

MODELLING AND SLICING

STANDARD OPERATIONAL
PROCEDURE

DOCUMENT VERSION

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This document is valid for the following versions of the product:

Item	CAD Program	COBOD Slice	Revit Plug-in
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Supplier information:

COBOD International A/S

Address:

Skudehavnsvej 17A
2150 Nordhavn
Denmark

Contact:

techsupport@cobod.com

Changelog:

Item	Description
Wall info (Changes added on January 2024)	- Properties of 3DCP wall - Wall finishing - Concrete thickness - Insulation properties - Stability of a 3D printed wall - Printability overhangs - 3D printed slabs

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1.1 PURPOSE

This document provides step-by-step instructions for carrying out regular tasks that enhance efficiency and adhere to quality standards and processes in modeling and slicing for 3D construction printing.

The document serves four purposes:

- ▶ **Improve compliance:** By utilizing this document, you can ensure adherence to best practices for modeling and slicing in 3D construction printing, aligning with international guidelines such as ISO standards. This not only saves resources but also minimizes issues and enhances efficiency right from the design phase.
- ▶ **Standardize processes:** A key benefit of this document is the establishment of consistent design procedures, enabling you to make informed decisions and effectively address any obstacles that may arise during the process.
- ▶ **Streamline onboarding:** This document also simplifies the training and onboarding of new employees. They can easily follow the standardized procedures outlined in the SOP to successfully execute their work orders.
- ▶ **Preserve knowledge:** By implementing this SOP, the valuable techniques and expertise acquired by COBOD International are effectively preserved, ensuring that they continue to be utilized and passed on within the organization.

This document provides a comprehensive overview of the procedures involved in modeling architectural and structural geometries and converting them into face-based or centerlines geometries that can be read by a slicer. Specifically, it focuses on the usage of COBOD Slice, a software program used to slice the geometry into horizontal layers of G-code, which can then be interpreted by the BOD2 3D printer. **The document encompasses the following areas:**

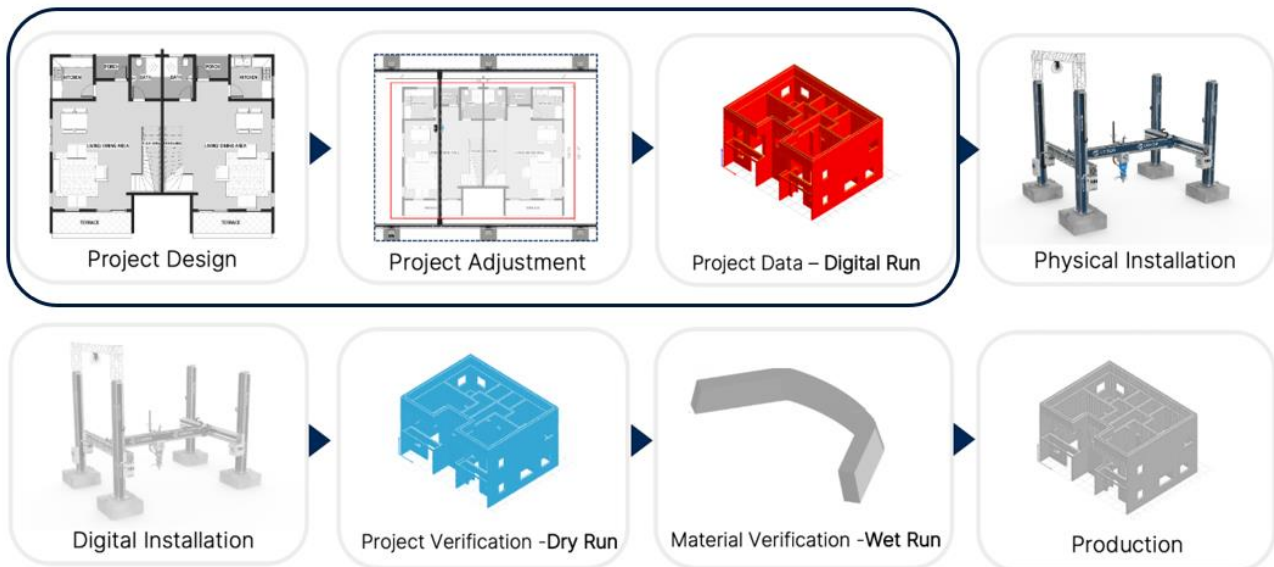
- ▶ Modelling 3D printed walls
- ▶ Modelling 3D printed formwork
- ▶ Modelling 3D printed openings
- ▶ Key performance indicators
- ▶ Slicing the geometry and transforming it into G-Code readable for BOD2 printer.

This document **does not** cover:

- ▶ Installation and operation of BOD2. Please refer to SOP – BOD2
- ▶ 3D printable materials. Please refer to SOP – COBOD's guide on D.fab
- ▶ How to calculate loads. Please refer to your local structural engineer.

1.2 APPLICABILITY

This document is essential during the Planning and Design phase of a project. It is crucial to thoroughly review all the procedures and associated documents referenced in this SOP to ensure the creation of a design with minimal chances of errors. By diligently studying and understanding these processes, you can greatly reduce the likelihood of mistakes and improve the overall quality of the design.



1.3 DEFINITIONS

- ▶ **3DCP** - 3D Concrete Printing (3DCP) is an innovative technology that utilizes software to precisely guide the deposition of materials for constructing three-dimensional objects or structures, eliminating the need for traditional formwork. The predominant method in 3DCP involves the extrusion of cement-based composites, which can either be a fine aggregate mortar or a concrete mixture with larger aggregates. This cutting-edge technology offers numerous benefits, including the ability to create intricate geometries using a fully automated setup. Additionally, 3DCP facilitates material savings, enhances efficiency in producing complex concrete products, unlocks fresh architectural perspectives, and enables novel design strategies.
- ▶ **SOP** - A standard operating procedure is a set of written instructions that describes the step-by-step process that must be taken to properly perform a routine activity. SOPs should be followed the exact same way every time to guarantee that the organization remains consistent and in compliance with industry regulations and business standards.
- ▶ **PI – Printable area** is the area in which you can model a geometry to be 3D printed.

- ▶ **IA – Installation area** for the printer only.
- ▶ **Seam** – Seam or Z-seam is line of print defects that runs along the Z axis of a 3D print from top to bottom. The resulting print defects are usually discontinuities and sometimes accompanied by concrete “chips” or small over extruded pieces of material. A Z-seam is usually visible on smooth and round objects that have not been printed in Vase Mode.
- ▶ **Flap** – is piece of material in many cases made from steel or plastic which is attached with screws to the nozzle and acts as a barrier to create the desired wall thickness. The flaps are also helping to smoothen the surface quality of the 3D printed layers.
- ▶ **Slicing** - A slicer is a simulation software which converts a geometry made from surfaces/centerlines into a G-CODE file. The concept of slicing is based on contouring / splitting a geometry horizontally. These generated contours of curve are converted to point-based G-code and later are imported into the printer.
- ▶ **Centerline** – is a face-based geometry which can be imported into the COBOD Slice and turned into G-code. Centerlines need to be created to run through the middle of the modeled printed geometries.
- ▶ **Toolpath** – is a trajectory the printer follows to print one layer.
- ▶ **G-code** - is the name of the most prevalent programming language for computer numerical control (CNC) in computer-aided design and manufacturing (CAD/CAM). G-code provides metric-based numeric control of CAM-controlled equipment such as CNC milling machines.

1.4 ROLES AND RESPONSIBILITIES

The **printer operator** is responsible for overseeing printer operations and ensuring accurate printing of the model. It is recommended that a person with a background in architecture or structural engineering handles the task of modeling a 3D printable geometry and also carries out the printing process.

1.5 TOOLS

The following tools can be used to export centerlines or face-based geometries as **step or stp** files to be imported into the COBOD Slice, which then will be converted into g-code.

Rhino 3D can create, edit, analyze, document, render, animate, and translate NURBS curves, surfaces and solids, subdivision geometry (SubD), point clouds, and polygon meshes. In Rhino you can create centerlines and export them as STEP file. https://www.rhino3d.com/	
SpaceClaim is a solid modeling CAD software that runs on Microsoft Windows and developed by SpaceClaim Corporation. SpaceClaim is mainly used for mechanical engineering, however you can use it to create centerlines and export them as centerlines. https://www.ansys.com/	
Autodesk Revit is a building information modelling software for architects, landscape architects, structural engineers, mechanical, electrical, and plumbing engineers, designers, and contractors. In Revit you can create any building or geometry using our COBOD Revit Template. Together with our plug-in you can export the centerlines of a project with one click. https://www.autodesk.com/products/revit/	
Revit plug-in + Template provided by COBOD International to be able to model buildings that can be 3D printed and will help you export the step file.	
Autodesk Fusion 360 is a commercial computer-aided design, computer-aided manufacturing, computer-aided engineering, and printed circuit board design software application, developed by Autodesk. It is available for Windows and macOS, with simplified applications available for Android and iOS. In Fusion you can create face-based geometries and export them as a STEP file. https://www.autodesk.com/products/fusion-360	
COBOD Slice is a simulation software which converts a geometry made from surfaces /centerlines into a G-CODE file. This program allows you to print a geometry digitally before printing it physically.	
Any other CAD program that can export [step, stp] files as surfaces.	

1.6 ENVIRONMENTAL HEALTH AND SAFETY (EHS)

EHS is the department, or a company, tasked with ensuring that the work undertaken by the company does not cause environmental harm, put the workers' health and safety at risk, complies with applicable local legislation and follows the best practices.

Here are the best practices for EHS:

- ▶ The most important procedure of EHS is to design and model according to your regional building regulations.
- ▶ Your licensed architect should handle the design of your building or geometry.
- ▶ When you design, consider the safety recommendations for the printer: See SOP – BOD2.
- ▶ When you design, consider the dimensions of the printer and its printable area in width, length, and height.
- ▶ Architects who have taken the course of Modeling for 3DCP should model geometries for the 3D printer.
- ▶ The architect creating the site plan for the project should be aware of all the EHS measures from the 3D Printer, to position the model, all the systems and secondary equipment to ensure safety on site.

1.7 KEY PERFORMANCE INDICATORS

3DCP LOGISTICS

- ▶ **Definition:** 3DCP logistics is the optimization of your printable units, site planning and printing time in accordance with the volume output of material per hour.
- ▶ **Description:** Managing logistics at the printing site must be well determined in the design phase. The printing site will contain the printer, material delivery system, hose management system and secondary equipment stations. It is important to position the equipment and the system in such a way as to facilitate the most effective and safe operation on the construction site. All of these will result in throughput of material per hour.
- ▶ **Measurement unit:** m³ of material/h.

MODELING CONSIDERATIONS

- ▶ **Definition:** The modeling considerations are the key elements which will make your geometry 3D printable, including printable area, wall design, and openings.
- ▶ **Description:** Unlike conventional construction, 3D printed models have some elements that are specific to this layer-based construction. The technology can create different or similar geometries to conventional construction; therefore, these considerations must be considered when you are designing for 3D printing.

- ▶ **Measurement unit:** Yes/No.

STRUCTURAL CONSIDERATIONS

- ▶ **Definition:** Structural considerations are the key elements which will be approved by your structural engineer to obtain the building permit. These will include foundation, columns, and slabs.
- ▶ **Description:** Modeling structural elements will require you to collaborate with an authorized structural engineer which will model the structure you need for your building. After knowing these sizes, you need to design the 3D printable formwork for some of these elements such as columns, beams, slabs. You can use conventional elements as well; however, it is more cost effective to 3D print formwork.
- ▶ **Measurement unit:** Yes/No.

VOLUME

- ▶ **Definition:** Volume is the estimated material necessary for printing a specific design.
- ▶ **Description:** When you are modeling a geometry, you must consider the total volume needed for printing such geometry, this does not include the material poured or casted, only the 3D printed material is estimated here.
- ▶ **Measurement unit:** Liters/hour.

TIME

- ▶ **Definition:** Time is the duration in which a geometry or building is 3D printed with BOD2.
- ▶ **Description:** Time consists of the settings from the COBOD Slice to optimize the printed elements and the travel time of the printhead in the most effective way possible, to decrease the total printing time.
- ▶ **Measurement unit:** Hours.

QUALITY OF THE PRINT

- ▶ **Definition:** The quality of the print is the visual and structural integrity of the result.
- ▶ **Description:** Visual and structural integrity of the print is mainly given by the material used, but some of the slicing parameters play a small role as well.
- ▶ **Measurement unit:** Satisfied/Not Satisfied.

COLLISION

- ▶ **Definition:** Collision is the act of trouncing or running into already existing objects on your printing site.
- ▶ **Description:** Collision is something you want to avoid in 3DCP, many times you might have existing objects that you want to avoid colliding with them. Colliding can result in damaging the printhead and/or misaligning the printer.

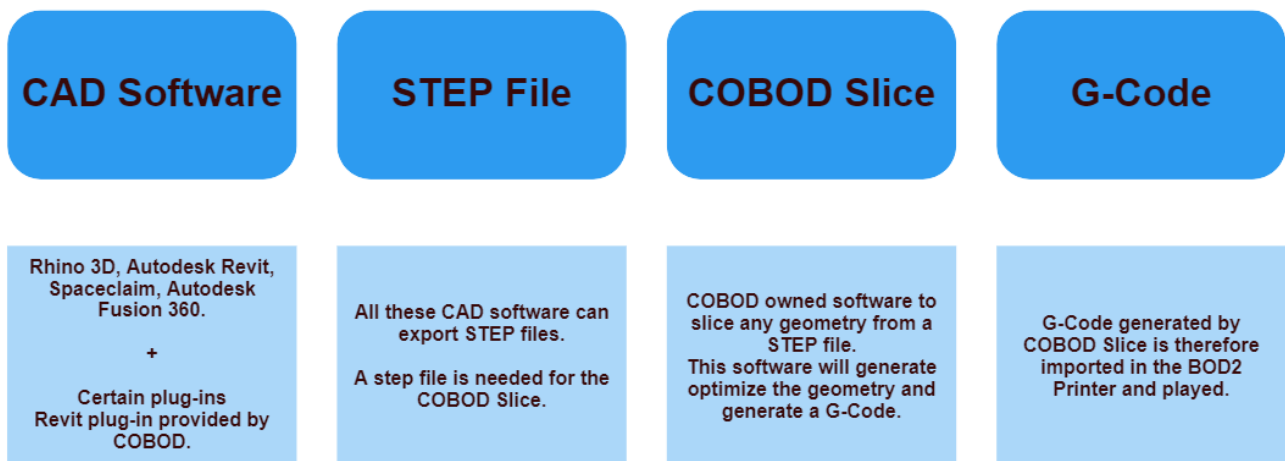
- ▶ **Measurement unit:** Yes/No.

PRODUCTIVITY

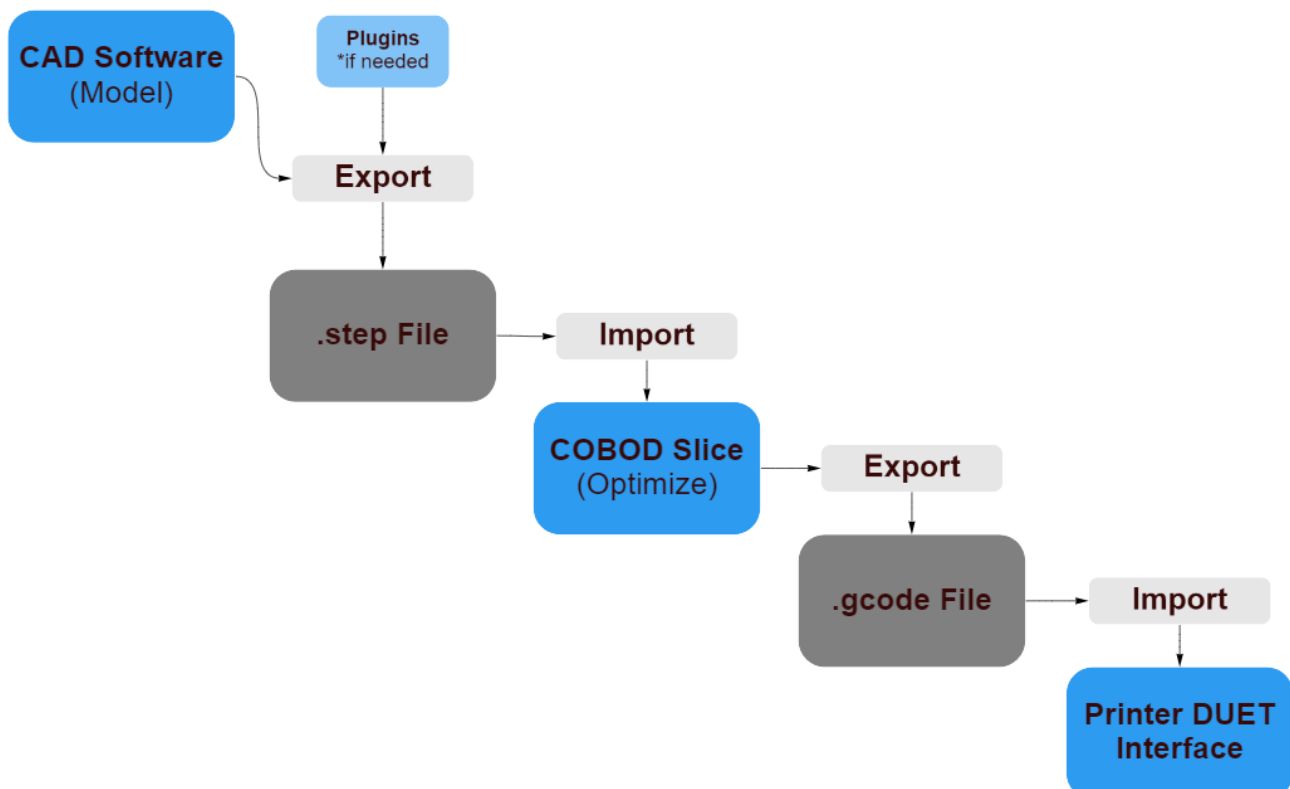
- ▶ **Definition:** Productivity is the amount of material you can extrude per hour.
- ▶ **Description:** This KPI is one of the most important ones when it comes to cost calculations for your projects. The higher the productivity, the higher the returns.
- ▶ **Measurement unit:** Liters/Hour.

2. COMPONENTS

2.1 INDEPENDENT COMPONENTS



2.2 INTEGRATED COMPONENTS



3. MODELLING PROCEDURES

BEFORE MODELING CHECKLIST	
Local Building regulations	
Wall type selection	
Printability of sloped walls	
Layer height and Layer width considerations	
Flaps/no flaps	
Thermal bridge	
DURING MODELING CHECKLIST	
Reinforcement placement	
Structural elements considerations	
Cost considerations	
Printable area	
Geometry in XYZ space	
Printing time optimization	
Continuous loops in your design	
Seams	
External objects	
Connection with conventional elements	
Expansion joints	
Other printable elements	
AFTER MODELING CHECKLIST	
Testing your model	
Exporting a STEP file	

3.1 BEFORE MODELLING

Before modeling the following procedures should be considered.

3.1.1 LOCAL BUILDING REGULATIONS

They play a very crucial role when you model a residential or commercial building not only in conventional construction but also in 3DCP. Building regulations must be implemented in such a way that it can save power and fuel, protect natural beauty, promote large development, maintain eco-balance and they put in place regulatory processes for making the drawings for your building.

The drawings for a 3D printed building must be produced by an architectural and structural local company.

3.1.2 WALL TYPE SELECTION

In the design manual for 3DCP you will find different types of walls that can be 3D printed and it is important to note that the selection of the wall type must be discussed with the architect, structural engineer, and the project manager. In 3DCP the walls are produced layer by layer along a g-code path. These are some types of walls possible to do with BOD2:



The 3D printed walls can be structural, sandwich panels type or non-structural. The walls of a building are created at the same time one layer by layer unless the layer time for the print is greater than 25 minutes*. If the layer time for the geometry is greater than 25 minutes, then *25 minutes layer time is a rule of thumb, you should consult with your material expert and decide what is the minimum and maximum layer time needed for a specific material.

3.1.3 PRINTABILITY OF SLOPED WALLS

The slope of a 3D printed wall is determined by five factors: layer width, layer height, layer time, material properties and weather conditions. It is recommended to not create overhangs with a slope over 20 degrees, unless supports, reinforcement, or other kind of technique is used.

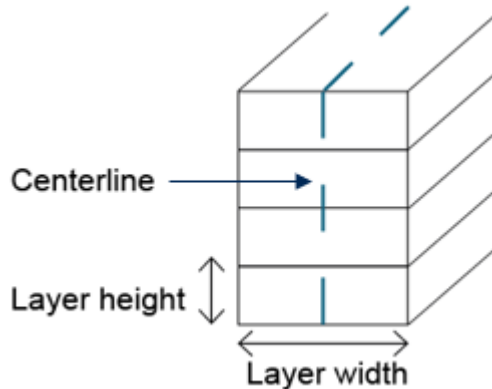
Refer to the Design manual for more information.

3.1.4 LAYER HEIGHT AND LAYER WIDTH

The height of the wall you are 3D printing is divided into layers. The height of the wall divided by the number of layers should result in a number without decimals. For example:

- ▶ Wall height = 3000mm
- ▶ Layer height = $3000/x$ = Integer (number without decimals)
- ▶ Number of layers can be:

Layer height	Nr of layers	
40 mm	75	✓
50 mm	60	✓
30 mm	100	✓
35 mm	85.71	×



Layer width is determined by the wall type used in the project, but also the structural engineer will decide on the thickness of the 3D printed wall.

Decide on the layer height and width before you start designing.

3.1.5 FLAPS/NO FLAPS

Flaps are pieces of metal, plastic or other material sheets attached to the nozzle to smoothen the surface of the material extruded by the printhead while 3D printing the structure.

If the flaps are used or not in 3D printing a project, this decision will have an impact on how the walls and joints are designed for a specific geometry.

If the geometry is designed to use flaps, the architect should consider the flaps cutting the already printed layers in case there are intersections in the walls.

If geometry is designed to not use flaps, then the geometry is more flexible.

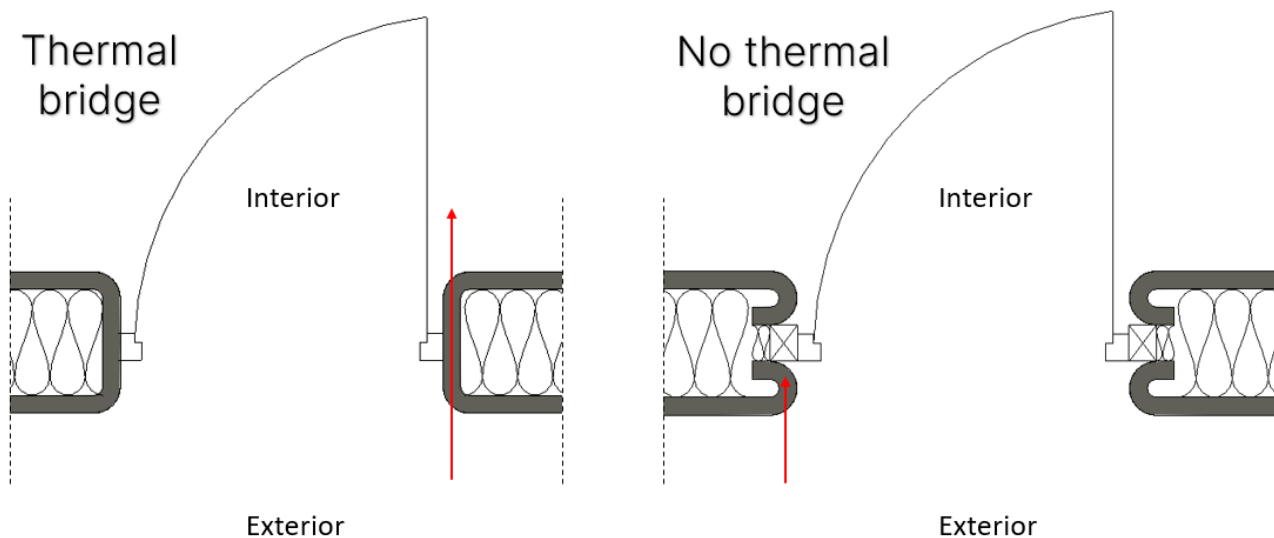
Decide on using flaps or not before you start designing.



3.1.6 THERMAL BRIDGE

Also known as cold bridge is a localized area of the building envelope where the heat flow is different (usually increased) in comparison with adjacent areas. In some countries the cold bridges are not mandatory to avoid, but you should check your local regulations to comply with them in case you need to avoid them or not.

In other words, to avoid a cold bridge, the exterior envelope of the house should not be connected to the interior envelope through large surfaces of high thermal conductive materials such as concrete.



Check local regulations to see if thermal bridges are mandatory to be avoided.

3.2 DURING MODELLING

3.2.1 REINFORCEMENT PLACEMENT

Reinforcement specifications and placement is calculated by the structural engineer, however in 3D printing, the architect must be in close communication with the engineering firm.

Design the 3D printed elements around the reinforcement and make sure the printhead will not be colliding with the reinforcement.

In 3D printing construction the reinforcement which needs a lot of consideration is the vertical one, located in the columns.

Just like in conventional construction all the reinforcement from the building must be connected and overlapped: Foundation → Columns → Beams → Slab/roof.

The vertical reinforcement is usually the one sticking out of the foundation for connecting the columns with, therefore the connection between this reinforcement and the cage of the column must be taken into consideration in the design phase.

There are two ways of connecting the cage with the existing reinforcement:

- ▶ Overlapping reinforcement. This overlap must be calculated according to the structural engineer and local building regulations, but it is usually 20 x the diameter of the vertical rebar.
- ▶ Leaving a small opening in the wall to connect the cage, either with couplers or steel wires.

All this analysis on reinforcement must be discussed with your structural engineer while in the design phase.

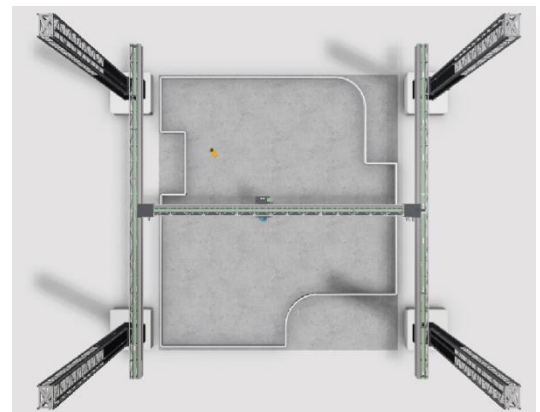
3.2.2 STRUCTURAL ELEMENTS CONSIDERATIONS (FOUNDATION, COLUMNS, BEAMS, SLABS)

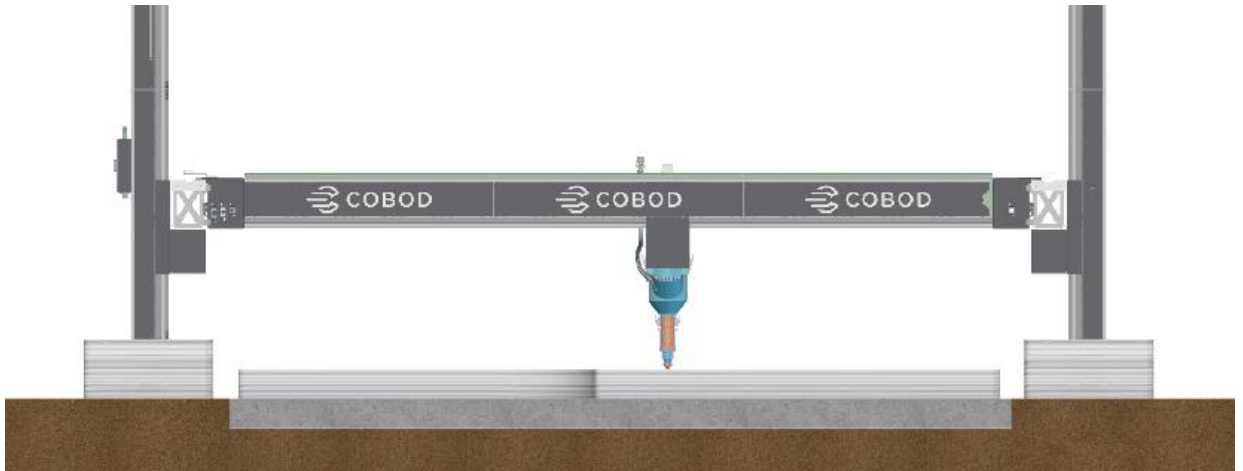
Structural elements can be designed or implemented from the conventional ways of construction. In 3D printing, there is the advantage of printing formwork for the structural elements, which decreases the cost of using conventional formwork, especially for irregular geometries.

- ▶ **Foundation.** The most common type of foundation used in concrete 3D printing is the raft foundation. It is recommended that the formwork for the slab is 3D printed, to avoid any misalignment with the walls and the foundation. It is possible to cast the foundation with conventional formwork as well, however the slab needs to be at least 5 cm bigger on every side and you will need a surveyor to map the foundation in a CAD drawing, in order to match the 3D printing file with the as built foundation.

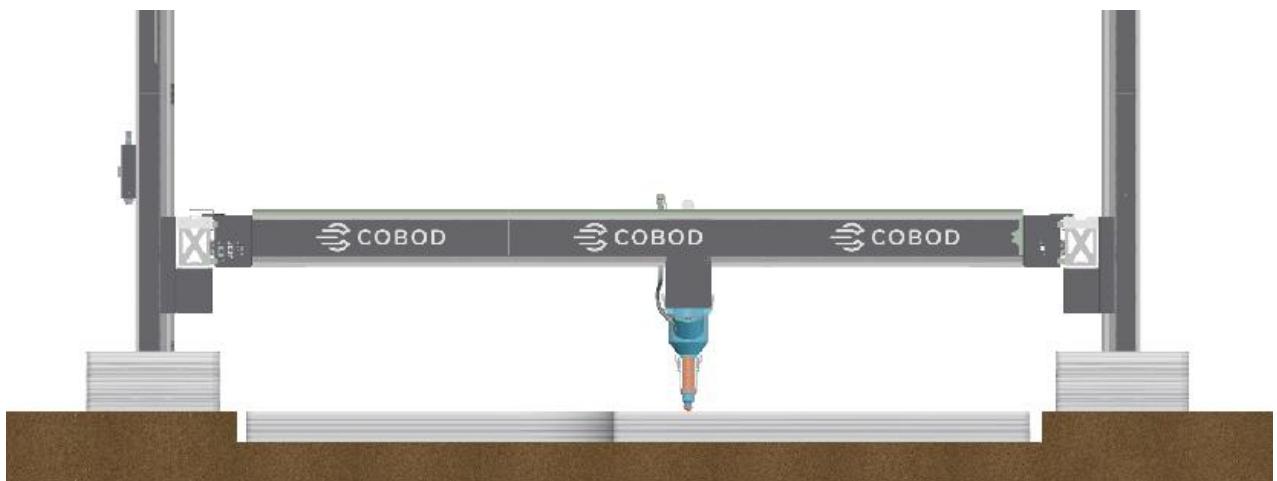
Examples:

- **3D Printing formwork for casting of foundation.** The soil can be dug out to make room for the foundation. As previously described, the base foundation can then be cast in conventional ways, and the top part can be 3D printed for an easy transition into 3D printing the walls of the building. As you can see in the pictures below the 3D printer can be installed on concrete feet. This will increase the reach of the height of the 3D printer used for each project. The use of concrete feet will typically add 60 cm of printing height.

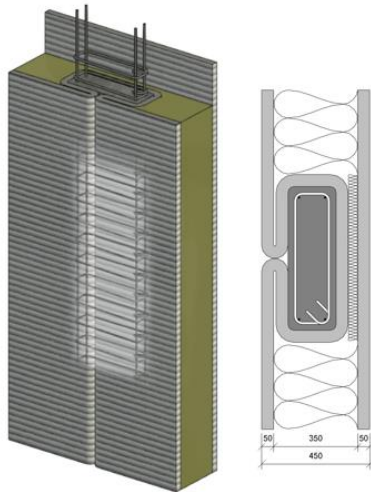




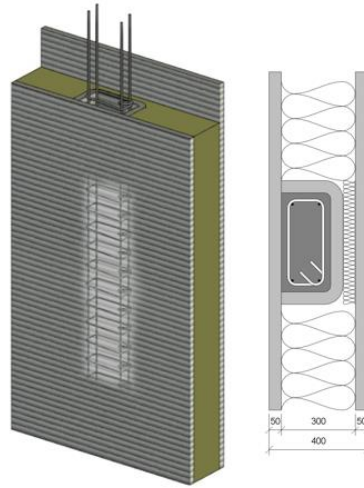
- **3D Printing a plinth beam foundation:** The height of the extruder allows the 3D printer to go below ground level. Allowing the 3D printer to go below ground level can be utilized as shown in the referenced figures. In this example, a double wall is created as a formwork for the plinth.



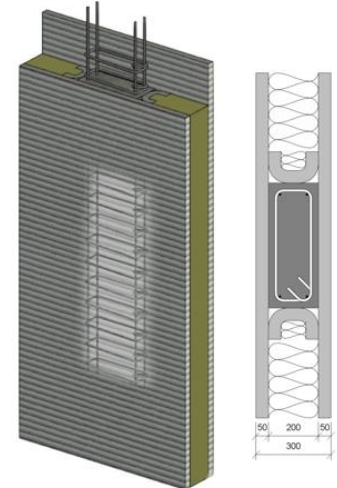
- **Columns.** Vertical structural elements are cast conventionally, but the formwork can be 3D printed. The design of this formwork is limited to the imagination of the architect; however, the dimensions of the column must comply with the calculations from the structural engineer and local building regulations.



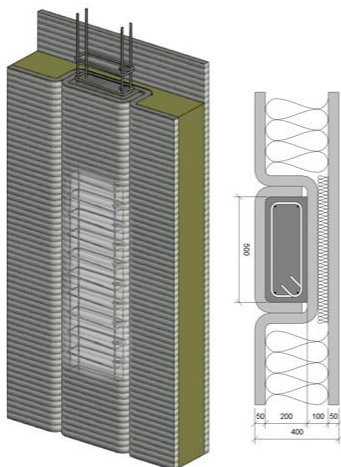
450mm wall with column integrated in the cavity.



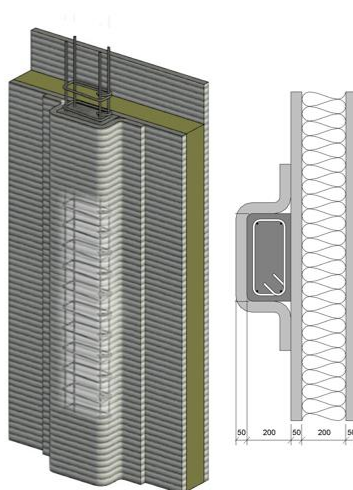
400mm wall with column integrated in the cavity.



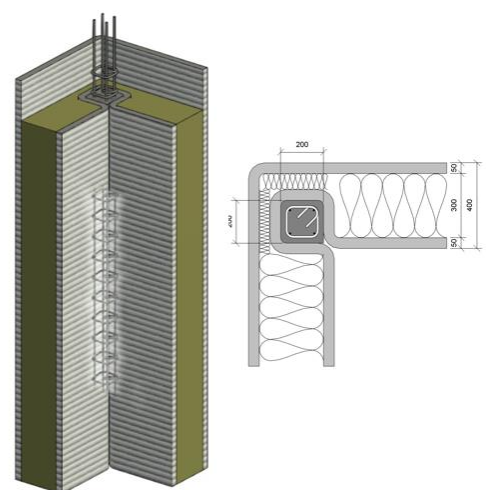
300mm wall with column integrated in the cavity.



400mm wall with column integrated in the cavity.



300mm wall with column on the inside.

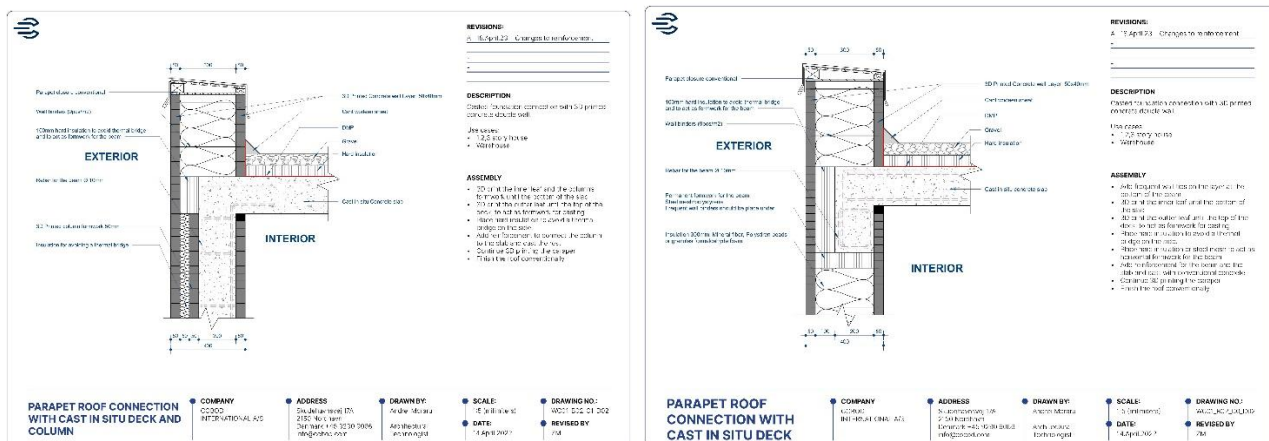


300mm wall with column integrated in the corner

- **Beams and slabs.** Horizontal structures can be cast in the 3D printed formwork, or directly in the cavity of the 3D printed wall. If you plan to cast beams in the cavity wall, the horizontal formwork cannot be removed after the concrete is hardened.

There are different types of slabs that can be used in 3DCP, these types of slabs can be used in floors as well as in roof structures.

- Cast in situ RCC.
- Precast slabs (hollow core, double T, etc).
- Filigree slabs (recommended when the shape of the building is complex. These slabs can be 3D printed).
- Steel or wooden decks.



Refer to Construction Details Document

- ▶ **The formwork** for the 3D printed slabs can be done on the foundation slab and after casting the slabs, place them beside the building and assemble them to the building after the 3D printed walls are cured.

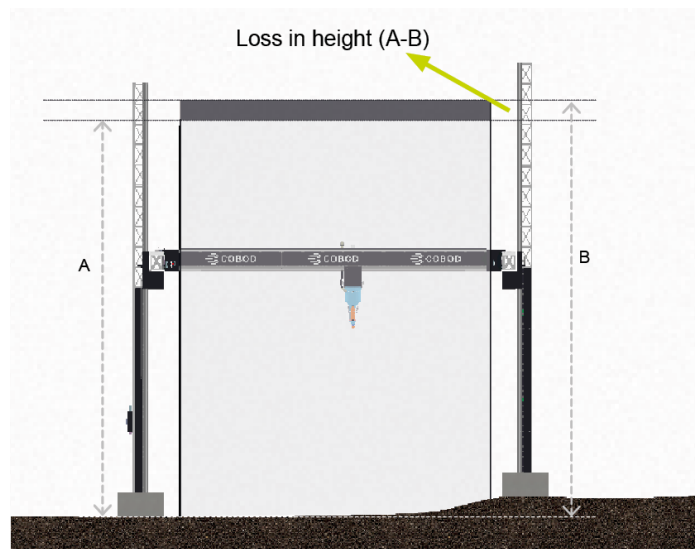
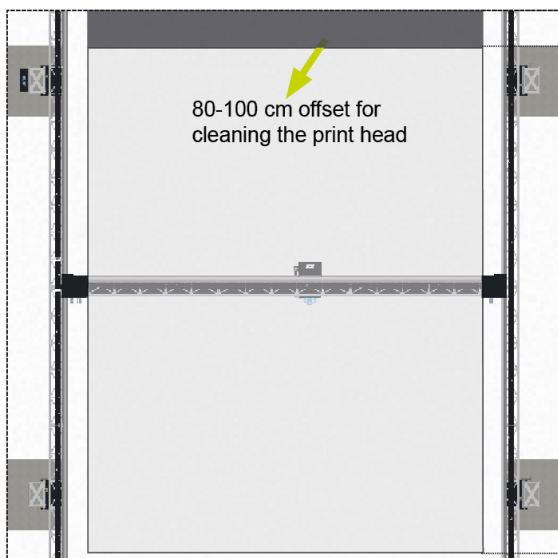
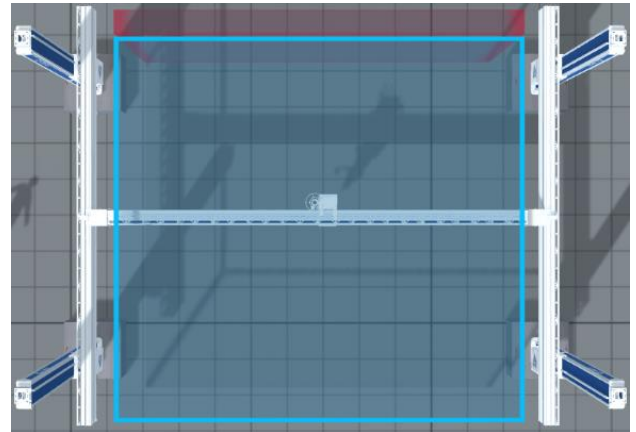
3.2.3 COST CONSIDERATIONS

There are several cost considerations when it comes to cost in the design phase. As in every project the design can increase or decrease the cost significantly, however in 3D printing the shape of the structure cannot increase the cost of the building, therefore, irregular geometries have the same cost as the regular ones.

3.2.4 PRINTABLE AREA

Printable area (blue) is the volumetric area in which you can design a geometry to be 3D printed. It is measured in width $\times$ length $\times$ height and it is different depending on the printer configuration you have purchased.

In the design phase, the printable area is your boundary, you can't design printable elements over this boundary to be printed at once, however you can think of ideas of printing small geometries, as in prefabricated elements and mount them together in case you have a design which exceeds the printable area.



3.2.5 CONSIDERATIONS FOR MOVING THE PRINTER

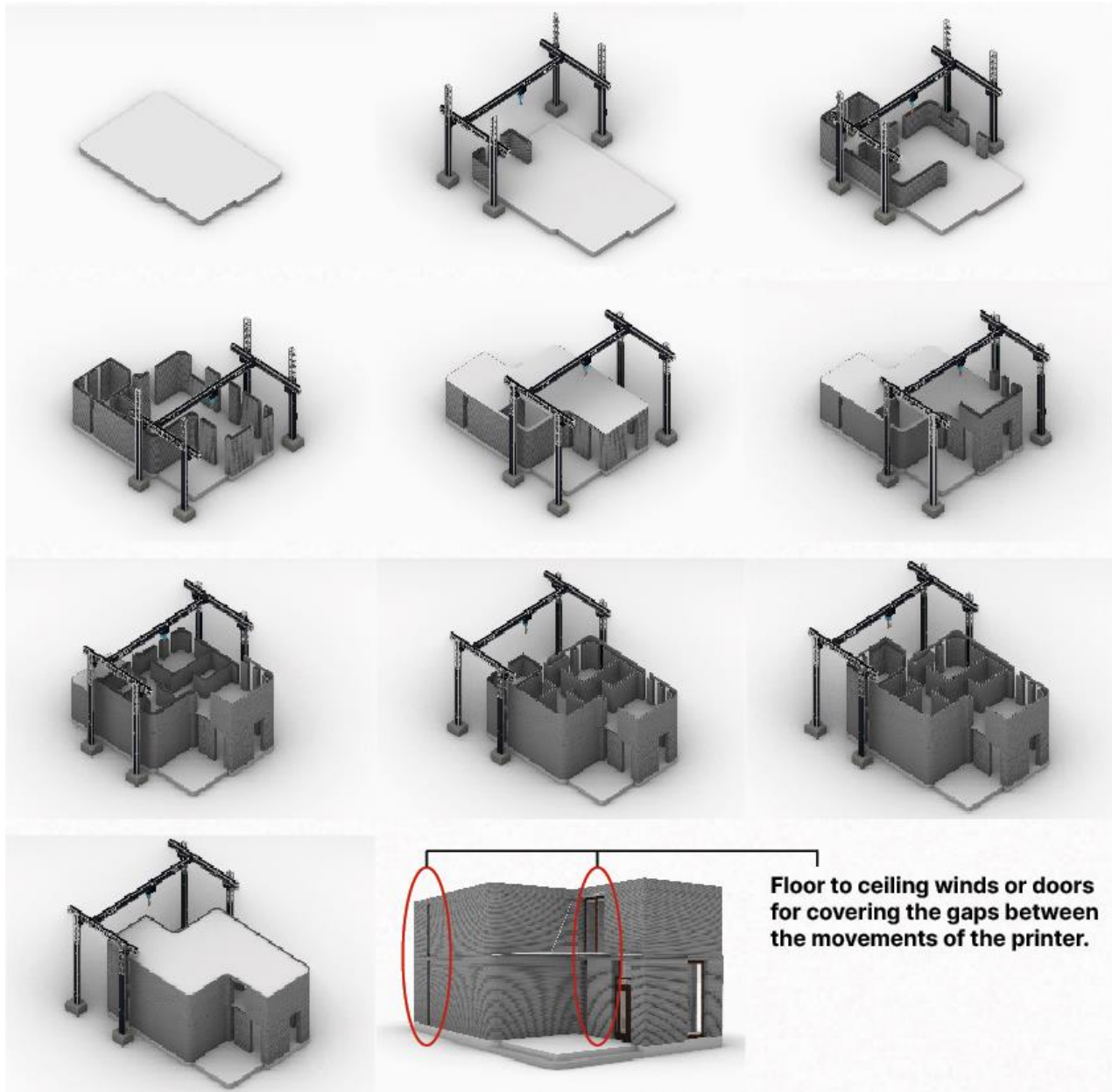
If your design is bigger than the printable area, you might consider splitting the building in 2-3 parts and print them individually.

In this case, you need to consider these movements of the printer when you are designing your building.

For this project, it was decided to have floor to ceiling windows to join perfectly the 3 3D printed sections.

There is a lot of design freedom on how to cover those gaps: floor to ceiling windows, cast concrete, 3D prints that section as a piece of wall and insert it in the gap, etc.

However, we recommend designing according to your printable area, and if you need to move the printer, design accordingly.



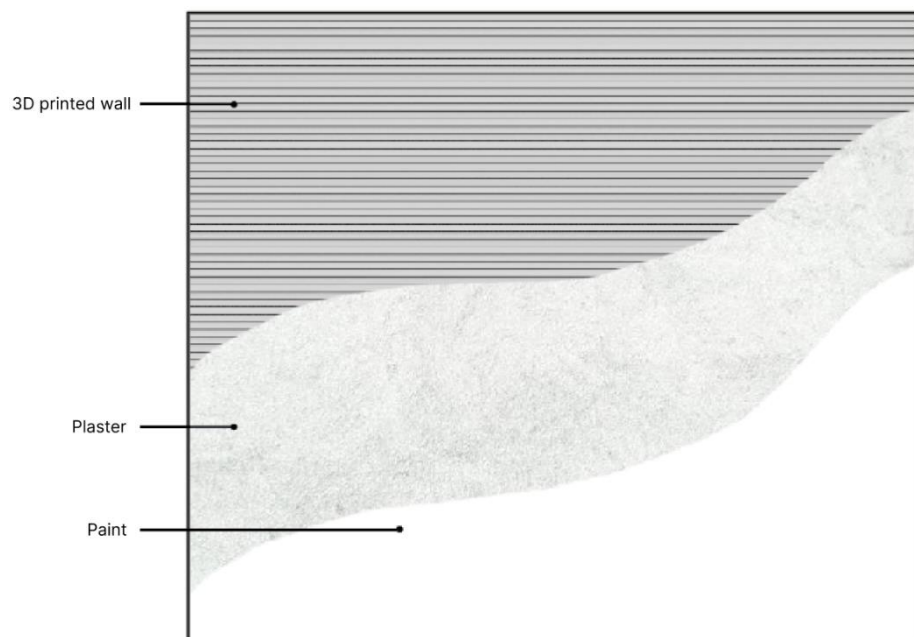
3.2.6 WALL FINISHING

The nozzle width defines the width of a single wall and the nozzle type defines the texture of an untreated 3D printed wall. Two layered flaps attached to the nozzle can produce more even plane texture. This can minimize the manual labour of finishing after post printing.



The 3D printed walls can be left untreated, leaving the indications of the horizontal layers visible.

If a different surface expression is desired, conventional methods for wall finishing such as applying plaster and/or paint to the wall after it has been 3D printed can also be applied.



3.2.7 PROPERTIES OF A 3D PRINTED DOUBLE WALL

The profile of a 3D printed wall usually consists of the Indoor layer, insulation, and external layer. The thermal conductivity (U-Value) of 1cm of the concrete layer without any insulation is 2.4W/m*K which produces a thermal phase shift of approx.14 minutes. This characteristic is important to prevent overheating/cooling of indoor spaces.

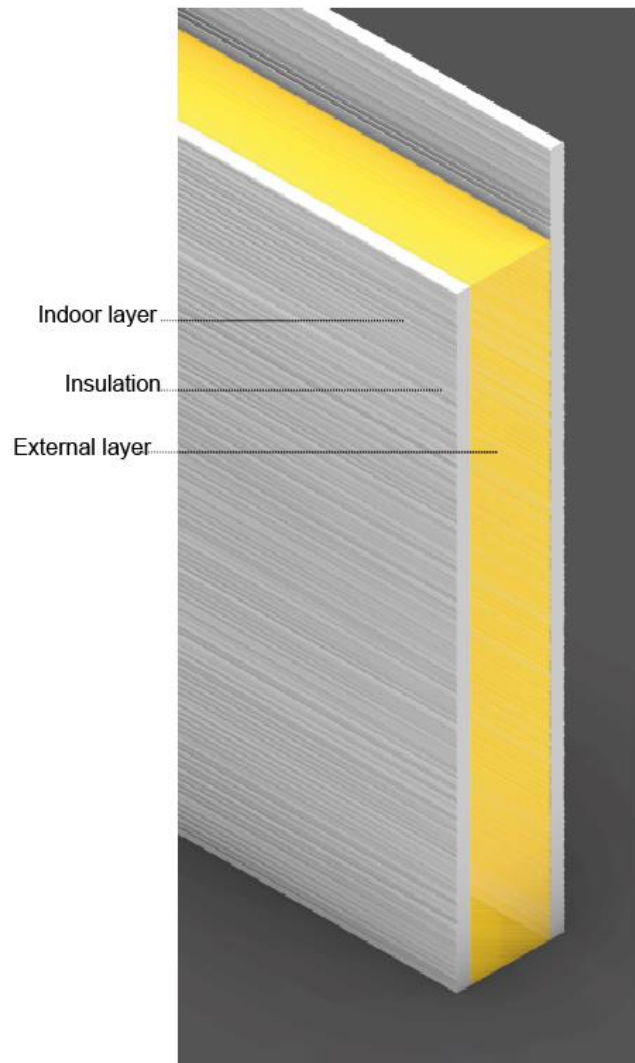
The thermal properties of a 3D printed wall depends upon:

- ▶ Thickness of the individual layers
- ▶ Thickness and properties of the insulation material used.
- ▶ Density and U-value of the insulation material

Different insulating materials can be used for example:

- ▶ Polyurethane foam insulation
- ▶ Rockwall
- ▶ Foam Concrete
- ▶ Cellulose insulation
- ▶ Other insulation materials

It is recommended to use flowable insulating materials as it will be easier to fill the void in a 3D printed wall.

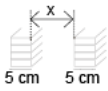
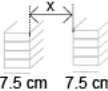
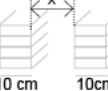
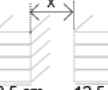
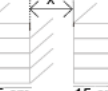


Thermal properties of a 3D printed double wall excluding insulation.

	Metric Unit	Imperial Units
Density	2400 kg/m ³	137 lbs/ft ³
Thermal conductivity (u)	~ 2.4 W/m*K	~ 1.39 BTU/(h*ft*°F)
	For one cm	For one inch
Thermal Resistance (r)	~ 0.004 m ² *K/W	~ 0.060 h*ft ² *°F/BTUT
Thermal Phase Shift	~ 14 minutes	~35 minutes

3.2.8 CONCRETE THICKNESSES VS THERMAL PHASE SHIFT

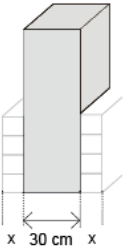
The table shows the Thermal resistance (R-value) of the printed concrete with different layer width without the insulation material.

	Total concrete thickness	Thermal Resistance		Thermal Phase Shift
	10 cm / ~4 inches	0.04 m ² *K/W	0.23 ft ² *h [°] F/ BTU	2 hours, 20 min
	15 cm / ~6 inches	0.06 m ² *K/W	0.35 ft ² *h [°] F/ BTU	3 hours, 30 min
	20 cm / ~8 inches	0.08 m ² *K/W	0.47 ft ² *h [°] F/ BTU	4 hours, 39 min
	25 cm / ~10 inches	0.10 m ² *K/W	0.59 ft ² *h [°] F/ BTU	5 hours, 49 min
	30 cm / ~12 inches	0.12 m ² *K/W	0.71 ft ² *h [°] F/ BTU	6 hours, 59 min

Note: X is the width of insulation and here the phase shift value is independent of r value.

Depending upon the thickness of layers printed, the thermal properties of the wall can be changed accordingly. The 3D printed outer walls are usually printed with 5-10 cm per layer. This gave an approx. thermal phase shift of 2 - 5 hour without insulation.

Insulation Properties

	Insulation type (loose fill)	Blown Cellulose, 30 cm		Mineral Wool, 30 cm	
	Total u-Value	0.14 W/m ² *K		0.12 W/m ² *K	
	Total r-Value	7.54 m ² *K/W	42.8 ft ² *h [°] F/ BTU	8.61 m ² *K/W	48.9 ft ² *h [°] F/ BTU
	Total Phase Shift	10 hours, 50 minutes		7 hours, 40 minutes	

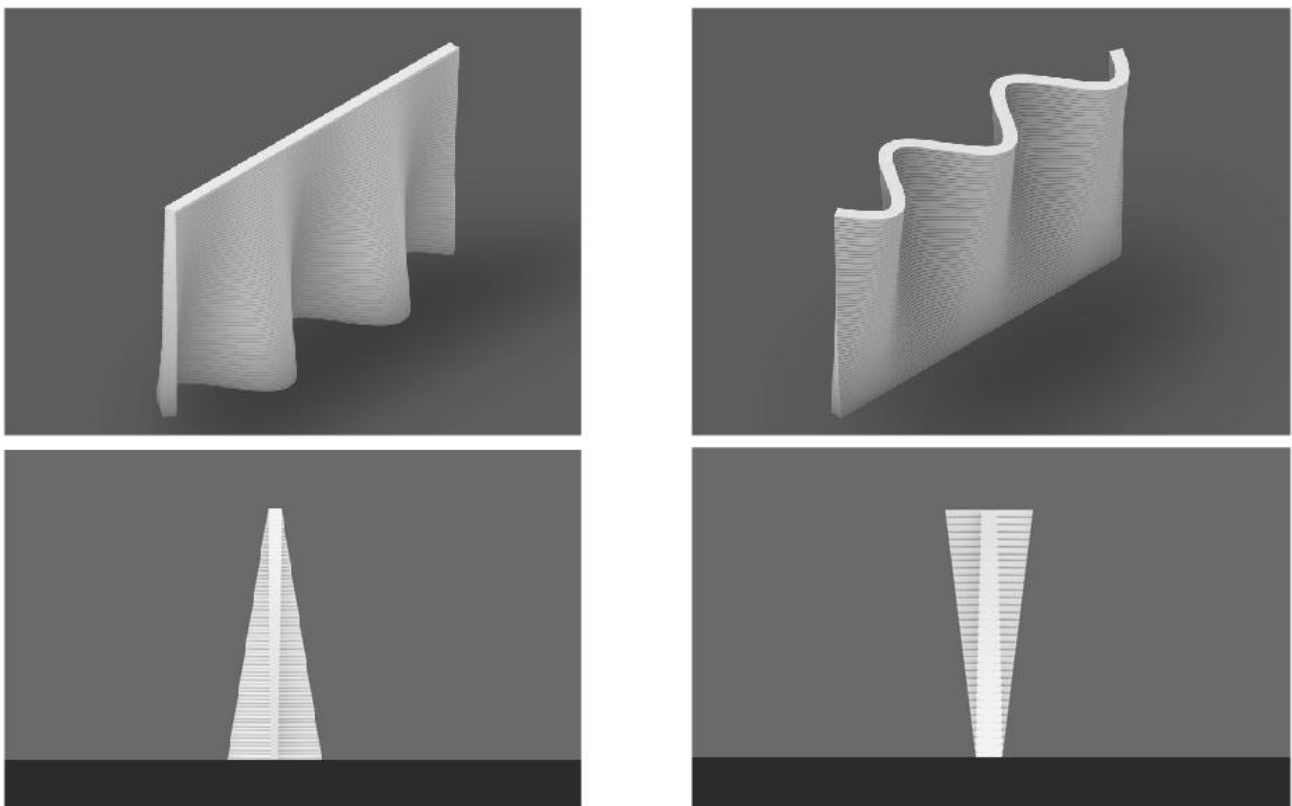
A 3D printed double wall with 30cm insulation has a u-value range between 0.12-0.14 W/m²*K.

3.2.9 STABILITY OF A 3D PRINTED WALL

Stability is one of the most important factors that need to be considered for a 3D concrete printing project.

- ▶ Fresh concrete has extremely low strength and stiffness.
- ▶ Concrete is thixotropic, which means vibrations will further weaken the structure in the early stage.
- ▶ For unstable structures, very small uncertainties in materials can influence the success of the print.

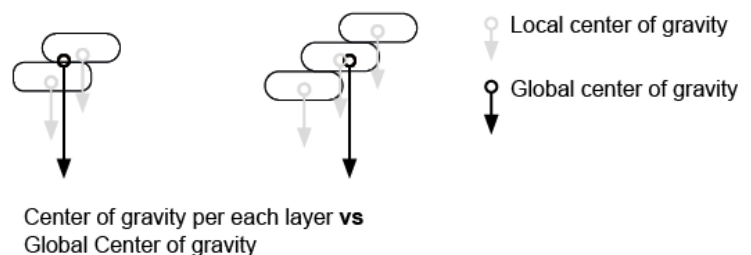
Geometry with a higher surface area on the bottom has more stability. To print an unstable wall, it needs accurate material and controlled environment.



Overhangs

The overhang in 3D printing means the extension of projection from the global centre of gravity. For printing a successful overhang, the global centre of gravity should be inside the support area.

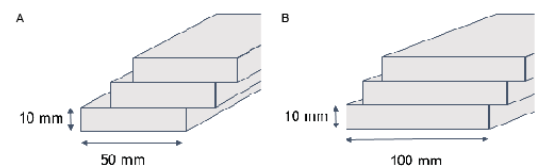
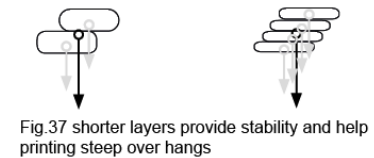
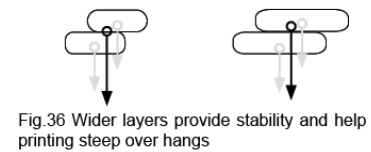
While printing an overhanging wall, it is not recommended to use the flaps with the nozzles. The flaps might cut off the layer below, which can ruin the entire print.



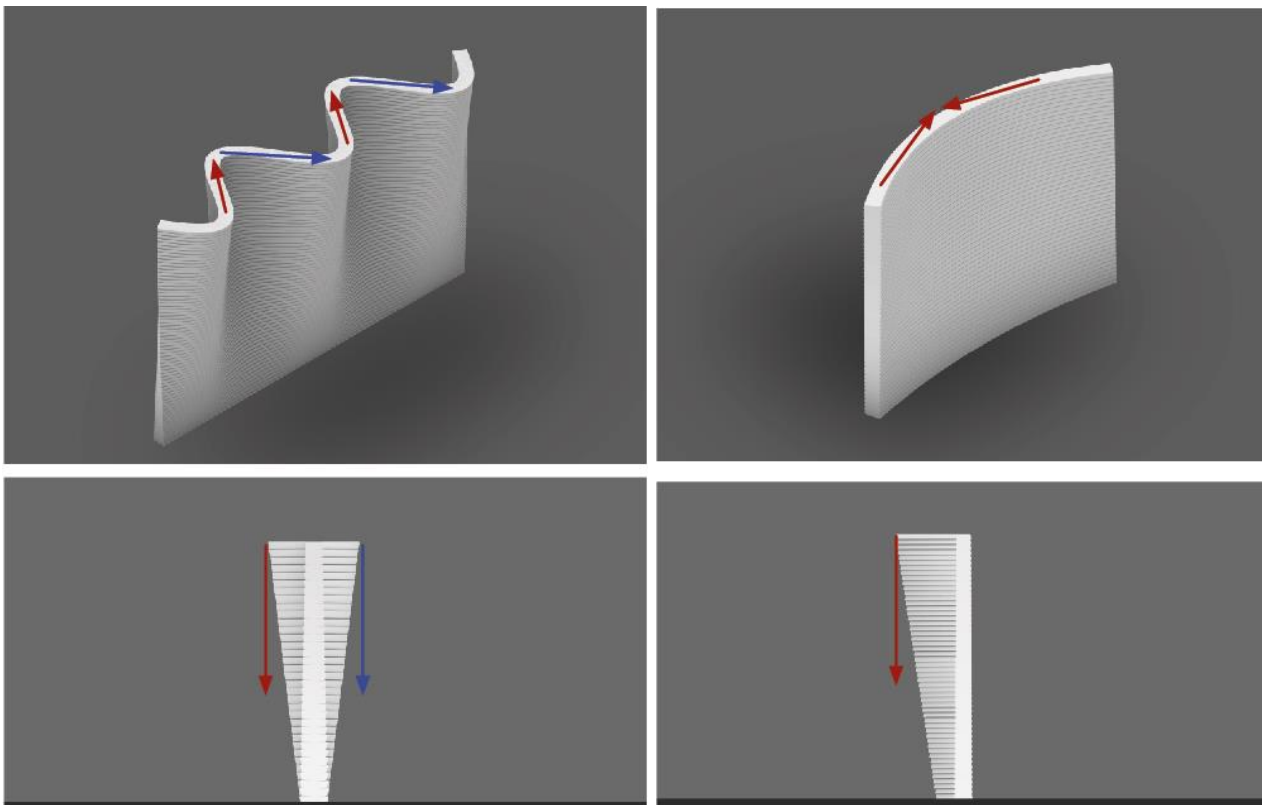
Printability of overhangs

The printability of overhang depends upon the following factors:

- ▶ Layer width: Wider layers help carry out steeper overhangs.
- ▶ Layer height: Lower layer height also play an important role in carrying out overhangs.
- ▶ Layer time: which is time needed to print one layer, this also relates to the size of the printed object. Larger objects would have a longer layer time, allowing the concrete to set initially and be ready for the next layers.
- ▶ Material properties: Shorter initial setting time can help printing steeper overhangs.
- ▶ Environmental condition: Controlled environmental conditions could ensure a successful print (Like temperature and humidity).



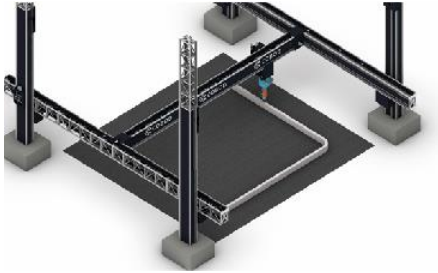
Normally, overhangs around 10 to 20 degrees are achievable.



On the left, the load is evenly distributed on both sides of support base, and on the right the load is large and uneven which will make the model collapse.

3.2.10 3D PRINTED ROOF SLAB

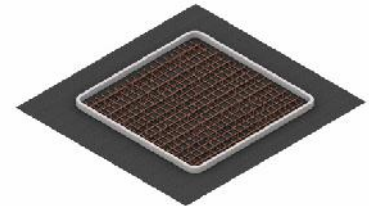
The workflow for a 3D printed precast roof slab consists of two stages. The initial stage/ prefabrication includes printing the formwork, inserting spacers for the reinforcement, reinforcement placement, and first layers of concrete. The second stage/onsite includes placement of the member over the building and the addition of the remaining concrete layer.



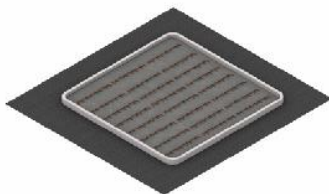
3D printing of the slab form work. The height of the form work printed depends on the thickness of the slab needed.



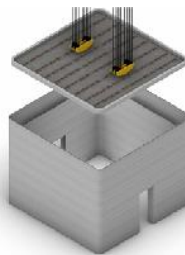
Spacers are placed at a regular interval. The spacers give an offset for the reinforcement from the floor level.



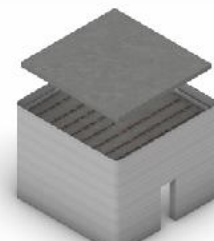
Reinforcement are placed over the spacers. The quantity and specification of the reinforcement should be according to structural drawing.



A first layer of concrete added over the reinforcement. For 20cm slab, 6-8 cm are usually filled with concrete offsite. There should be proper hooks for lifting the casted slabs.



The casted slabs are assembled onsite using lifting mechanism.

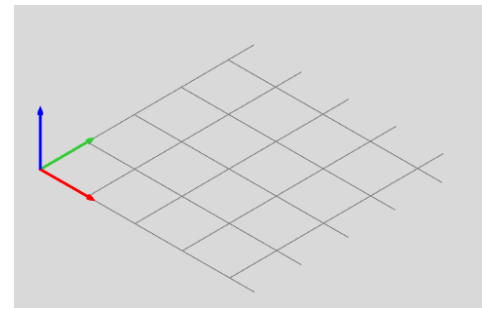


Prior to the final casting a similar layer of mesh reinforcement was placed on top of the existing reinforcement. This mesh reinforcement will be tied with structural reinforcement (Column) for structural integrity.

3.2.11 GEOMETRY IN XYZ SPACE

Like desktop 3D printers, the geometry designed to be 3D printed with BOD2 needs to be placed within the XYZ axes of your 3D modelling program. Any piece of geometry located outside these boundaries will not be recorded as g-code for the printer to follow and deposit material.

A common mistake when you design a building for 3D printing, is to create the foundation formwork under level 0, which makes sense in conventional construction, however in this case, you must set the level 0 when you start 3D printing, which means any geometry even if you want it under ground or not, needs to be above level 0, or as known as Z0.



XYZ space

3.2.12 PRINTING TIME OPTIMIZATION

In the design phase you can think of ways on how to optimize the printing time of your design. The printing time is described in three parts:

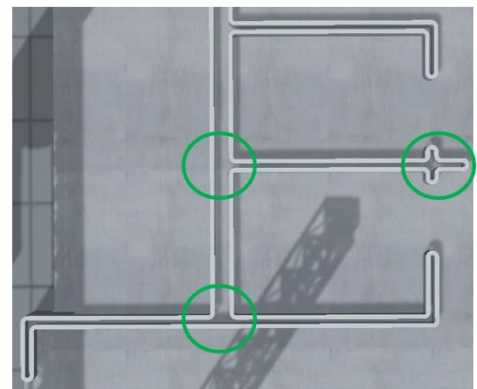
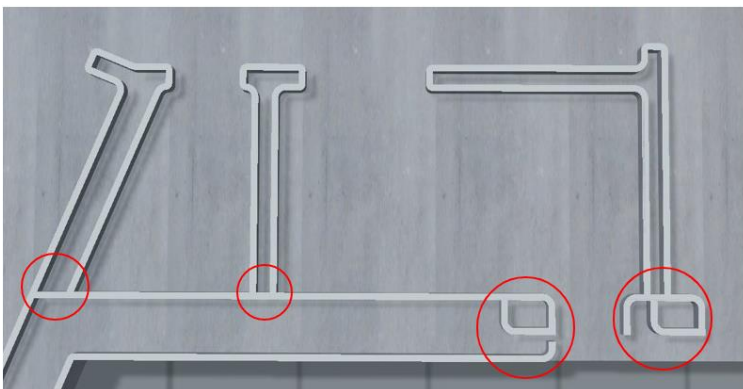
1. Start/stop of the print → increases printing time.
2. Travel of the printhead → increases printing time.
3. Actual printing time depends on the speed, but there is nothing you can optimize here.

Therefore, an optimized printing time should contain as little as possible the start/stop of a print and travel of the print head.

Avoid having too much travel time or too many start/stop times.

3.2.13 CONTINUOUS LOOPS IN YOUR DESIGN

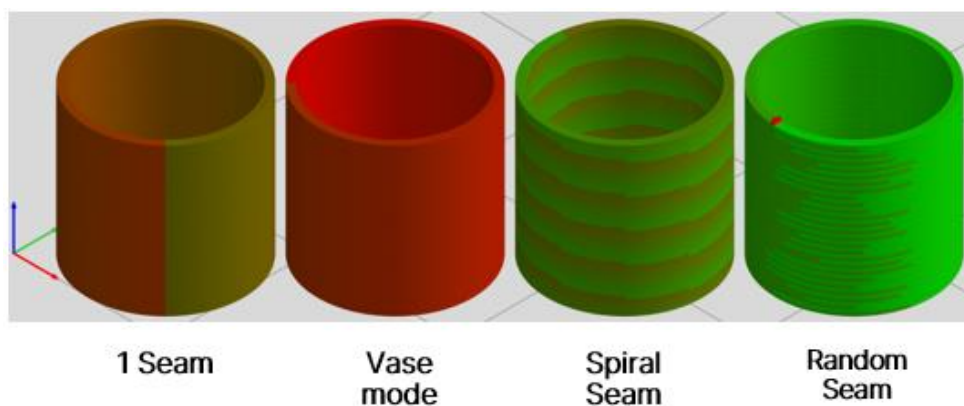
To avoid too much travel time or start/stops in your print, you can design your walls in as many continuous loops as you possibly can. This is another advantage of having an architect to do this optimization on your design. The architect will find creative and effective ways to create these loops in your design and optimize your print to the maximum.



3.2.14 SEAMS

A seam or also often called a Z-Seam, is a visible line of imperfections running down the Z axis of a print from top to bottom. These resulting print defects are usually discontinuities and sometimes accompanied by blobs or zits. A Z-Seam is usually visible on 3D printed loops that have not been printed in Vase Mode.

Consider whether you want your seam to be visible or not while you design the geometry. It is recommended to have one seam but you will need to hide it for example where the door/window will be installed.



3.2.15 EXTERNAL OBJECTS

External objects are often already 3D printed objects, reinforcement for the columns coming out of the foundation, or other objects on the printable area that cannot be moved or need to be in the printable area.

When designing your geometry, the solids must be designed as well. This will ensure that the printhead will avoid these objects while travelling.

Create solids for existing objects within the printable area to avoid collision.

3.2.16 CONNECTION WITH CONVENTIONAL ELEMENTS

In the design phase you must decide what conventional elements are going to be connected to the printed ones in your design and how are these connections going to be made in detail.

Many conventional construction details are very similar in 3DCP too, but you still need to adapt them to the geometry you want to print.

Create Detail drawings for all connections in your building/geometry.

3.2.17 EXPANSION JOINTS

A concrete expansion joint or control joint is a gap which allows the concrete to expand and contract as/when the temperature changes. It forms a break between the concrete and other parts of structure to allow movement without causing stress, which can lead to cracking.

In 3DCP usually the concrete is 3D printed in a full monolithic structure, therefore the expansion joints are a must to have in a 3D printed structure. These joints must be created in a range of 2-5m along the print, so this is another need for an architect to be creative on hiding or making visible these joints.

Create expansion joints every 5 linear meters to avoid cracking.

3.2.18 OTHER PRINTABLE ELEMENTS

3D printing technology offers many possibilities for architecture and construction, there are many designs that can be implemented in a house or other geometry you plan to create. Research on designs of landscape geometries, interior design geometries that can be 3D printed.

Use the most out of your concrete 3D printer.

3.3 AFTER MODELLING

3.3.1 EXPORT AS STEP FILE

After modeling the centerlines, they must be exported as a (.**step**) file, which afterwards will be imported into the COBOD Slice for generating a G-code.

3.3.2 TEST YOUR DESIGN

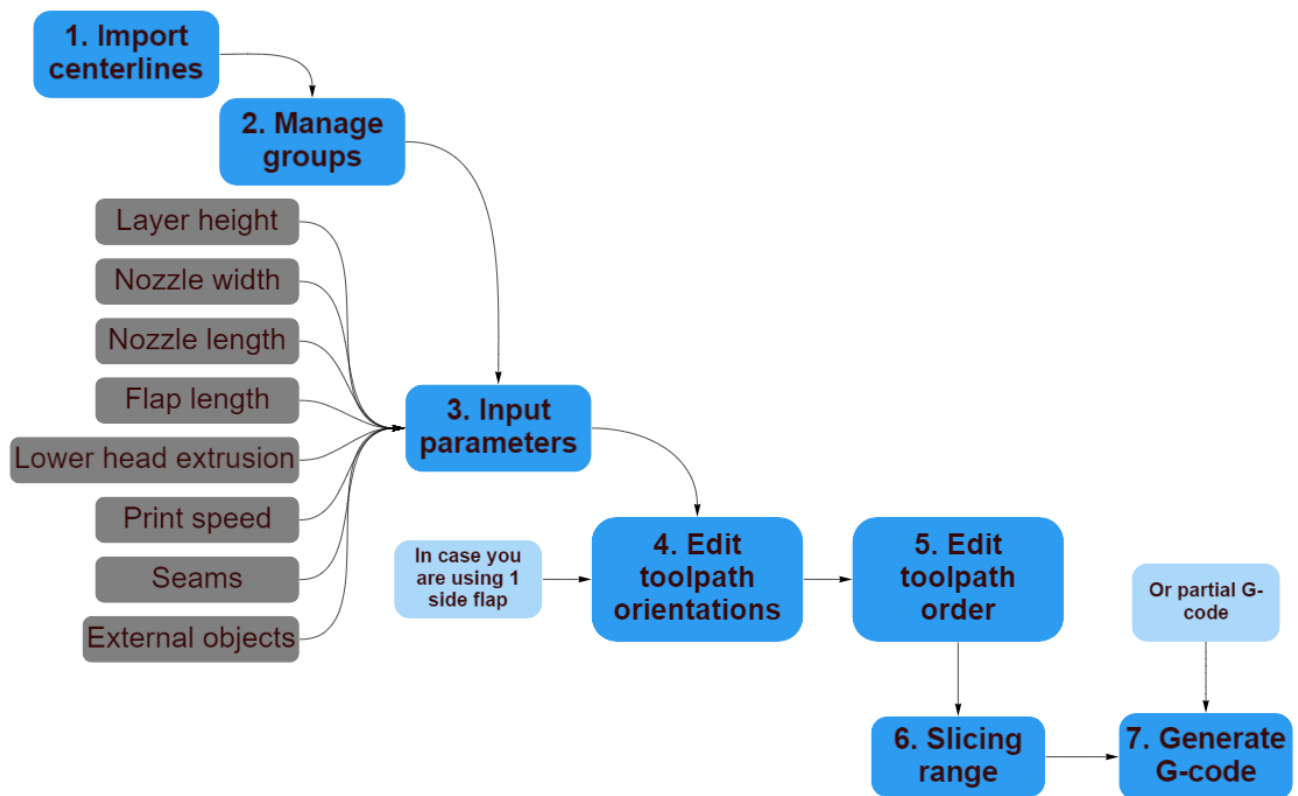
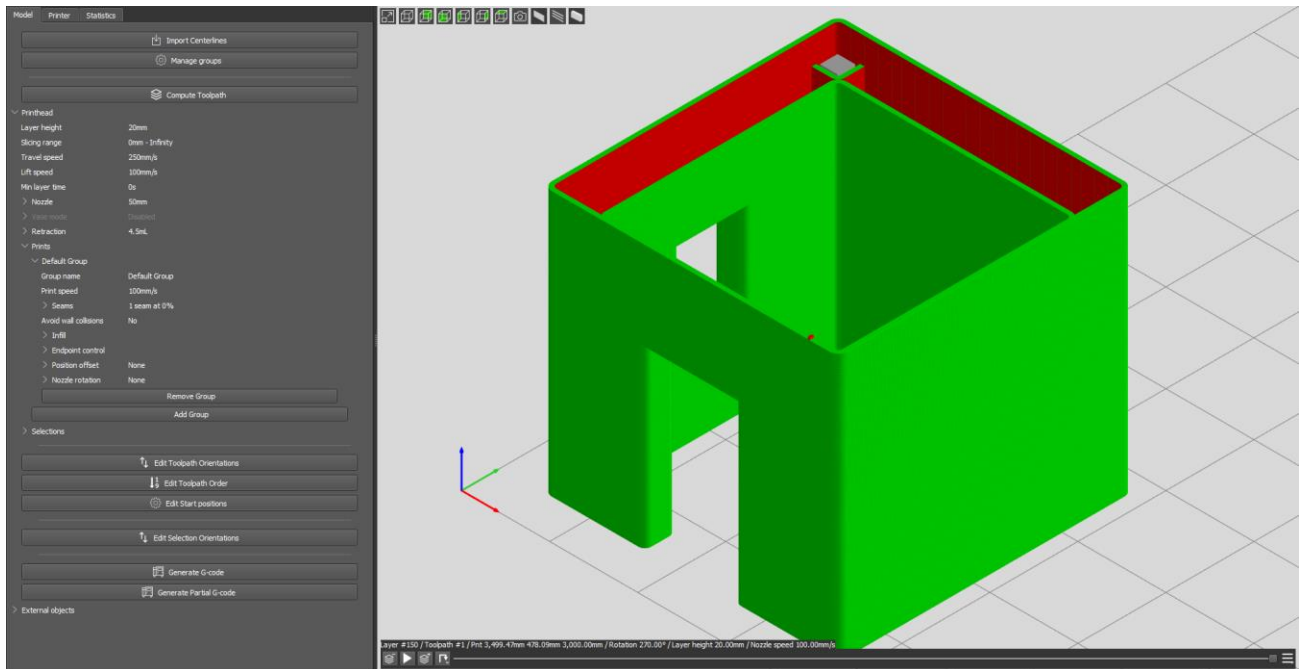
After you finish your design, it is time to import it in the COBOD Slice to check for mistakes or imperfections, wrong connections and so on. COBOD Slice lets you print your design digitally in the same way that it will be 3D printed physically, so this step is very important to do. Very often you will make many adjustments back and forth between designing and Slicing, until your desired result is achieved.

If you want to try a new technique, a specific geometry, or even a geometry you never tried printing it before, it is recommended that you test the design first, in a small scale, before implementing it in a house or larger project.

If you are using for the first time a concrete 3D printer, test everything first, print a small design until you achieve your desired results. Do not rush into printing a large-scale project in the beginning.

4. SLICING PROCEDURES

Step by step procedure to optimally slice a geometry for generating a g-code for BOD2 3D printer. Please also study the COBOD Slice Manual for more in depth understanding of all the parameters from the program before you slice any geometry. COBOD Slice User Interface:



SLICING CHECKLIST	
Import a STEP file	
Grouping	
External objects	
Nozzle parameters	
Nozzle width	
Nozzle length	
Layer height	
Flap length	
Printing speed	
Lower head extrusion	
Seams	
Fixed offset	
Seam count	
Seam distance	
Toolpath orientation	
Toolpath order	
Slicing range	
Statistics	
Partial G-code	
G-code	

4.1 SLICING: PARAMETERS AND FEATURES

4.1.1 IMPORTING A STEP FILE

Click on “Import Centerlines” to import your step file model. If you need to do changes in the model, you must do them in your CAD software. If you need to move your model in relation to the XYZ origin, you must do so in your CAD software.

4.1.2 GROUPING

Solids must be grouped from the centerlines to be added to the external objects. Click “Manage groups” to select each element individually and add a new group called “external objects” or in case of printing a house, you will have the reinforcement sticking out of the foundation created as a solid in your model. Add all the solids in a separate group from the centerlines.

Note that the slicer will not create g-code for printing solids, it is only creating code for centerlines.

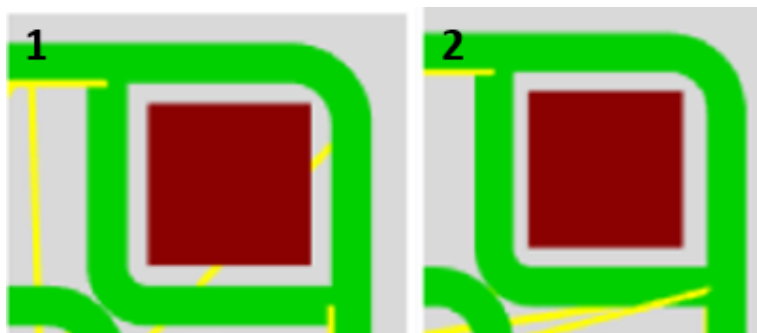
4.1.3 EXTERNAL OBJECTS

External objects are particularly important to avoid collision of the printhead with objects situated already on your printing area, for example reinforcement for the columns or other already printed elements.

The printer has the functionality to see these objects if you set them up in the Slicer.

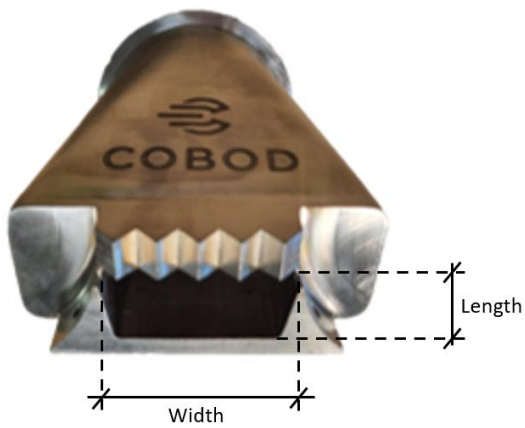
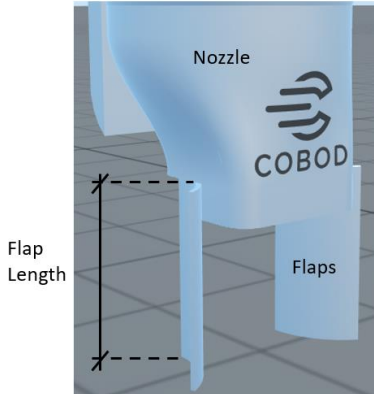
The yellow line is the travel path of the printer, and you can notice in the first picture the printer goes through the red square, which in this case is the reinforcement of the column represented by a solid.

After setting up the external objects, the printer will go around these existing objects from the printable area.



4.1.4 NOZZLE PARAMETERS

It is especially important to know your nozzle when you model but also when you slice. The nozzle determines the thickness of your 3D printed elements, and it influences the layer height as well.

Parameter	Description	Visual identification
Nozzle Width	The width of the nozzle gives the shape of the printed element. Without flaps. The standard one for concrete is 50mm, but it can be in any size.	
Nozzle Length	Length of the nozzle does not directly impact the layer height; however, is recommended to use a nozzle size of 50x40mm, for a layer of 50mm in width and 40mm in height.	
Layer Height	Height of the layer. This parameter will greatly influence the printing time of the geometry.	
Flap Length	Length of the flap must be added as a parameter to avoid collision of the flap with freshly painted walls. Add +30-50mm more for your flap length when you add this parameter in the slicer, to be even more sure it doesn't touch any of the fresh or dry layers.	

4.1.5 PRINTING SPEED

This is the speed calculated in mm/s of the printer while printing. Even though you can adjust the speed in the Slicer, you can also adjust the speed in the UI of the printer. Usually, you will add the speed here to estimate the duration of the print, but the real speed you will adjust it while printing your geometry because it will vary from material to material.

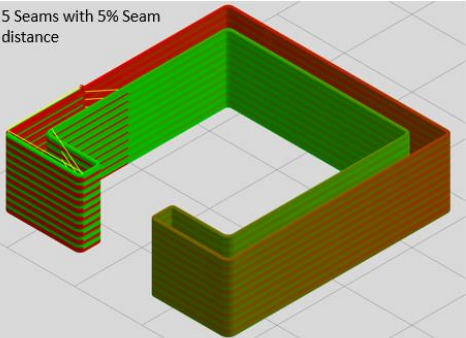
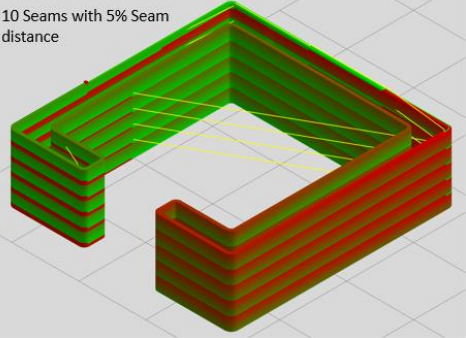
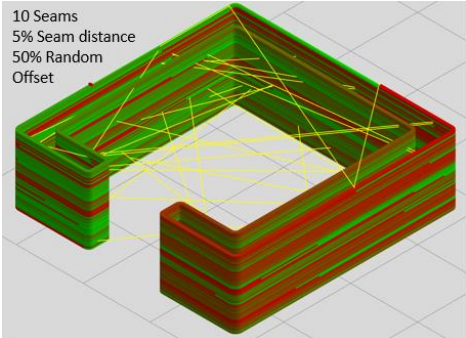
In the beginning you will use between 100-150mm/s until you get used to the machine and match a perfect recipe of material. After that you will be able to print at a speed of 200-250mm/s. The printer is limited to a printing time of 250mm/s.

4.1.6 LOWER HEAD EXTRUSION

When the printer travels to a specific point to start the layer of a geometry, it will arrive in the XY position and then it will slowly start to go down on Z axis to start printing. The lower head extrusion factor is telling the printer to start to extrude material while it goes down to start a layer. This way the start of the layer will be much better, excluding the situation where there is no material in the nozzle, or has been lost during travel, resulting in a bad inconsistent layer start.

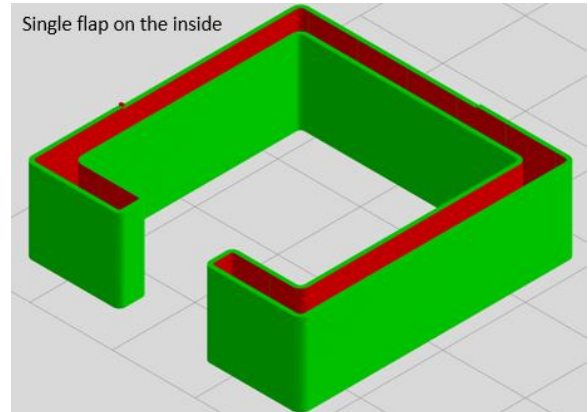
4.1.7 SEAMS

Seams, as explained earlier in this document, are the start and end of a layer, creating a line of seams if they are in the same place.

Parameter	Description	Visual identification
Fixed offset	Offset the start point of your seam by a fixed value. Fixed offset allows you to choose the starting point of your first seam. The input number is a percentage from the linear print of a specific loop.	 5 Seams with 5% Seam distance
Seam count	Number of seams before it starts from the first seam again. Use more than 5 seams if you want to them to not be very visible.	
Seam distance	The distance between consecutive seams.	 10 Seams with 5% Seam distance
Random offset	Randomizes where the seams are located, try it before you implement it in house design.	
		 10 Seams 5% Seam distance 50% Random Offset

4.1.8 TOOLPATH ORIENTATIONS

Toolpath orientation edits the direction of the printhead in which it prints a specific geometry. You can click on any geometry and edit its toolpath orientation. This is particularly used when you are using a nozzle with a single flap. It is important to decide if you are going to use two flaps, one flap, or no flaps for your walls.

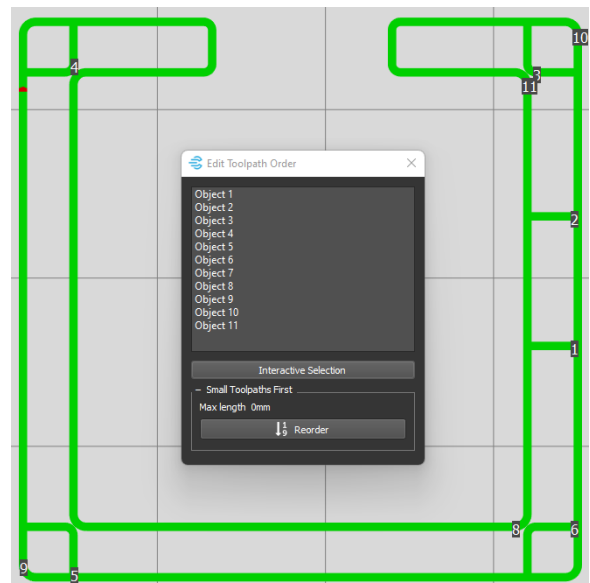


4.1.9 TOOLPATH ORDER

Toolpath order dictates in which order the individual elements will be printed and you can optimize the printing time by choosing the perfect order.

You can do so by clicking on *Edit Toolpath Order* then click on *Interactive Selection*, then simply click on the elements in the order you want to be printed.

This order is the exact order in which the elements will be physically printed. Choose the order with the shortest travel between the objects.



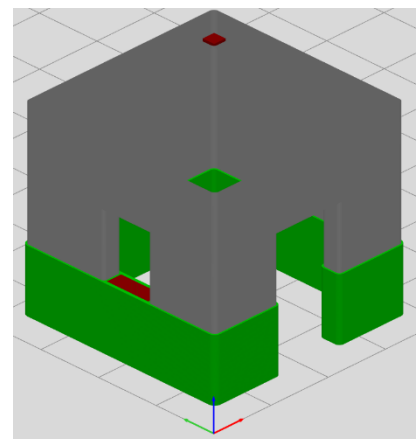
4.1.10 SLICING RANGE

When you are printing a house for example, you will print in multiple days, therefore it is easier and better to have multiple g-codes from the entire model.

This parameter offers you the possibility to slice a specific range in height from the total model.

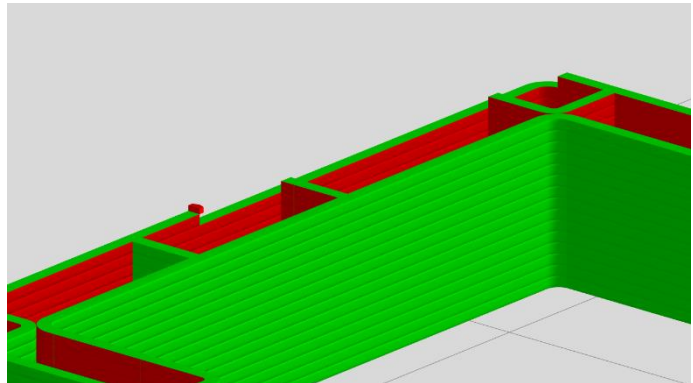
In this example, the model is sliced at every 1 meter, defining the bottom of the window, the 2nd meter closing the top of the window, and the 3rd meter finishing the geometry.

Use the *Slicing range* parameter to define the range you want measured in *mm*.



4.1.11 GENERATING PARTIAL G-CODE

Assuming you had to stop a print and continue the next day for various reasons such as: material inconsistency, power outage or other unforeseen events, the printer will need an input of that specific point or close to that point in a G-code format. Therefore, you will need to generate a *Partial G-Code*.



Partial G-code works together with the animation slider you will find in the bottom part of the program. Let the animation play until it's close to the position where you stopped the day before. Then hit Generate Partial G-code and it will generate a g-code from that specific point and upwards.

4.1.12 STATISTICS

The statistics tab from the Slicer will give you an understanding of the estimated time needed to print the geometry, as well as the estimated material quantity.

Every time you change a parameter in the **Model** tab, make sure you check the statistics as well to see if anything changed, improved, or not.

Average layer time is another important factor you will look for because this number should not be below 4-5 minutes and not greater than 25 minutes.

Volume per hour will indicate to you how productive you are going to be with this geometry, but it will still be an estimation.

Model	Printer	Statistics
Total length 993.37m		
Print length 618.24m		
Rapid length 375.13m		
Estimated duration 2h 9m 11s		
Estimated concrete volume 1,236.44L		
Layer count 25		
First layer Z 0.04m		
Last layer Z 1m		
Average layer time 5m 10s		
Min layer time 4m 51s		
Max layer time 5m 20s		

Layer	Print length	Rapid length	Duration	Print speed	Volume	Volume per hour
1	24.73m	10.51m	4m 51s	100mm/s	49.46L	610.44L/h
2	24.73m	15.02m	5m 10s	100mm/s	49.46L	574.13L/h
3	24.73m	15.47m	5m 11s	100mm/s	49.46L	570.77L/h
4	24.73m	12.35m	4m 59s	100mm/s	49.46L	594.55L/h
5	24.73m	12.1m	4m 58s	100mm/s	49.46L	596.57L/h

4.1.13 GENERATING G-CODE

After your model is optimized, even if you want to generate a full G-code for the geometry, or just a Slicing range, click on *Generate G-code* to generate the file which you will import into the printer DUET interface.

5. TROUBLESHOOTING

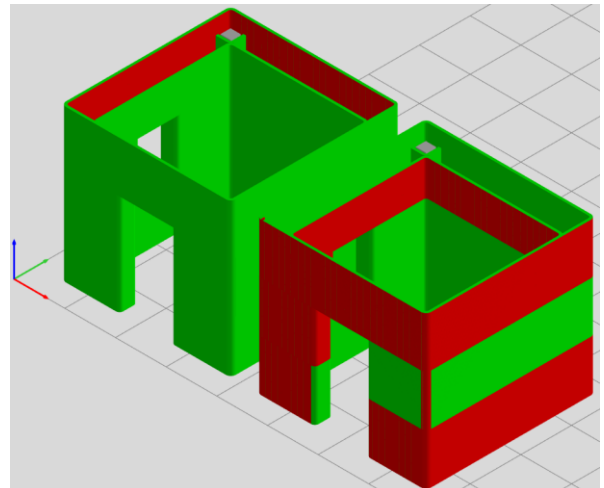
5.1 COMMON

5.1.1 SURFACES/CENTERLINES ARE NOT JOINED

Surfaces that should be 3D printed in a loop or in one go without stops, need to be joined in the CAD software. The fastest way to test if your surfaces are joined is to export your model as a STEP file and import it into the COBOD Slice. In our Slicer software you can easily visualize if the surfaces are joined, because you will need to organize the order in which these centerlines should be printed.

The picture on the right is an example of how to check if the centerlines are joined from COBOD Slice, however this is also possible to see in the CAD software you are designing the geometry.

Join all the surfaces of individual objects to be 3D printed faster, without interruptions or other problems that might arise during printing because of the designed geometry.



5.1.2 SURFACES/CENTERLINES ARE JOINED

Some objects are necessary to not be joined to choose the most optimized object order for printing. In this case, in the picture on the right, the support for the window opening is joined to the side of the opening. Therefore, when this geometry is imported into the Slicer, there will be only 1 object to select, and you will not be able to define a specific order of these objects to be 3D printed.

In some cases, the surfaces that seem to be joined do not necessarily need to be joined if you want to choose the order in which these elements need to be printed.

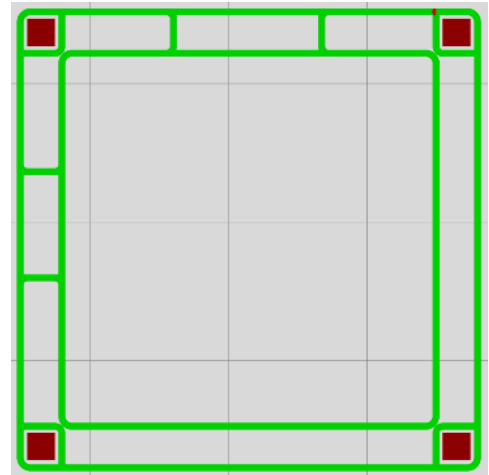
Make sure you understand which surfaces need to be joined and which do not.

5.1.3 SOLIDS

Solids represent the external objects you might have within your printable, they can represent reinforcement for the columns or other already printed objects you want to avoid with the printhead.

Solids must be modelled in the STEP file to be avoided by the printhead. After you model them, make sure in the Slicer, you add them as external objects.

In the picture on the right, contains reinforcement represented by red solids. The color of the solids can be changed when you make a new group.

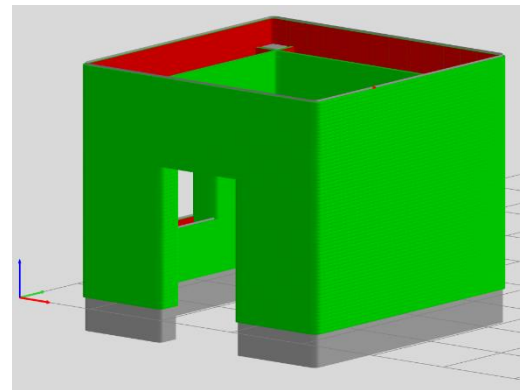


5.2 LESS COMMON

5.2.1 GEOMETRY IS NOT PLACED AT Z0

Every geometry must be modeled in 3D from Z0 and upwards. Even if in your CAD program your foundation is situated underground, meaning you will model it under level 0, when you want to export it for the Slicer, you need to elevate all the printable elements to Z0. Anything that is placed under Z0, the Slicer cannot generate a G-code for it.

Make sure to elevate the model to Z0.



5.2.2 HEIGHT OF THE DESIGN

The height of any geometry modeled for printing must have a height equal to an integer of the layer height. You must consider the layer height when you define the height of any 3D printed geometry.

5.3 RARE

5.3.1 INTERSECTED CENTERLINES

If you have centerlines that are intersecting or even crossing each other, you can observe that either in your CAD software or in the Slicer. However, you can correct these modeling mistakes only in the CAD software.

6. QUALITY ASSURANCE:

- ▶ Follow all the checklists to ensure you modeled and sliced everything accordingly.
- ▶ Perform tests, after modeling a geometry, export it and look at how it will be 3D printed digitally to avoid flaws or imperfections in the model.
- ▶ Read the related documents that support this SOP.
- ▶ Fail a few times, if you don't fail in the beginning, you are doing something wrong.

7. RELATED DOCUMENTS

In addition to this SOP, the following documents should be consulted:

- ▶ COBOD Slice Guide
- ▶ Design Manual
- ▶ Modeling in Autodesk Revit Guide

End of the SOP