditional architectural processes. The design strategy can take many forms but mainly responds to two main questions:

What? Designing a building for 3D concrete printing, which follows specific requirements and is influenced by many aspects. The most important aspects that should be taken into account are the **site context**, **motion system** technology, and **material** used.

- First, the building design and construction process should correspond to the location in both legal and technical sense.
- Second, the dimension of the building should be compatible with the maximum working area of the motion system used, and the site's size should be able to accommodate the printing machine.
- Third and the most important, the material used for the printing process should be known before starting the design itself, since different materials give us different opportunities to design architectural forms with required structural stability.

How? In the case of 3D concrete printing, it is recommended to design and model the building entirely in a BIM software which allows us to work simultaneously on the 3D model used by the 3D printing machines and on the architecture paperwork required for obtaining the building permit. In our case, **Autodesk Revit** is used for the design and modeling process, where we can easily extract only the printable geometry needed in different phases, and the model can be easily exported in different formats supported by different 3D printing machines. Both steps, global design and design optimization, will be done by creating a design phase for each one directly in **Autodesk Revit**.

For the final results, the **BIM model** will be presented in **IFC format**, and the printable components will be exported in **STL format** for both real-scale 3D concrete printing and small-scale 3D models since the majority of 3D printers work with this format. Because of the scale effect, for the small-scale model to be more rigid, the geometry includes more printable layers and is not limited to concrete ones. The small-scale model will be printed in plastic at a scale of 1:100 and used for demonstration purposes to better explain the printing and assembly stages.

4.1.1. Site context

The site context in architecture is the first and most important aspect when designing a building, regardless of the construction processes and technologies applied. In the case of 3D concrete printing, site context aspects such as climate, topography, etc. dictate the design and construction processes, for example, the possibility of on-site printing, the availability of local materials, the thickness of the walls and their number of layers, etc.

For this particular methodology, the construction site location was considered in Romania, with a flat topography, and there were no plot dimension limits taken into account. The construction site is considered to be available for 3D printer installation and printing on-site.

4.1.2. Motion system

The choice of the motion system is dictated by the site context and construction strategy and, by itself, has an impact on the dimension of the building and the thickness of the wall layers.

In our case, it is considered to be a gantry system, one of the most reliable 3D printers in the 3D concrete printing field. For example, the COBOT gantry printer is a modular device that can create structures that are 12 meters wide, 27 meters long, and 9 meters tall. With modules measuring 2.5 meters in width, length, and height, the 3D printer's size may be increased. There are no constraints on length, although its maximum capacity can hold 6 modules with a width of 15 meters and 4 modules with a height of 10 meters [22].

4.1.3. Material

Knowing the material before you start the design process is important for design prospects, especially for structural load and architectural decoration.

The printing material considered for this methodology is concrete, including fiber-reinforced concrete, which can be prepared in many forms by adding different types of additives. Concrete was chosen for 3D printing because it is the most appropriate material used for building and brings it closer to traditional methods. Regardless of the use of concrete, the same 3D printing principles apply to most kinds of materials.

4.2. Global Design

The initial design process for 3D concrete printing is mainly the same as that for conventional construction methods; the difference is that the architects are not limited to rectangular shapes and are more free to design free floor plan shapes in a cost-efficient way. In contrast to the complicated forms that we can create, the simpler we keep the design, the lower is the probability for problems to arise during the printing process, so there must be a compromise between these two extremes.

The global design can be represented by a model started from scratch or an existing project that is being adapted for 3D concrete printing. In both cases, printing supports are taken into account in the initial global design process.

There are two types of printing supports that are complementary to each other:

- **Printing bed:** Permanent main support for the 3D printing components in order to guarantee printability and stability during and after the printing process.
- **Printing suport:** Temporary support for the overhanging 3D printing components in order to guarantee printability during the printing process.

In this stage, the multiple-layer walls and slabs are treated as a whole with an approximate thickness while following the general configuration and dimensions, as seen in **Figure 21**.

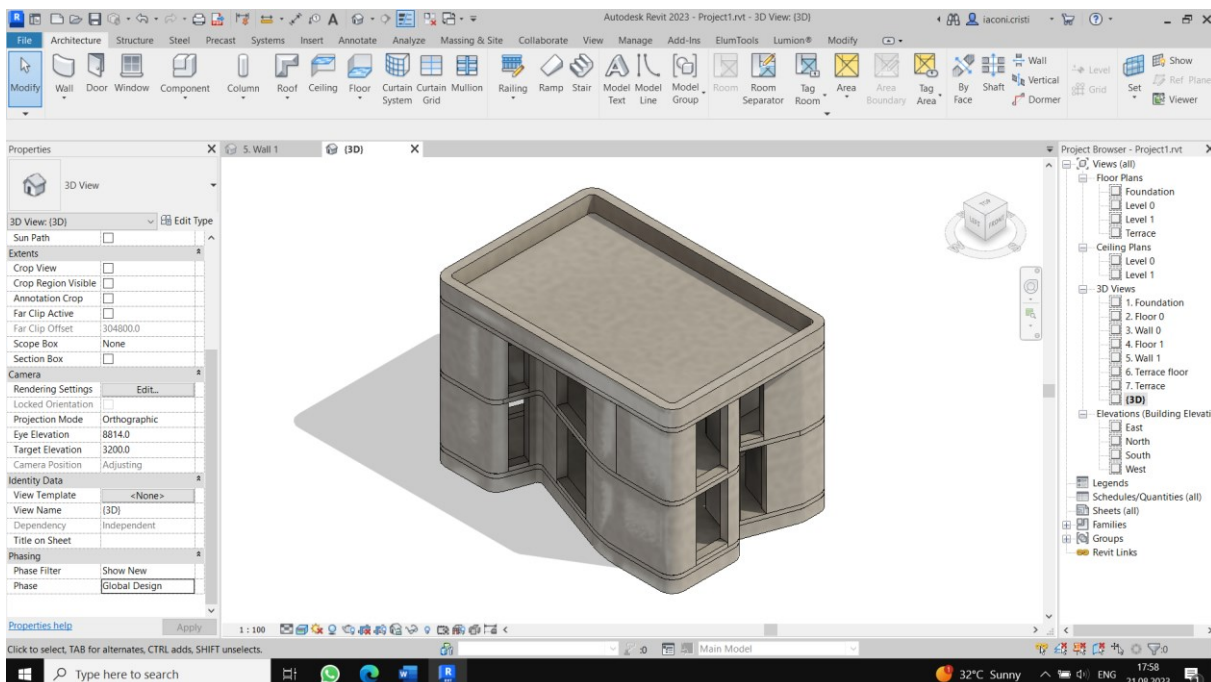


Figure 21: Global Design phase of the building

4.3. Design Optimization

Design optimization for 3D concrete printing consists of preparing the BIM model for the use of 3D printing as a construction method. This optimization process includes the creation of a construction strategy for each printing stage and adapting the 3D model in accordance with it. As a result, the model must include the precise printable geometry required by the 3D printer, separated and arranged into discrete phases for simple extraction and export in the printable format.

The **construction strategy** begins with figuring out the printable phases and printing approaches for each building component. Therefore, it is important to determine the exact printable parts and their relationship with the elements built by traditional methods. The approach provides answers to several problems that are unique to each component, such as how printable components function and will be printed, the number of printed layers and their thickness, the printing order, type, and direction of the printing process, etc.

The primary goal of **3D modeling** for concrete printing is to highlight the printable parts and clearly separate them from other components. Starting with a global design, the project is further detailed in individual elements and layers, as seen in **Figure 22**. The process is similar to the detailing in traditional architectural 2D drawings; the difference is that the 3D printer uses the actual extracted geometry directly from the BIM model.

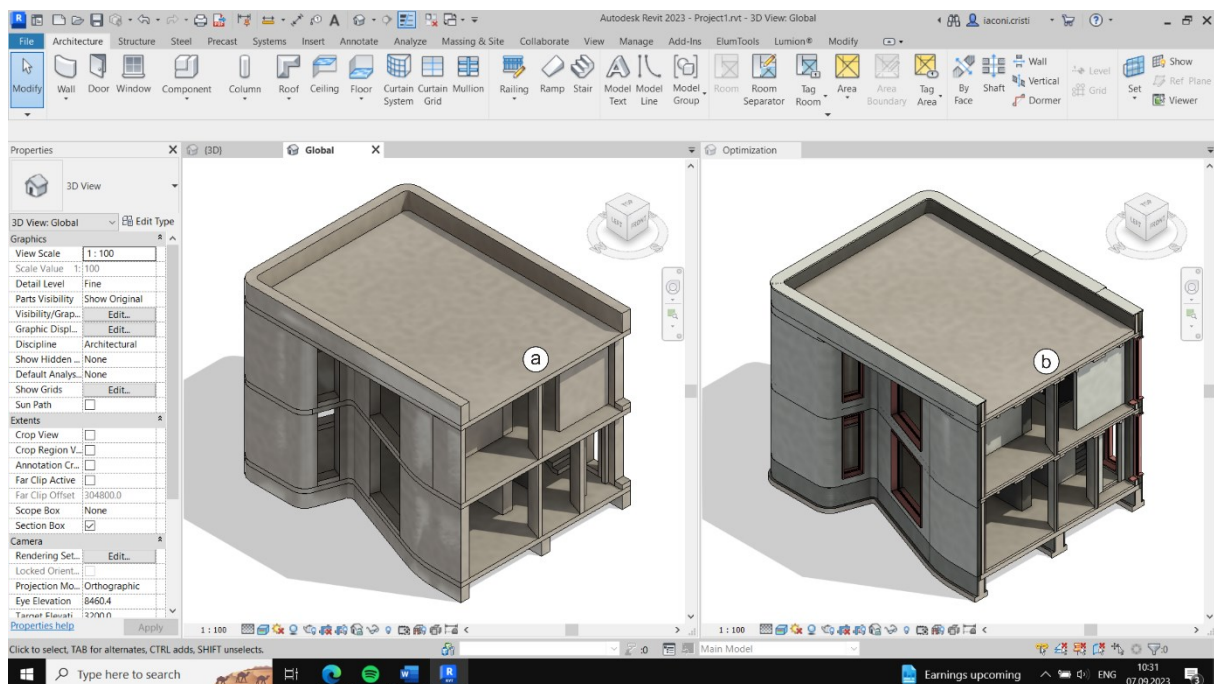


Figure 22: Sectioned model of both design phases: (a) global design and (b) design optimization

4.3.1. Foundation

For most 3D concrete printing buildings, the foundation is designed to be created using traditional construction methods, but we are not limited by technologies to do it in the same way. The foundation can be 3D printed in whole or in part, and depending on the circumstances, it can be done on-site or preprinted off-site, followed by installation on the construction site.

Construction strategy: For this particular project, the foundation is designed to be created by a combination of 3D printing and traditional methods directly on the construction site. The first step is to create a foundation slab that gives us a flat surface and rigid support where we can start the printing process. Then we print the printable parts that serve as formwork; in this instance, the foundation is mostly similar to the conventional technique of filling the gap with reinforced concrete. For construction purposes, the exterior foundation wall is higher than the interior one, but both printable parts have the same properties as a printed wall, as seen in **Figure 23**.

3D Modelling: For modeling the foundation, a structural foundation slab is used as a printing bed. Foundation printed parts were considered walls; starting with a basic wall family, a new type was created and named (Printed Foundation Wall 60 mm). This new type is used only for foundations and was assigned a width of 60 mm and a specific material. The foundation walls are separated from the rest of the building and can be easily selected and exported independently.

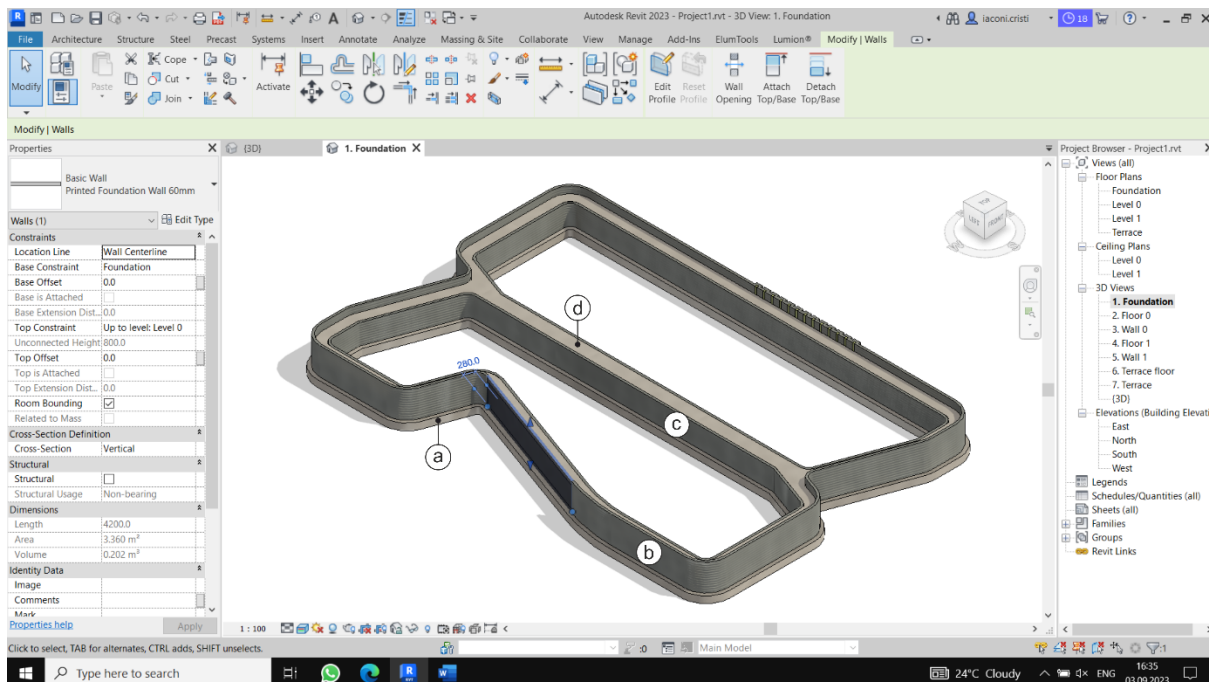


Figure 23: Foundation: (a) precast printing bed, (b) exterior printed foundation wall, (c) interior printed foundation wall, and (d) reinforced concrete filling

4.3.2. Ground floor slab

The ground floor slab is one of the most crucial elements in 3D-printed buildings; it serves as the base and support for the entire printed building. As with the foundation, the ground-floor slab is usually built in traditional ways, although it can be 3D printed. To choose the optimal resistance qualities of the slab and to have a better connection with the foundation, a cast-in-place slab for the ground floor level is still more reliable.

Construction strategy: The slab will be cast in place and reinforced in order to create a very rigid platform. The connection between the foundation and the slab can be done as a typical construction project. In the same way, the interior void space between the foundation and the floor will be filled with a typical filling material used for creating the bed for precasting the floor. The ground floor slab will serve as a printing bed for the printed structural and interior walls.

3D Modelling: The slab was modeled using a predefined architectural floor family from Revit and created as a new type with a specific thickness and material. While the exterior foundation wall was modeled higher to be used as formwork, the slab perimeter has an offset of 10 cm from it to leave free space for the perimeter thermal insulation that was also modeled as a separate insulation wall, see **Figure 24**. As a result, the floor slab's upper surface is the same height as the thermal insulation wall and outside foundation that served as formwork.

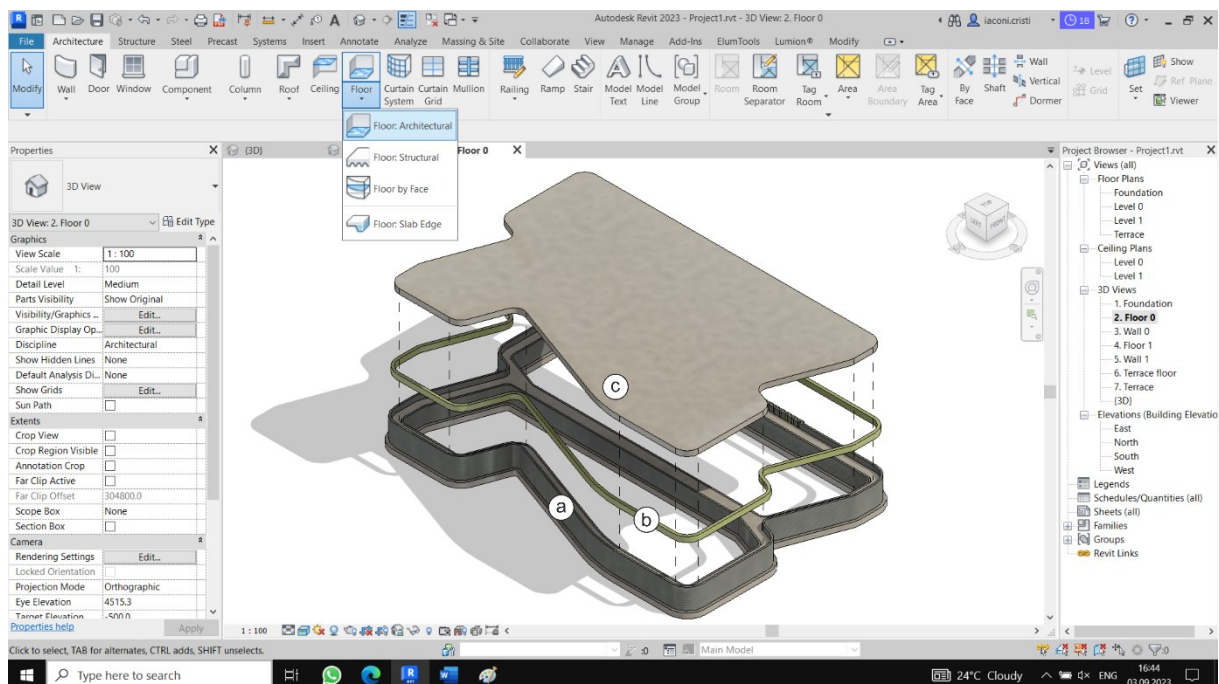


Figure 24: Ground floor slab: (a) foundation, (b) perimeter thermal insulation, and (c) cast-in-place reinforced concrete slab

4.3.3. Ground floor walls

The most printable part of a building are the walls, and most 3D concrete printing projects are limited to printing only the walls. Also, 3D-printed walls in a project account for the majority of the building's constructed volume. The geometry of the walls is extended on a vertical axis, and the printing layers are self-supporting, one on top of another, excluding the use of formwork during construction and other structural supports overall. Depending on the design strategy, walls can be printed in multiple ways and layers.

Construction strategy: The envelope wall of the building is designed to be printed in multiple layers. The printable parts of the envelope are composed of one exterior decorative layer and two interior structural layers that form a closed room space that can be filled with concrete for structural purposes. The exterior layer is strictly for decorative purposes and is entirely separated by a 10 cm thermo-insulation barrier from the interior structural layers. Besides the perimetral structural layers, there is also an interior structural wall that works in the same way. On the other hand, the simple interior wall's purpose is only for compartmentation and consists of two printed layers that form a closed, elongated space between them that can be filled or not with material for different reasons, like sound insulation. Overall, we have three types of printed walls: exterior decorative walls, structural walls, and interior compartment walls, as seen in **Figure 25**.

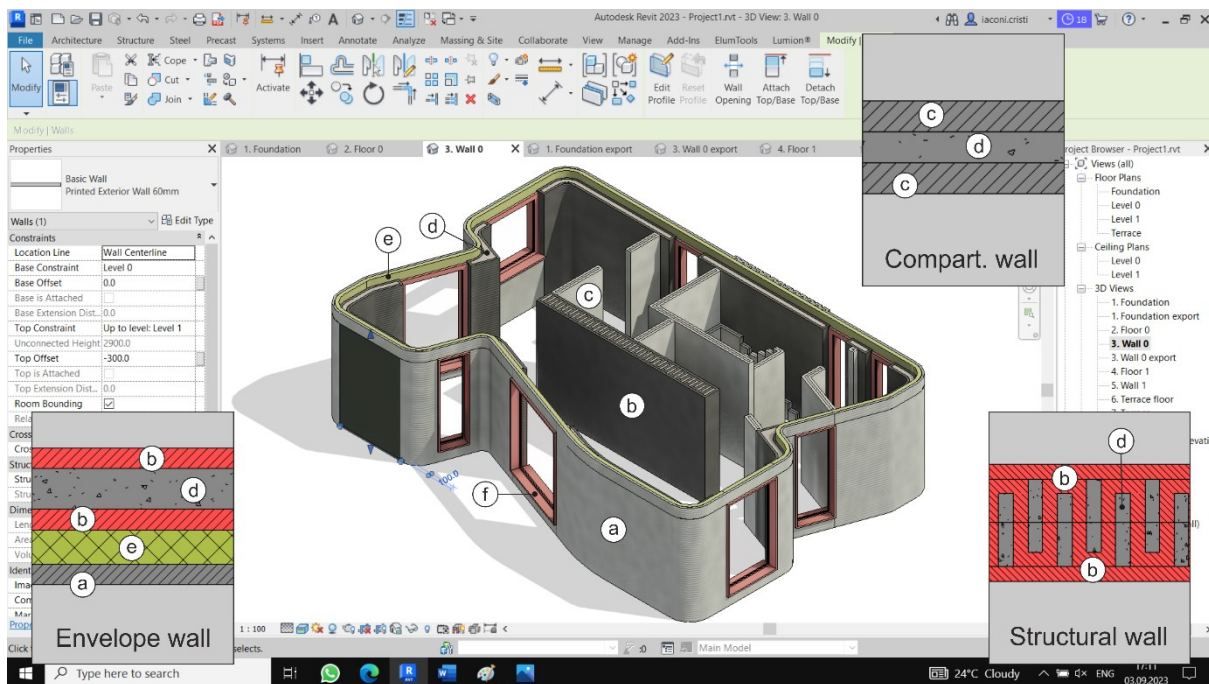


Figure 25: Ground floor walls: (a) exterior decorative wall, (b) structural wall, (c) interior compartment wall, (d) wall-filling material, (e) thermal insulation, and (f) openings

3D Modeling: For modeling the walls, five categories were concluded, as seen in **Figure 26**, and for each one, a new wall type was created starting from the basic wall family. Since the printer is going to use the same nozzle for printing the entire building, all wall types have the same thickness of 60 mm.

The walls were modeled and categorized by constructability and printing stage as follows:

- a) Exterior decorative wall:** It is modeled as one continuous wall, completely separated from other types of walls. It serves as an exterior finish and works as a protection for the thermal insulation layer. In comparison with other types of walls that use the slab as a printing bed, the exterior wall uses the foundation wall as a printing support.
- b) Upper part of the exterior decorative wall:** The printable part starts after installing printing supports on the openings. It was modeled separately in order to be easier to export as a separate geometry.
- c) Perimetral structural wall:** It follows the path of the exterior wall and is modeled in two printable layers that form a closed void space between them.
- d) Interior structural wall:** It is similar to the perimetral structural wall but with a larger void space between printed layers and located in the middle of the building.
- e) Interior compartment wall:** The wall is modeled in two concrete layers with a 60 mm gap between them and is self-closing without joining other types of walls.

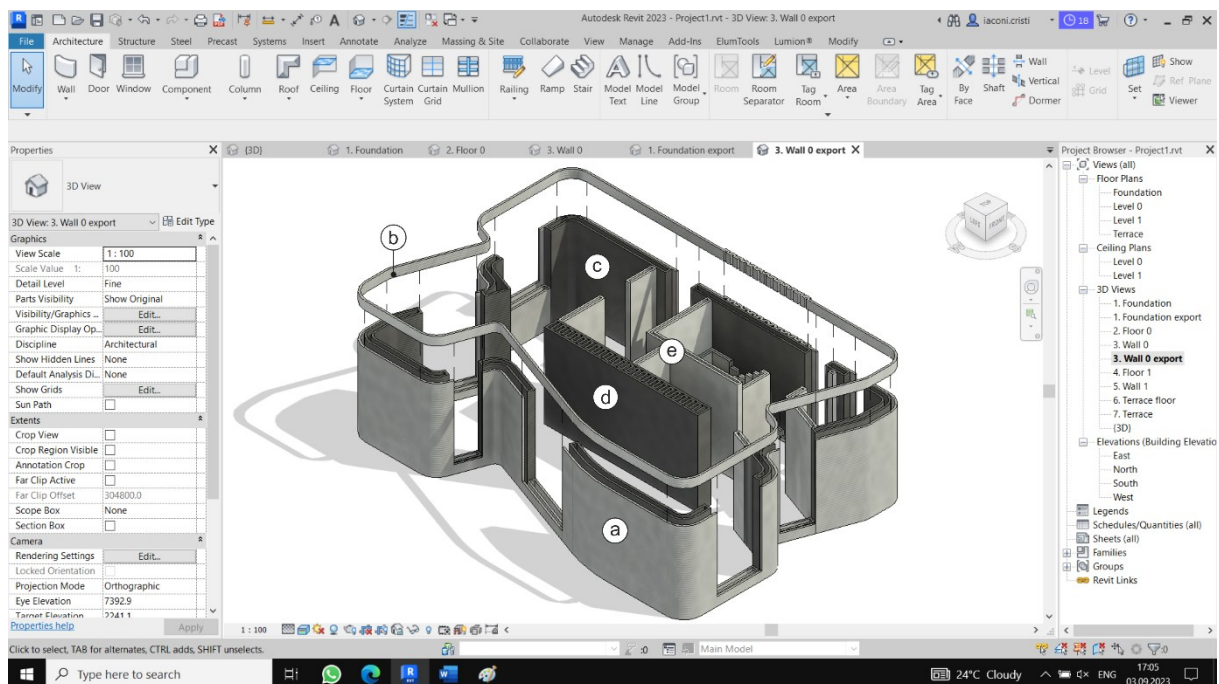


Figure 26: Ground floor printed walls: (a) exterior decorative wall, (b) upper part of exterior decorative wall, (c) perimetral structural wall, (d) interior structural wall, (e) interior compartment wall

4.3.4. First floor slab

The floor slab between levels is the most controversial component of a 3D printed building since its geometry is expanded horizontally and is nearly entirely suspended in the air. There is no technology available that can print horizontally without using a support for printing; for this reason, the slabs are made using traditional methods. Nevertheless, there are options for using 3D printing in slabs; they can be manufactured off-site by printing them in a vertical orientation and then installing them horizontally, or a better choice is to employ indirect printing techniques, such as printing the slab's formwork.

Construction strategy: Three different slab-creation techniques were taken into consideration from an architectural standpoint; however, a structural engineer's perspective should be used to determine the best slab design. For this project, the slab was designed to be easily done by casting in place, using traditional prefabrication panels, or using indirect printing for prefabrication.

3D Modelling: First, the entire slab was divided into six smaller slab panels, as seen in **Figure 27**, this division is speculative because there was no structural engineer involved in this design process. The panels were created using the predefined slab family from Revit; each slab panel is composed of two sections: a solid section and an optimized section. The optimized section was designed to reflect the ultimate optimization following structural design intervention but does not contain a resistance calculation.

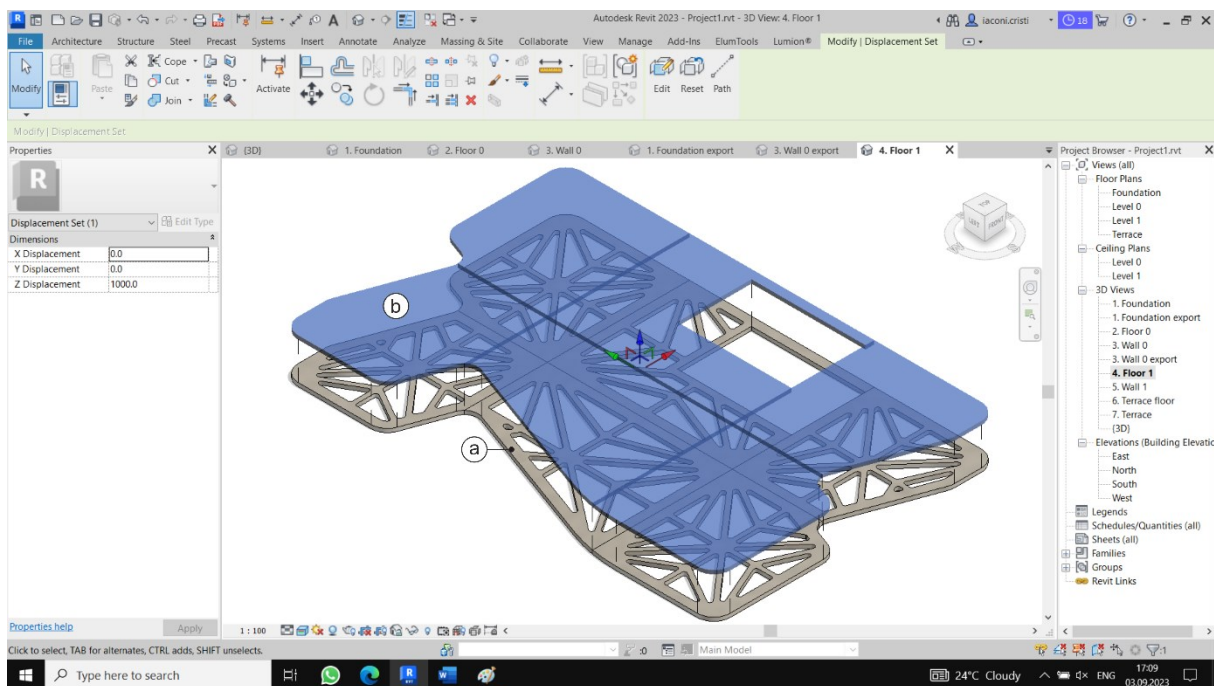


Figure 27: First floor slab: (a) optimized panel section, (b) solid panel section

4.3.5. First floor walls

Printing the walls on the second level of the building is pretty much the same as printing the walls on the ground floor, but at a different height and with different printing supports. The printing process on the second level starts after the complete printing of the previous level, and there is no way to go back and print something that was missed. It is mainly considered a repetitive process, even if some geometry differs from level to level.

Construction strategy: Most of the walls are repetitive, especially the structural ones that exactly overlap with the structural walls of the ground floor; the exceptions are only the interior compartment walls that do not follow the same pattern as on the ground floor. The level slab is used as a printing bed for the walls; only the exterior decorative wall is printed directly on top of the previous exterior wall from the ground floor in order to create a smooth transition between levels and leave the printed wall as an apparent finish. The window opening widths and positions are the same on both levels of the building, which helps to keep the project simpler and reduce the potential errors that might appear during the printing process.

The noticeable difference in terms of constructability is the upper part of the decorative exterior wall, as seen in **Figure 28**. The upper part is designed to change its printing path at some point in order to be aligned with the roof; for these small changes, temporary printing supports will be used.

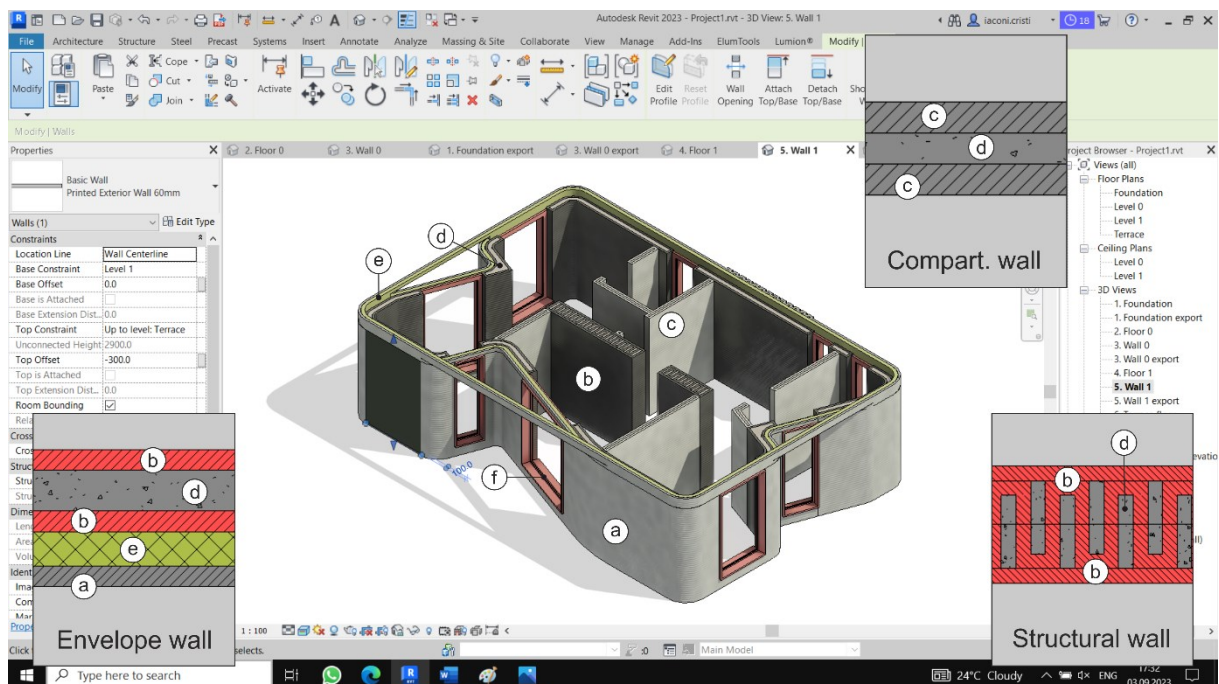


Figure 28: First floor walls: (a) exterior decorative wall, (b) structural wall, (c) interior compartment wall, (d) wall-filling material, (e) thermal insulation, and (f) openings

3D Modelling: For modeling the walls on the first floor, the same five categories of walls from the ground floor were used, as seen in **Figure 29**. Most of the walls were copied from the ground floor and aligned to the first floor level.

The walls were modeled and categorized by constructability and printing stage as follows:

- a) **Exterior decorative wall:** Decorative walls were copied and pasted from the ground floor by aligning them to the current level; the decorative wall is completely similar to the ground-floor one.
- b) **Upper part of the exterior decorative wall:** On this level, the upper part of the decorative wall differs from the ground-floor one and needs additional printing support for some of its parts. It was modeled separately in order to be easier to export as a separate geometry, taking into account that it is going to be printed after installing the necessary print support.
- c) **Perimetral structural wall:** The walls were copied and pasted by aligning them to the current level; the perimetral structural wall is completely similar to the ground-floor one.
- d) **Interior structural wall:** The walls were copied and pasted by aligning them to the current level and then separating them into two parts in order to create an opening.
- e) **Interior compartment wall:** Wall compartmentation is different from the ground floor and was modeled from scratch.

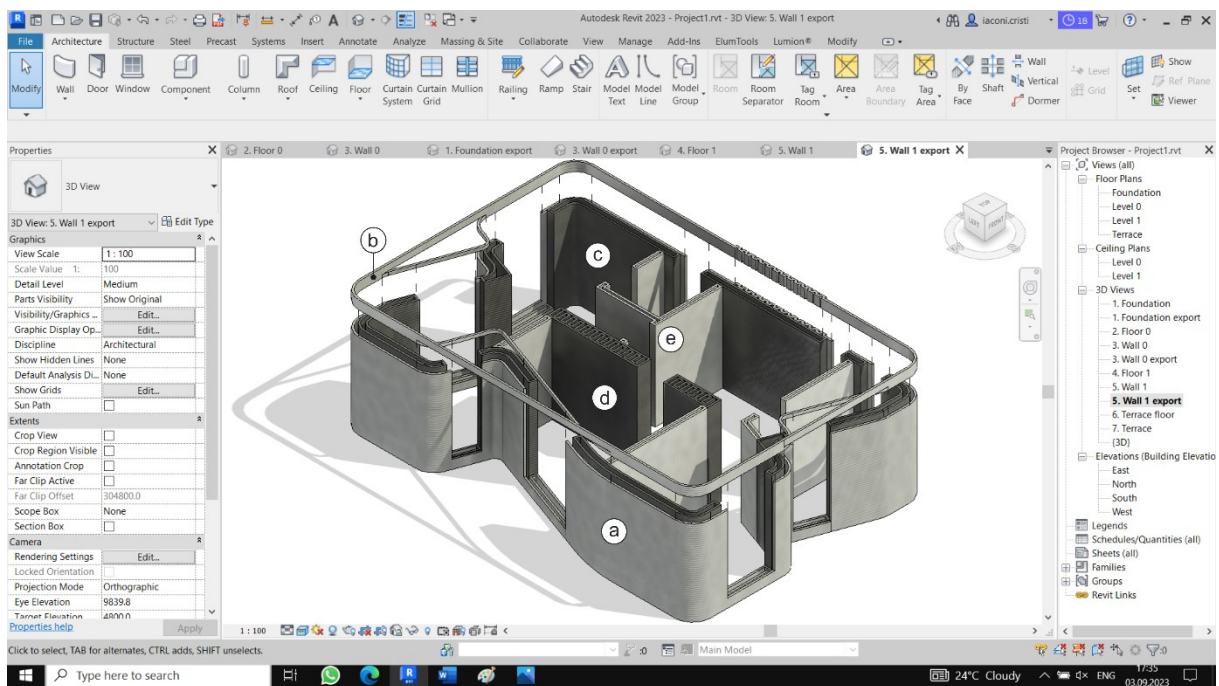


Figure 29: First floor printed walls: (a) exterior decorative wall, (b) upper part of exterior decorative wall, (c) perimetral structural wall, (d) interior structural wall, (e) interior compartment wall

4.3.6. Roof slab

For a 3D concrete printing building, the roof is usually made using traditional methods and involves light materials such as wood. It all depends on the type of roof desired; for example, a flat roof can be built similarly to a level slab. However, similarly to a floor slab, there are options for using 3D printing in creating the roof slab, such as preprinting or indirect printing.

Construction strategy: From a purely architectural standpoint, the building roof is created with a rectangular shape rather than mimicking the basic contour of the structure. The slab follows the same construction strategy as the floor slab, but with some small additions, as seen in **Figure 30**. Those additions work as a transition from the general wall shape to the roof parapet shape; on the lower part, there is a thermal insulation layer, and on the upper part, the solid panel section will have a different shape in order to cover the whole new structure. The roof slab will serve as a printing bed for the printed perimetral roof parapets.

3D Modelling: Both panel sections were created using the architectural slab family category. The optimized panel section is modeled to follow the general shape of the walls; on the other hand, the solid panels follow the rectangular shape of the roof. The difference between the panel section shapes is completed with a thermal insulation layer modeled using the model-in-place tool under the roof category.

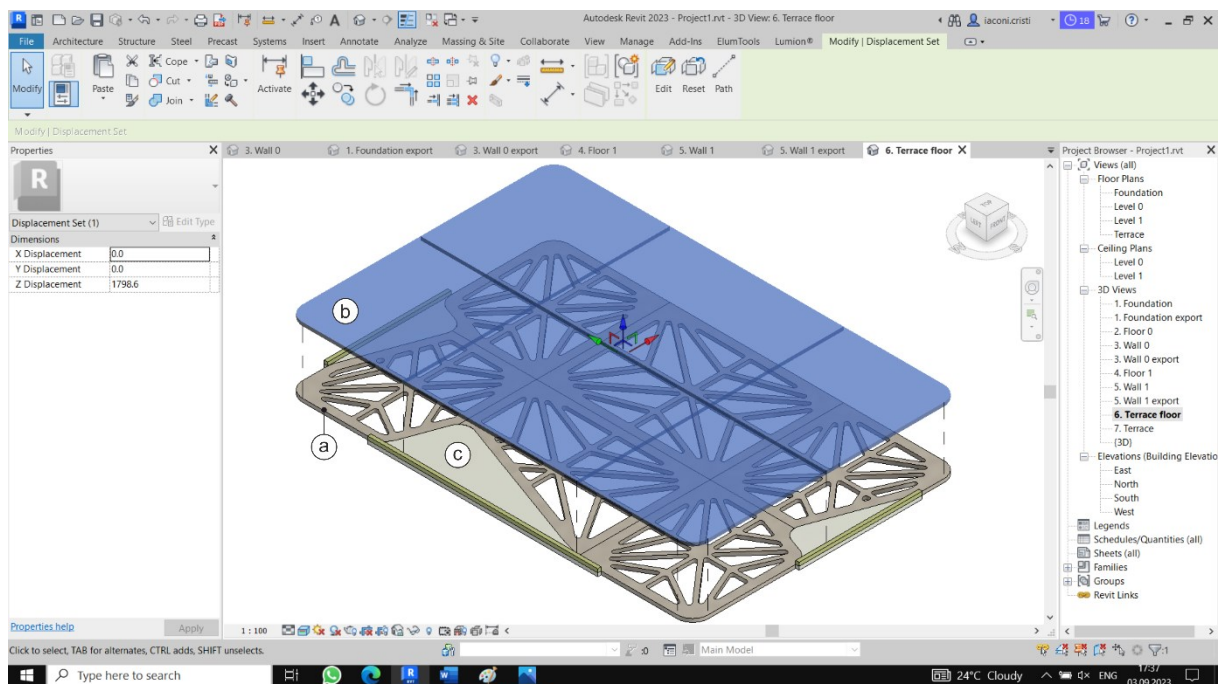


Figure 30: Roof slab: (a) optimized panel section, (b) solid panel section, and (c) thermal insulation layer

4.3.7. Roof parapets

Printing the parapets on a flat roof slab is similar to printing the walls on a perfect printing bed, making it one of the simplest steps in the printing process. The parapets can use the same layer format configuration as the exterior walls of the building or can be simplified in order to use fewer materials. Besides the printed parts, all other aspects of the parapet are similar to those made with traditional methods.

Construction strategy: The roof parapets were designed to follow the rectangular form of the roof slab, as seen in **Figure 31**. The parapet uses the same configuration as the perimetral walls from the current levels: an exterior decorative layer that is printed directly on top of the previous wall and works as a continuation of the facade, and two structural layers with a hollow between them for rigidity purposes. Both types of layers are separated by thermal insulation. For the final covering, a metallic cover is designed for parapet protection.

3D Modelling: The parapet walls on the roof were aligned from scratch because the path differs from the one used by the walls on the current level. In total, the parapet wall consists of three printable wall layers, one thermal insulation wall layer, and one fill layer modeled as an extrusion under the wall category. For modeling the metal parapet cover, model-in-place tolls were used within the roof category.

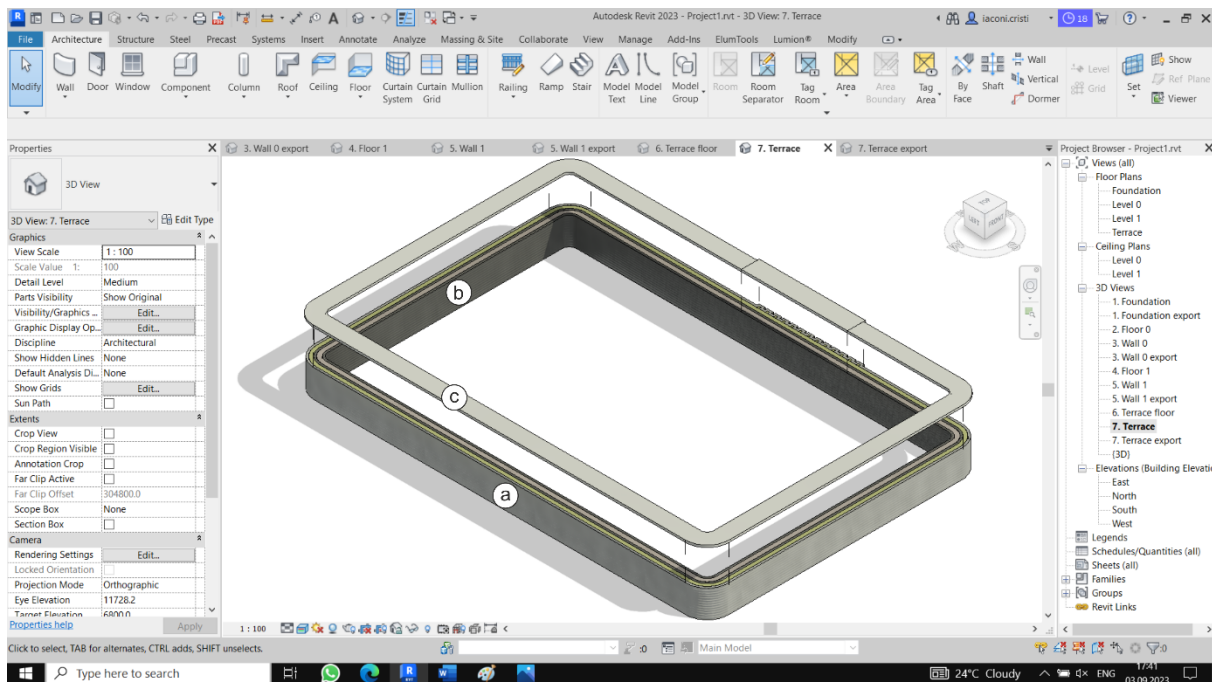


Figure 31: Roof parapets: (a) decorative wall, (b) support wall, and (c) parapet cover

4.3.8. Printed elements

Diverse 3D-printed elements can be added to a printed building in order to complete it. One of the most crucial components of the building are the stairs, which are regarded as an integral part of the construction. The stairs in a building can be built in many ways, including by printing them directly on-site or prefabricating them. In a 3D printing project, it is crucial to know exactly how the stairs will be built before the printing process starts.

Construction strategy: The stairs are separated into two main parts: the stairs support and the actual stairs, as seen in **Figure 32**. The stair support (a) was thought to be printed vertically directly on-site at the same time as the walls and made of two printed wall layers next to each other. The actual stairs, separated into two smaller parts (b and c), are going to be printed off-site in a horizontal direction. The stairs are going to be installed directly on the support after the printing of the ground floor walls and before installing the first slab floor.

3D Modelling: The support was modeled as a wall, and a new specific wall type was created for this purpose with the same thickness of 60 mm. The actual stair was modeled with the help of the model-in-place tool as an extrusion under the stairs category. The stairs are separated into two parts in order to be exported as a separate geometry and printed individually; on the other hand, the stairs supports, which are considered walls, will be included in the wall export.

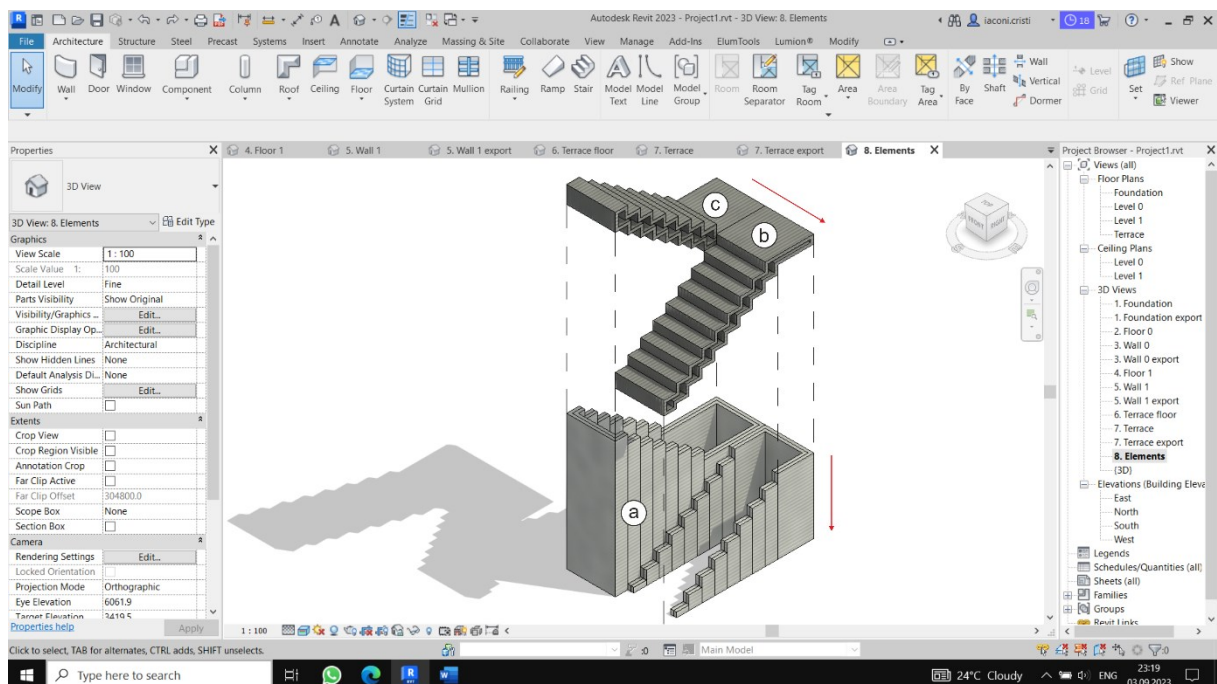


Figure 32: Printed stair elements: (a) stair support wall, (b) first printed stair section, (c) second printed stair section

5. Model exporting and slicing for 3D printing

A 3D printing machine always requires a digital model as its base of operation, regardless of the software used to design the building. Most 3D printers work with models translated from **STL format**, no matter the printer type, size, or method. Preparing the digital model and exporting it to the required format is a must-have step in the 3D printing workflow.

The digital model can be found in two forms: a digital model that contains only the printable geometry (modeled just for printing purposes) or a digital model that contains all the elements of the building (a multipurpose BIM model). When the digital model contains only printable geometry, the whole model is exported. In the case of a complete BIM model, like in our project, it is necessary to extract and export only the printable parts separately.

Exporting the printing model from Autodesk Revit is straightforward thanks to the *"STL Exporter for Revit"* addin that was created inside the software. For exporting the specific geometry from the model, it is enough to open a 3D view, hide the unwanted elements, keep the current view open, and go to export. In this way, only the elements seen in the current view will be exported as one object in STL format.

Export by clicking on **File > Export > CAD Formats > STL** as shown in **Figure 33**.

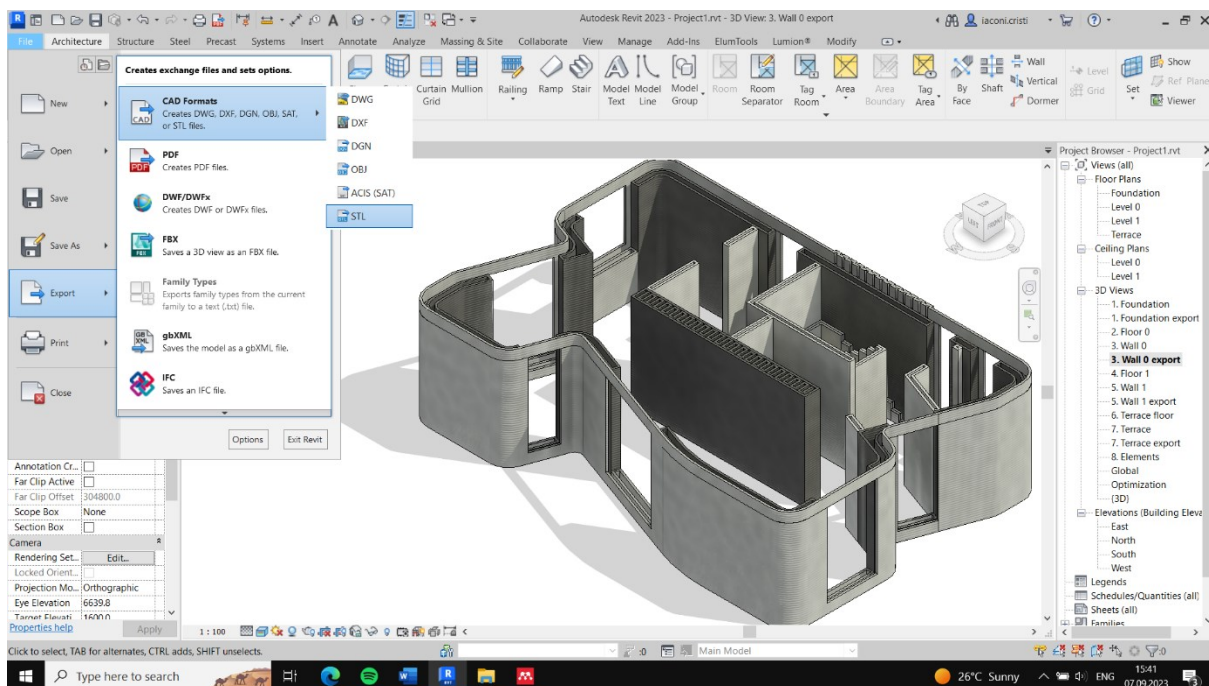


Figure 33: Exporting to STL format directly from Revit

5.1. Exporting and slicing for real-scale 3D concrete printing

Exporting the digital model in STL format is done separately for each printable component and for different printing stages. To facilitate this process, multiple 3D views were created inside Revit, as seen in **Figure 34**.

The printable components can be exported in many variations, as follows:

- a) **Foundation:** Exported as one type of wall or one printing phase.
- b) **Ground floor walls:** Exported as one type of wall and one phase; separately as three types of walls or as two printable phases, where the upper part of the external decorative wall is considered another printing phase, etc.
- c) **First floor walls:** Exported as one type of wall and one phase; separately as three types of walls or as two printable phases, where the upper part of the external decorative wall is considered another printing phase, etc.
- d) **Roof parapets:** Exported as one type of wall and one phase or two types of wall and one phase.
- e) **Elements:** Exported as one element.

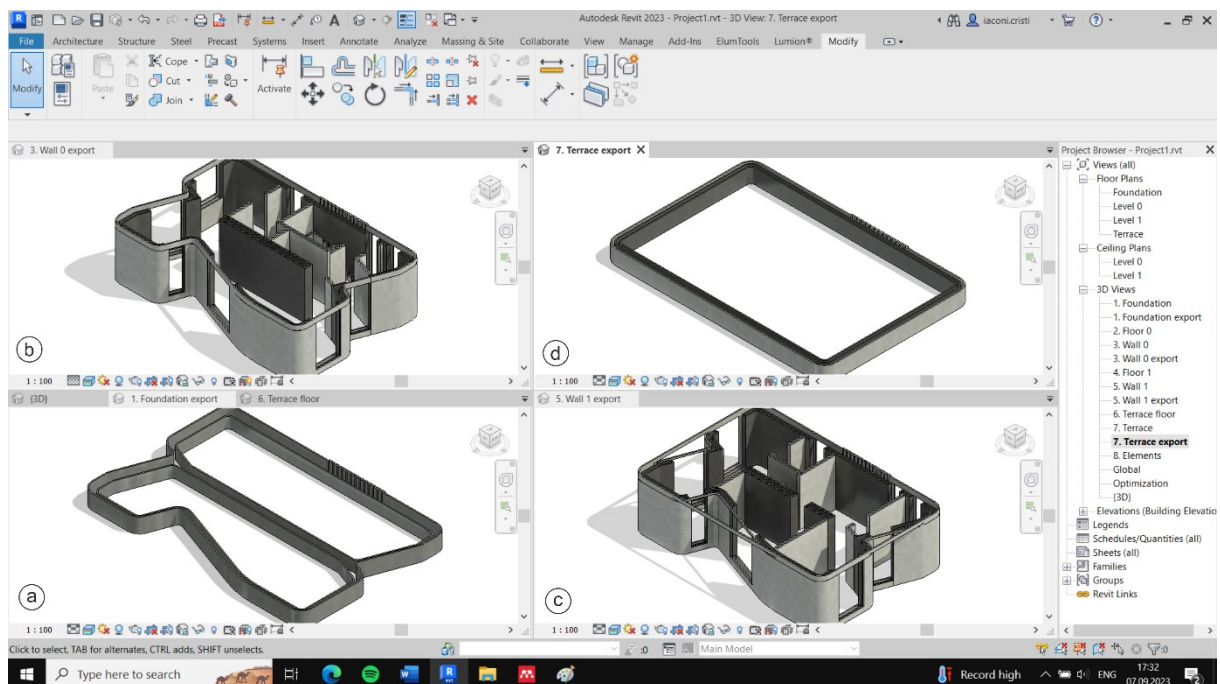


Figure 34: 3D views for model exporting: (a) foundation, (b) ground floor walls, (c) first floor walls, and (d) roof parapets

Slicing is the next stage after exporting the STL models and is considered to be a bridge between the digital model and the real printed object. Although the architect is not responsible for this stage, it is still essential to get familiar with it and get a better understanding of the 3D printing process.

Slicer is a software that transforms digital 3D models into instructions for producing an object on a specific 3D printer. The instructions also provide user-entered 3D printing options for layer height, speed, and support structure, in addition to the model itself. By adding material layer by layer, every 3D printing process produces 3D things. This makes the name of the program, "slicer," quite apt, as it effectively "cuts" 3D models into several horizontal 2D layers that will eventually be printed one at a time [23].

Most 3D printers come with their own 3D printing slicer software, so we don't need to worry about this next phase of the process. It is recommended to slice the model for checking purposes before delivering the final digital model. Sometimes, after the slicing step, it is necessary to go back and adapt the model in order to get a better printing path and avoid possible printing mistakes. Slicing, from an architectural point of view, can be used for checking the correctness of the digital model and as a source of feedback.

An online cloud-based slicer where you can inspect the slicing of the model for free is a nice option if there is no slicing software on hand. The STL model of one stair component from the project was uploaded to the platform and sliced, as seen in **Figure 35**.

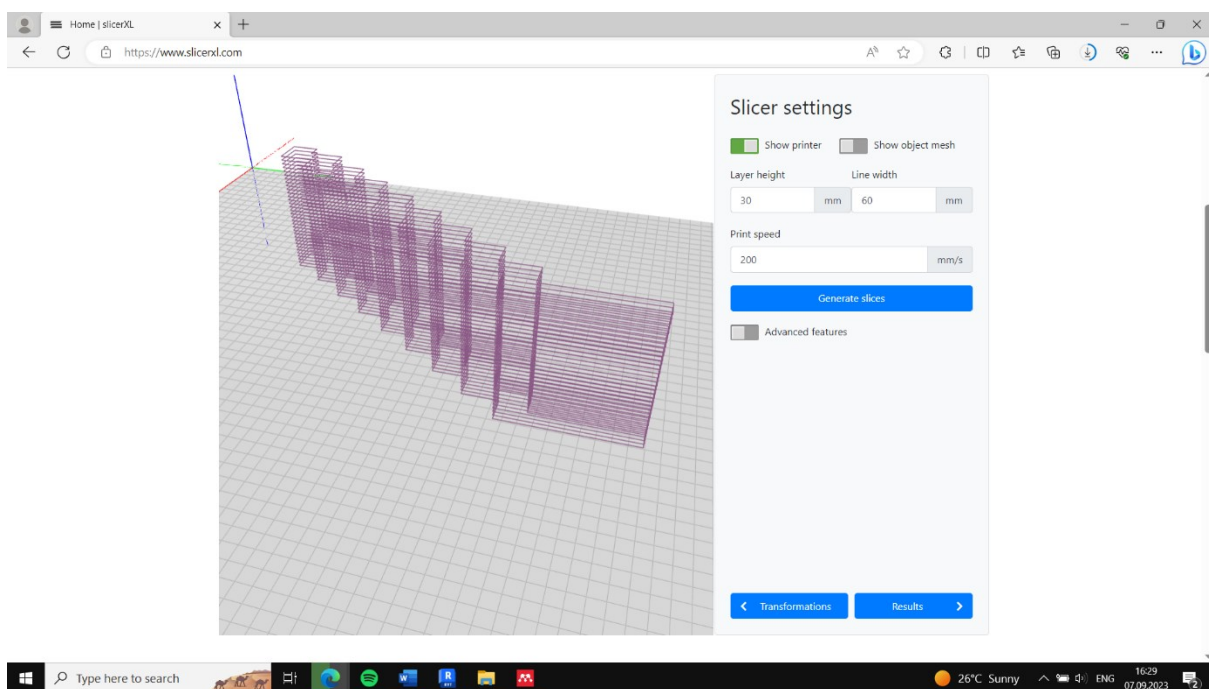


Figure 35: Online, free cloud-based slicer (www.slicerxl.com)

5.2. Exporting and slicing for small-scale 3D printing model

Exporting the model for a small-scale print differs from exporting for a real-size model due to the scale effect and the material used for printing. To do this, a duplicate of the Revit file was generated without altering the original model, and all the pieces were updated and adjusted, particularly for printing on a small model.

The printable parts were adapted as follows:

- a) **Foundation:** includes the foundation slab and concrete fill.
- b) **Ground floor slab:** a tolerance of 0,1 mm was added on the horizontal directions of the element.
- c) **Ground floor walls:** includes the thermal wall and all the concrete fill on the walls.
- d) **First floor slab:** upper parts of the exterior wall were added to the slab, and a tolerance of 0,1 mm was added on the horizontal directions of the element.
- e) **First floor walls:** includes the thermal wall and all the concrete fill on the walls.
- f) **Roof slab:** upper parts of exterior wall were added to the slab, and a tolerance of 0,1 mm was added on the horizontal directions of the element.
- g) **Roof parapets:** includes the thermal wall and all the concrete fill on the parapets.

The exported parts were uploaded to the **FlashPrint slicer** on a smaller scale in order to inspect the elements geometry and the connection between them, as seen in **Figure 36**.

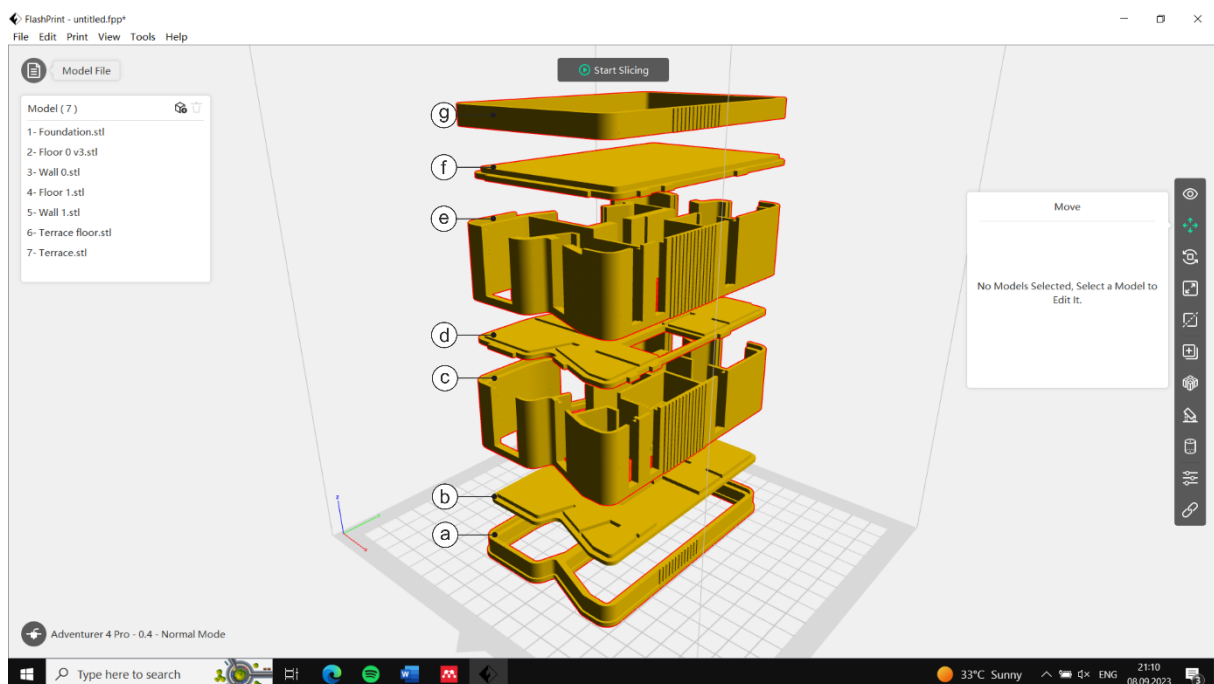


Figure 36: STL models in the slicing software for small-scale model

Slicing checks are the next step after the overall examination of the uploaded STL model sizes and connections between the printing parts. The process is very intuitive and starts with the configuration of the slicing settings.

Slicer settings are crucial since each 3D printer, each material, and each 3D model vary from one another. As a result, various settings will always be needed to produce high-quality prints on different printers and materials. The temperature of the heated components as well as the thickness of each wall and layer are all adjustable through the slicer. You need to be aware of the key parameters to adjust on your slicer if you want the best prints or just to print anything as rapidly as feasible [23].

The printable parts were sliced inside the FlashPrint slicer one by one, similar to the ground-floor wall model seen in **Figure 37**. The model parts were uploaded and scaled to 1:100, meaning one printed centimeter equals one meter in real-scale construction. Since the model has already been revised to eliminate any overhanging sections, setting printing supports was not required.

There were several attempts with different settings of the nozzle size (0.6 mm or 0.4 mm) and different percentages of fill density before the model was finally printed with a 0.4 mm nozzle diameter. The model parts were printed one by one and inspected for quality by comparing the slicing solution and the materialized printed parts.

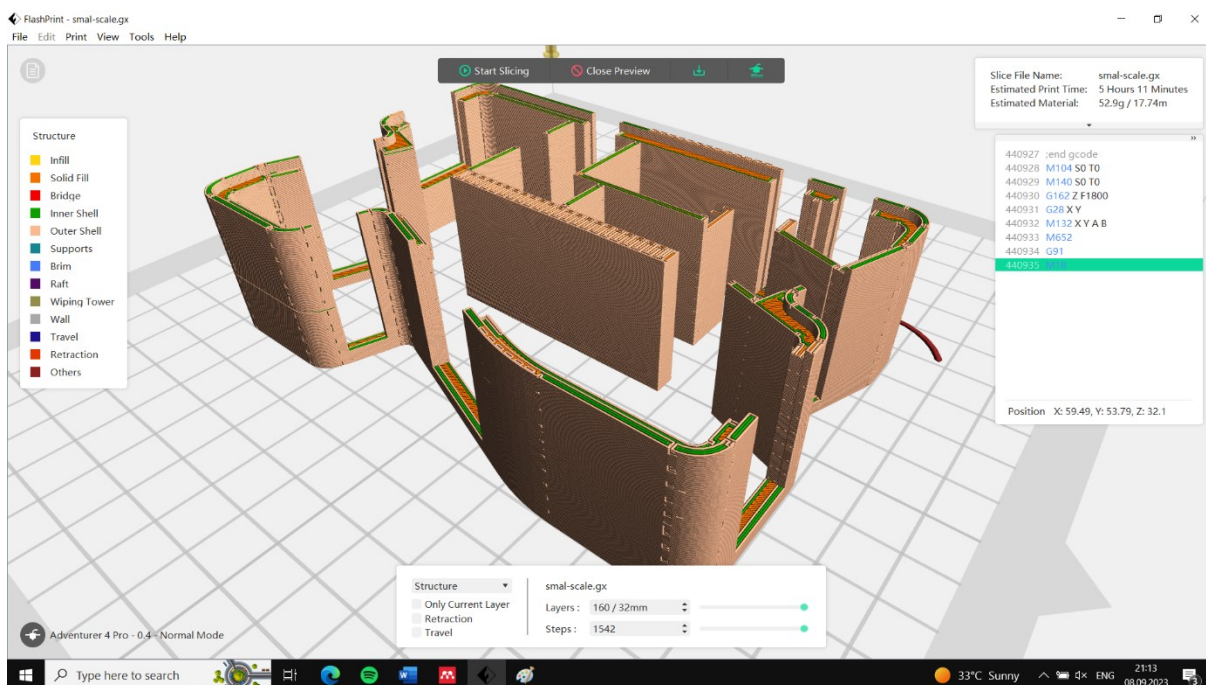


Figure 37: Slicing for a small-scale model

6. Results

The results of the methodology are meant to be similar to those produced and delivered by an architect who designs a building for 3D concrete printing in a real workflow scenario. All deliverables should be identified at the beginning of the design process and might differ according to the printing technology being utilized.

For this particular thesis work, three main types of results were concluded as follows:

- BIM model in IFC format
- STL models for 3DCP
- Small-scale 3D printed model

6.1. BIM model in IFC format

The final BIM model has been exported and displayed in IFC format, see **Figure 38**, since IFC is an open file format utilized by Building Information Modeling for importing and exporting building objects and their properties. In our case, the model was exported as a whole building, which includes all types of elements. As an alternative, the model may be exported as a BIM model in IFC format using only the printed parts of the model.

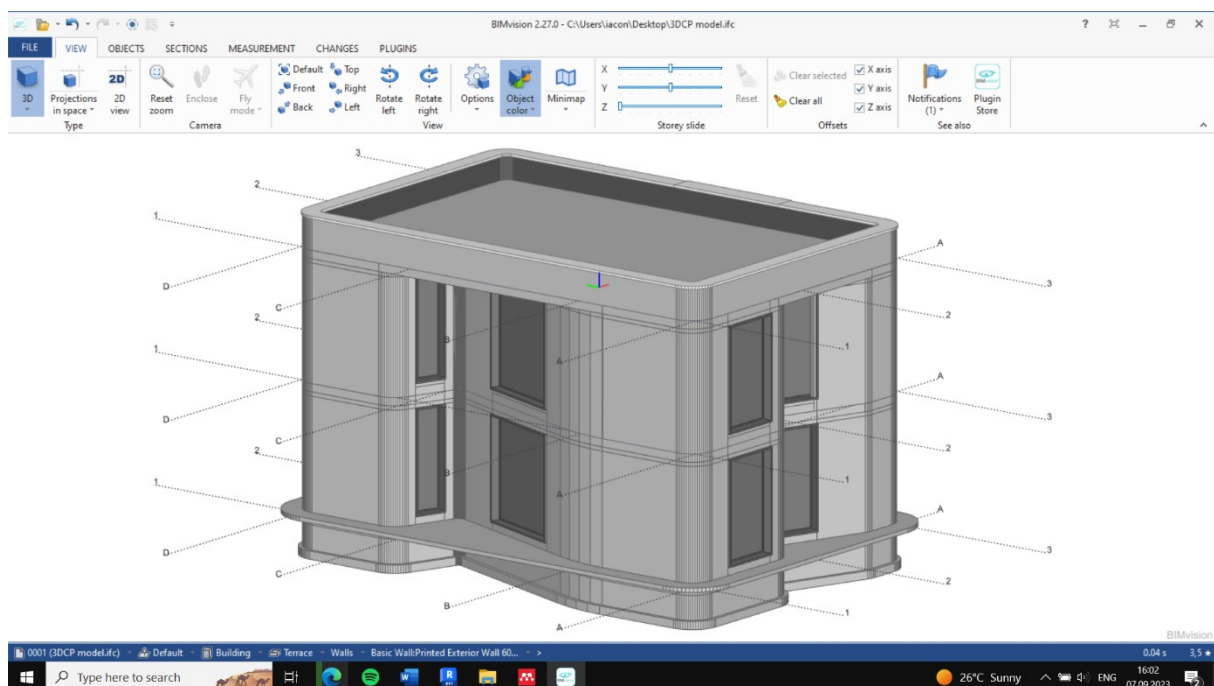


Figure 38: IFC model of the project

6.2. STL models for 3D concrete printing

The printable components have been exported and displayed in STL format one by one (see the figures below with the model opened in MeshLab), since STL is a file format utilized by most 3D printing machines for translating the model into a printing instruction.

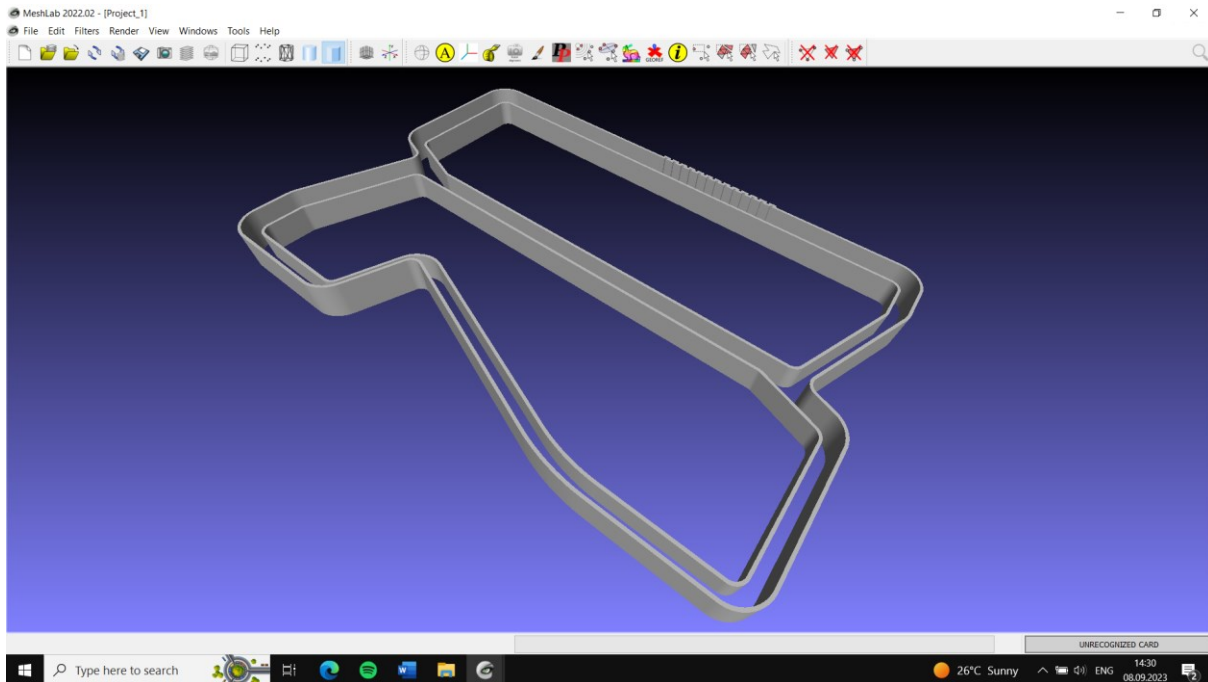


Figure 39: STL model of the foundation

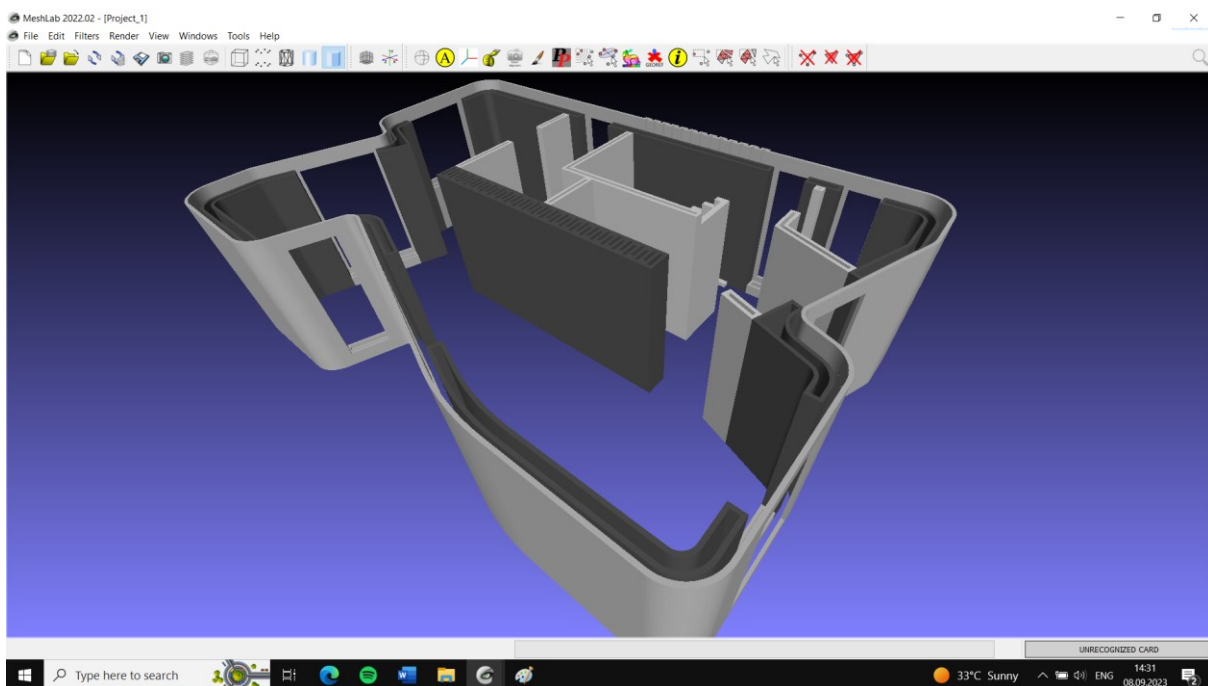


Figure 40: STL model of the ground floor walls

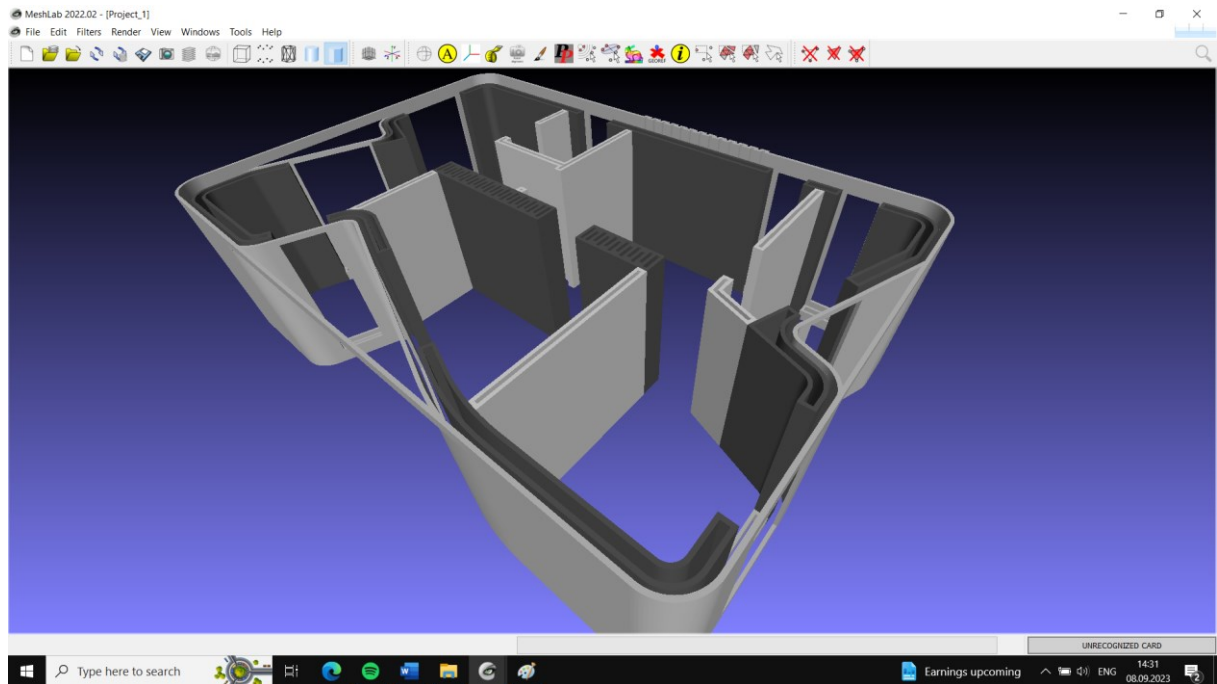


Figure 41: STL model of the first floor walls

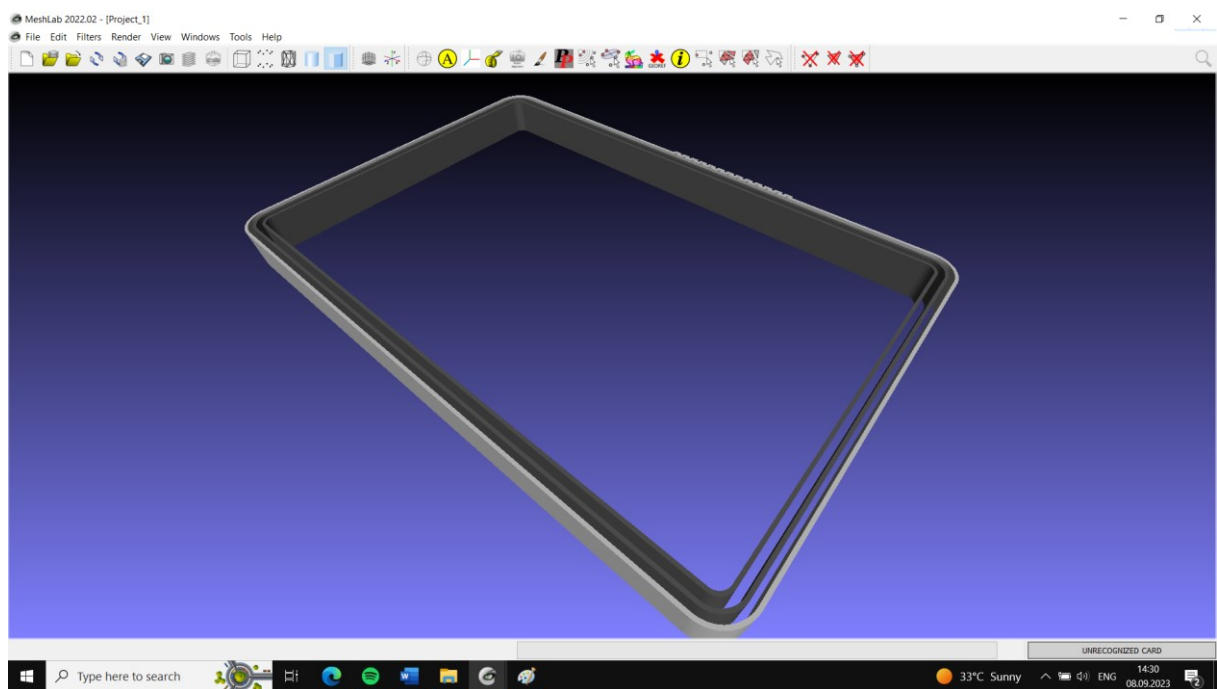


Figure 42: STL model of the terrace parapets

Note: Only four printing components were selected and presented as results.

6.3. Small-scale 3D printed model

The small-scale model was printed in multiple individual parts, as seen in the **Figure 43**.



Figure 43: Small-scale 3D printed parts

The model parts are meant to be assembled by fitting one into another and forming a small-scale architectural model, as seen in the **Figure 44**.



Figure 44: Assembled small-scale 3D-printed model

7. Conclusion

In conclusion, designing a building and preparing the digital model for 3D concrete printing are relatively simpler than most architects anticipate. With a small amount of research on printing technologies and some general logic, this workflow can be done by most engineers. It is important to know that many other types of professionals are involved in the process, and it does not rely only on architects or structural engineers.

Understanding 3D printing technology is not that difficult since all 3D printing machines have similar principles of operation, no matter if it is a large-scale concrete printing machine or a small-scale plastic one. For example, creating and exporting a digital model is pretty much the same for all types of 3D printers, and in truth, almost every 3D printing technology that is now in use produces a digitally sliced version of a 3D object.

Another concluding aspect is that the design and modeling for 3D concrete printing can be done using the same conventional BIM software already used by architects and engineers, which means that there is no need for additional software or applications for the architectural design process. On the other hand, all 3D printers on the market come with their own operating and model-slicing software. In the worst-case scenario, there are a lot of other types of alternatives, like open-source modeling and slicing applications.

7.1. Future work and limitations

Future work is required in order to improve the quality of the digital model for 3D concrete printing. This can be done by making several real-scale printing attempts in order to physically determine the printability of a specific component or node, which can differ from building to building. Also, to improve the design of the building by creating specific printing patterns on the walls, a digital model is not enough; further work is needed by going beyond the default slicing software and manually creating a parametric printing path.

Some limitations of the 3D concrete printing technology, like the impossibility of printing overhanging components without supports or integrating structural elements in the printable parts, constrain the way a building is designed and how the digital model is prepared for the process. Those limitations keep 3D concrete printing being used as an alternative method rather than totally replacing traditional construction methods.

After all that was said, there should always be a compromise on how complicated the design of a 3D concrete printing building should be.

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