

3D Printing Protocol

Step by step instructions for finding initial printing parameters for large scale robotic 3d printing

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3D Printing Protocol

Step by step instructions for finding initial printing parameters for large scale robotic 3d printing

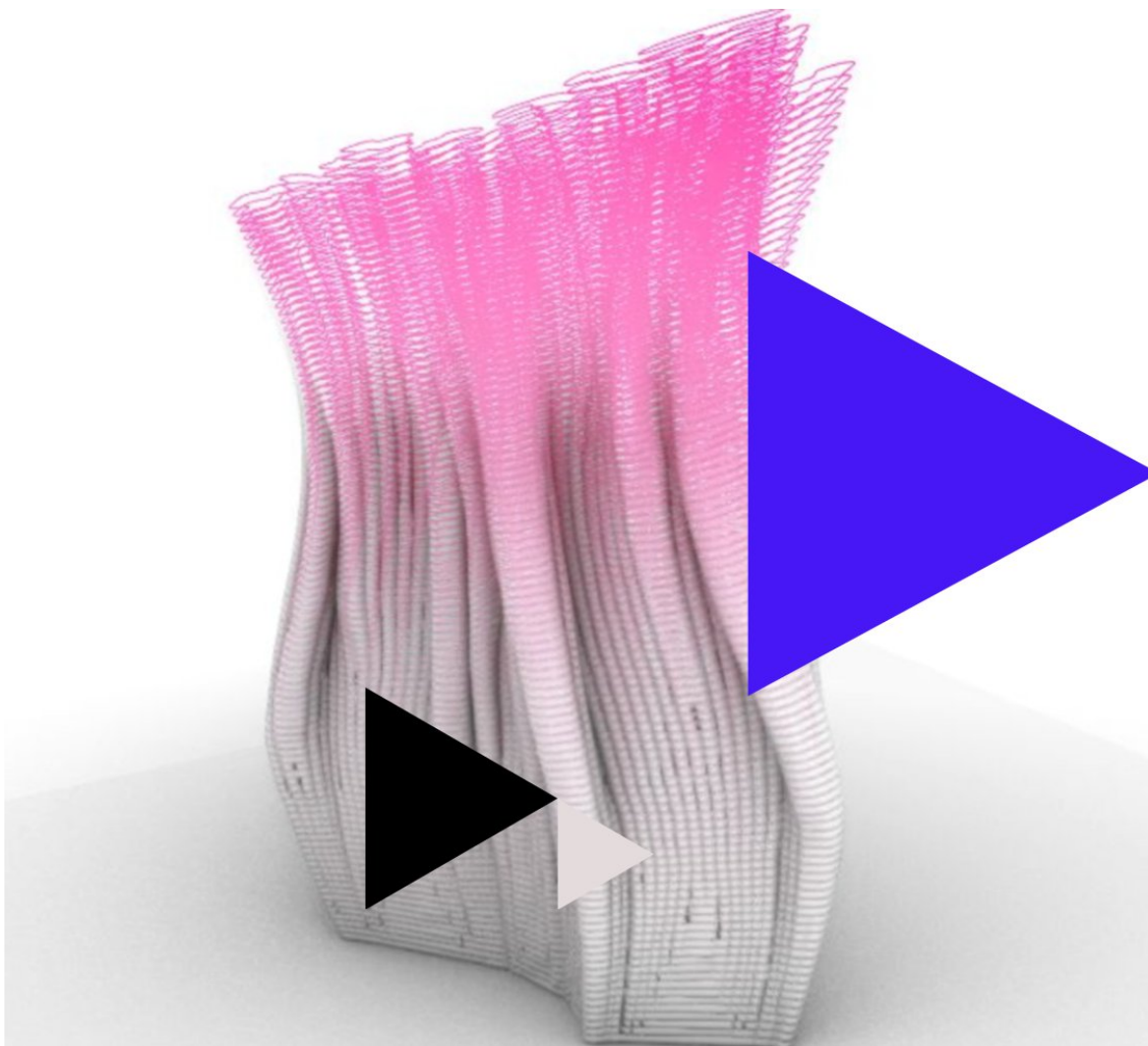


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Introduction

This is the first draft of the large scale 3d printing protocol for granulated thermoplastics. The main purpose of this document is to share the key steps of operating, preparation, data entry, and optimization procedures while handling the robotic 3d printing equipment. One main aspect of this protocol is that it is independent of specific 3d printing hardware or software setups. The aim is to have the users from robotic 3d printing from various technologies follow these steps and be able to set the basics up when it comes to handling such 3d printers.

Why 3d printing protocol?

In many common polymer based manufacturing processes such as injection molding, companies directly refer to the data sheets provided from their suppliers to operate the manufacturing process. Usually, plastics that are produced are tested and certified for the industry standard production methods. However, the field of Additive Manufacturing is relatively new and unexplored. Also, plastics due to their nature not necessarily behave as expected in additive way of manufacturing vs other commonly applied methods.

Standardized data-sheet for several 3d printing filaments exist for variety of desktop 3d printers or aka XYZ printers. However, the purpose of this research does not concern the plastic in the filament form but in the form of granulates. The main objective was to enable the possibility reusing plastic as the objects created with certain plastics can be shred into granulates and be potentially reprinted.

Based on previous experiences with granulate plastics and robotic 3d printing, the team of Robot Lab, had concluded that handling such materials has high level of uncertainty. Therefore, extensive knowledge when it comes to setting up the base for relatively good quality of print outcome.

And since this knowledge is difficult to gain the goal was to document and formulate a protocol as a clear set of instructions to follow that any user with no prior knowledge can perform and achieve standard results.

Guideline for Data Entry

The users of this protocol, have access to the spreadsheet as the database of test parameters. In that spreadsheet, there are several fields that are required to be filled as each single parameter is assigned to the test. Once a test is printed, a paper tape is used to indicate the parameters of the test. The tape will be stuck to the print sample and the test will be documented carefully.

Documentation:

1. A picture shall be taken of the test including the sticker tape with clear written parameters under suitable lighting condition.
2. The parameters of the test will be entered into the spread sheet in the related fields.
3. For the rows related to the failed test, the entry shall be marked with the red color
4. In case there are special notes to be added to the printed sample, they can be written with a concise and clear way in a separate field of comments.

[illegible]

Evaluation Criteria

In order to increase the level of accuracy of this protocol, it is recommended to have each test repeated and evaluated at least 3 times. This would guarantee that the tests are not results of accidental success and every parameter is carefully examined.

The evaluation criteria is mainly revolving around some key aspects from the printed results. These criteria:

1. Total layer height
2. Outer radius
3. Layer height
4. Weight
5. Layer thickness

How to evaluate?

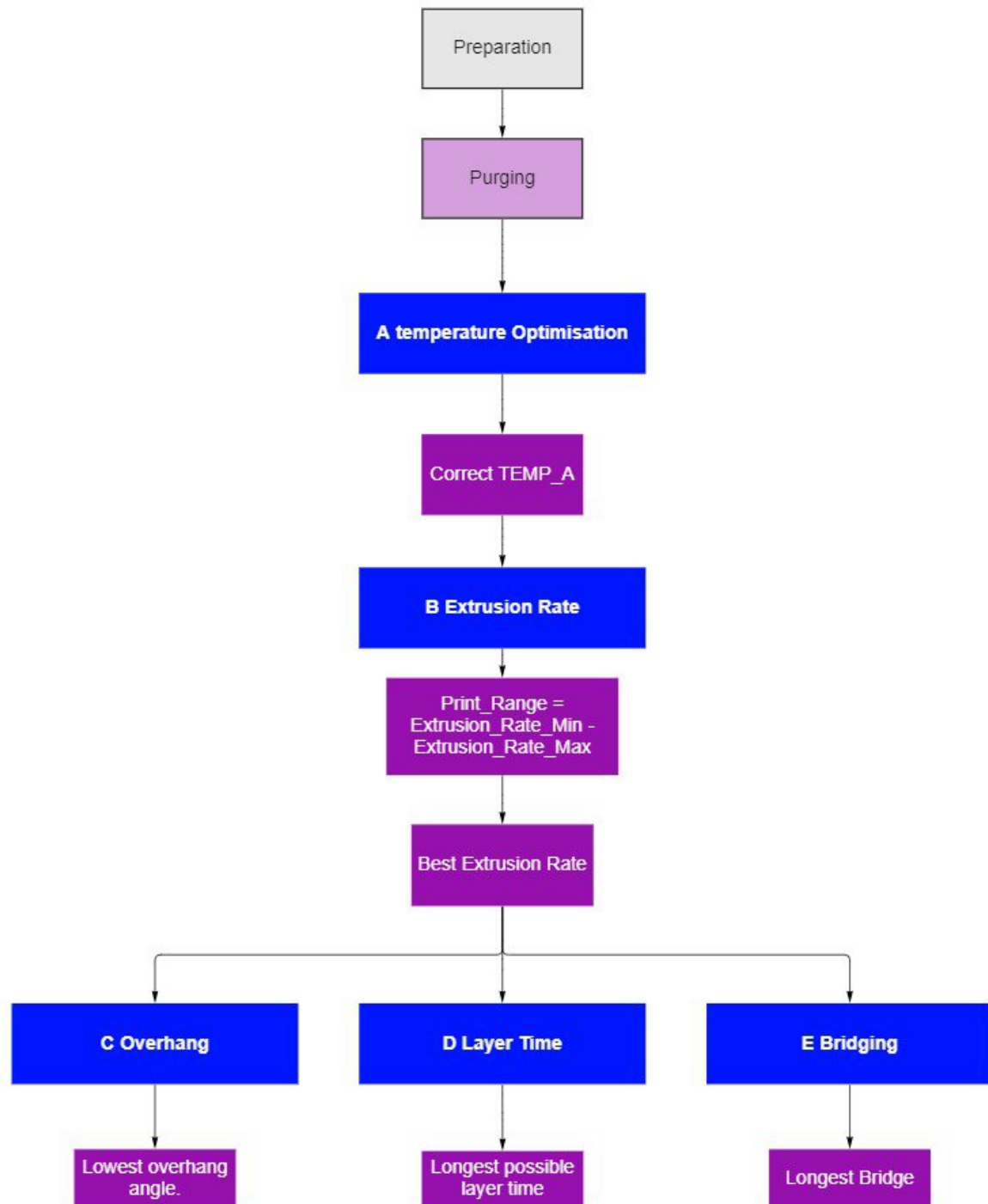
Once every sample is printed, the above mentioned features shall be accurately measured. The measured results are the metrics with which the outcomes of each individual test is compared. Once the results are entered in the spreadsheet. These metrics are then used to score the results from 1 to 6. The 1 representing the best outcome and the 6 to be least suitable outcome.

The prints that are within this score range are all considered successful, however, the success is not always measurable by plain eye sight. The scoring system takes into account the amount of average deviation from the input parameters in the designed test initial geometry. The higher the average deviation, the lower the score of the result. The average deviation and scoring is done automatically once the measured results are entered in the spreadsheet database.



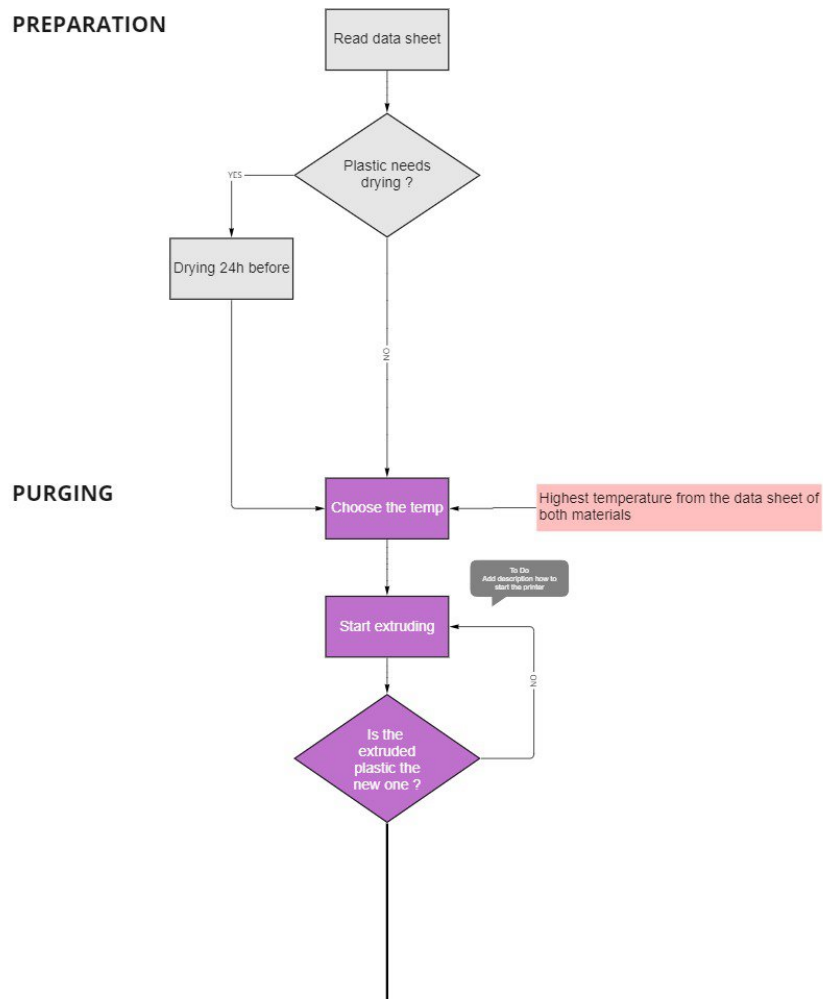
[illegible]

Overview



Image_01. Main overview of the protocol

01 - Preparation



Image_02. Preparation step flowchart

Drying:

If plastic needs to be dried, Dry the plastic within 24hrs before use
(please look into the Dryer manual)

Purging:

Purging is the process of removing the old plastic in the hose and entering the new material in the system.

With 3d printing hardware that are equipped with hose system, purging is an essential step that needs to be done when changing the plastic.

Plastic_A: Existing plastic

Plastic_B: New plastic

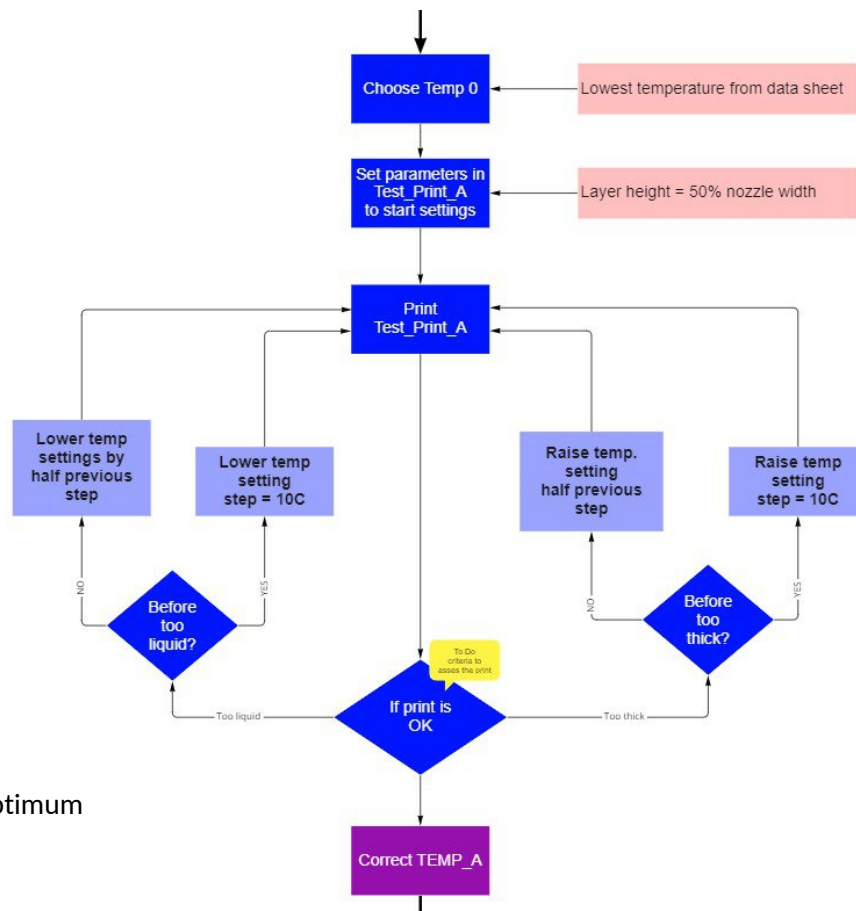
Check the data sheet of both plastic types. Select the higher melting temperature. For example:
Choose Temp_A:

If the result of $(Temp_A - Temp_B) > 0$

Feed the **Plastic_B** through the hopper and start extruding until the extruded plastic is **Plastic_B**

02 – Find Temperature

Usually plastics have a range of melting temperature. Start with the lower bound of the temperature. The initial layer height to extrude is 0.5 of the diameter of the nozzle. If the plastic data sheet is providing a single value for the



Image_03. Finding the optimum temperature flowchart

Temperature adjustment:

Start printing. If the outcome print is satisfactory, you have found the correct temperature else, there will be two scenarios:

1. The print viscosity is too high (too liquid)
2. The print viscosity is too low (too thick)

If the print viscosity is too low (too solid):

1. **Increase** the temperature by 10 degrees
2. Print another sample
3. Evaluate the result

If the print viscosity is still lower than expectation:

1. **Increase** the temperature by half of the previously **increased** value. e.g. if previous **raised** temperature was 10 degrees. Now **increase** 5 degrees. Or if the previously **raised** temperature was 5 degrees, now **increase** the temperature by 2.5 degrees.
2. Print another sample
3. Evaluate the result

If the print viscosity results higher than expectation:

1. **Decrease** the temperature by half of the previously **raised** value. e.g. if previous **raised** temperature was 10 degrees. Now **decrease** 5 degrees. Or if the previous **raised** temperature was 5 degrees, now **decrease** the temperature by 2.5 degrees.
2. Print another sample
3. Evaluate the result

If the print viscosity is too high (too liquid):

1. **Decrease** the temperature by 10 degrees
2. Print another sample
3. Evaluate the result

If the print viscosity is still higher than expectation:

1. **Decrease** the temperature by half of the previously **reduced** value. e.g. if previous **reduced** temperature was 10 degrees. Now **decrease** 5 degrees. Or if the previous **reduced** temperature was 5 degrees, now **decrease** the temperature by 2.5 degrees.
2. Print another sample
3. Evaluate the result

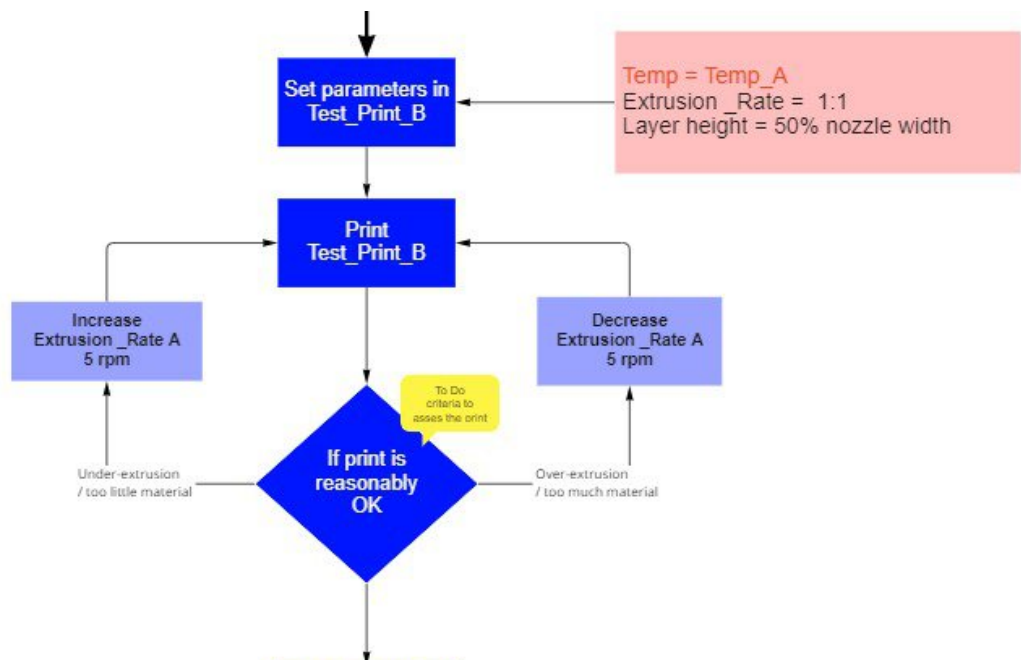
If the print viscosity results lower than expectation:

1. **Increase** the temperature by half of the previously reduced value. e.g. if previous **reduced** temperature was 10 degrees. Now **increase** 5 degrees. Or if the previous **reduced** temperature was 5 degrees, now **increase** the temperature by 2.5 degrees.

2. Print another sample
3. Evaluate the result

03 - Find Default Extrusion Ratio

The extrusion ratio is calculated based on the extrusion rate in RPM divided by the speed of printing in mm/s



Image_04. Finding the base extrusion ratio

Starting point

There are certain characteristics that are expected in case of the default ratio definition
These values are as followed:

1. The initial layer height should be set to (0.5 x nozzle diameter).
2. The default extrusion rate shall result in print width that is 1.6 times the nozzle size

Example:

Diameter of the nozzle = 5 mm

The initial layer height will be set to 2.5 mm

The print speed 25 mm/s The extrusion flow 25 rpm

Starting extrusion ratio = 25 : 25 = 1:1

Expected width of printed outcome:

$1.6 \times 5 \text{ mm} = 8 \text{ mm}$

Finding default extrusion ratio:

Start printing with the defined initial settings. For the temperature, use the previous best temperature setting to print.

If the print outcome is reasonable, move on to the next step.

If the resulted print width is more than 8 mm (over-extrusion):

1. **Decrease** the extrusion rate by 5 rpm.
2. Print another sample
3. Evaluate the result

If the resulted print with is less than 8 mm (under-extruded):

1. **Increase** the extrusion rate by 5 rpm.
2. Print another sample
3. Evaluate the result

After decreasing the rpm; If the resulted print width is still more than 8 mm:

1. **Decrease** the extrusion rate by half the previous decreased value in rpm. If the previous decreased value was 5, now **decrease** the rpm by 2.5.

Note: depending on the extruder system it may be the case that float numbers such as `2.5` are not valid input, in this case you can round the number to the ceiling value. Therefore, in this case insert `3` instead of `2.5`

2. Print another sample
3. Evaluate the result

If the resulted print with is less than 8 mm (under-extruded):

1. **Increase** the extrusion rate by 5 rpm.
2. Print another sample
3. Evaluate the result

After increasing the rpm; If the resulted print width is still less than 8 mm:

1. **Increase** the extrusion rate by half the previous decreased value in rpm. If the previous decreased value was 5, now **increase** the rpm by 2.5.
2. Print another sample
3. Evaluate the result

Note: depending on the extruder system it may be the case that float numbers such as `2.5` are not valid input, in this case you can round the number to the ceiling value. Therefore, in this case insert `3` instead of `2.5`

Repeat this cycle until desired print outcome is achieved.

The final extrusion ratio = default extrusion

Example:

First print

Print speed = 25 mm/s

Extrusion rate = 25 rpm

Ratio = 25:25 → 1

First result: print width > 8 mm (over extruded)

Second print

Print speed = 25 mm/s

Extrusion rate = 20 rpm

Ratio = 20:25 → 0.8

Second result: print width > 8 mm (over extruded)

Third print

Print speed = 25 mm/s

Extrusion rate = 15 rpm

Ratio = 15:25 → 0.6

First result: print width = 8 mm (print is fine!)

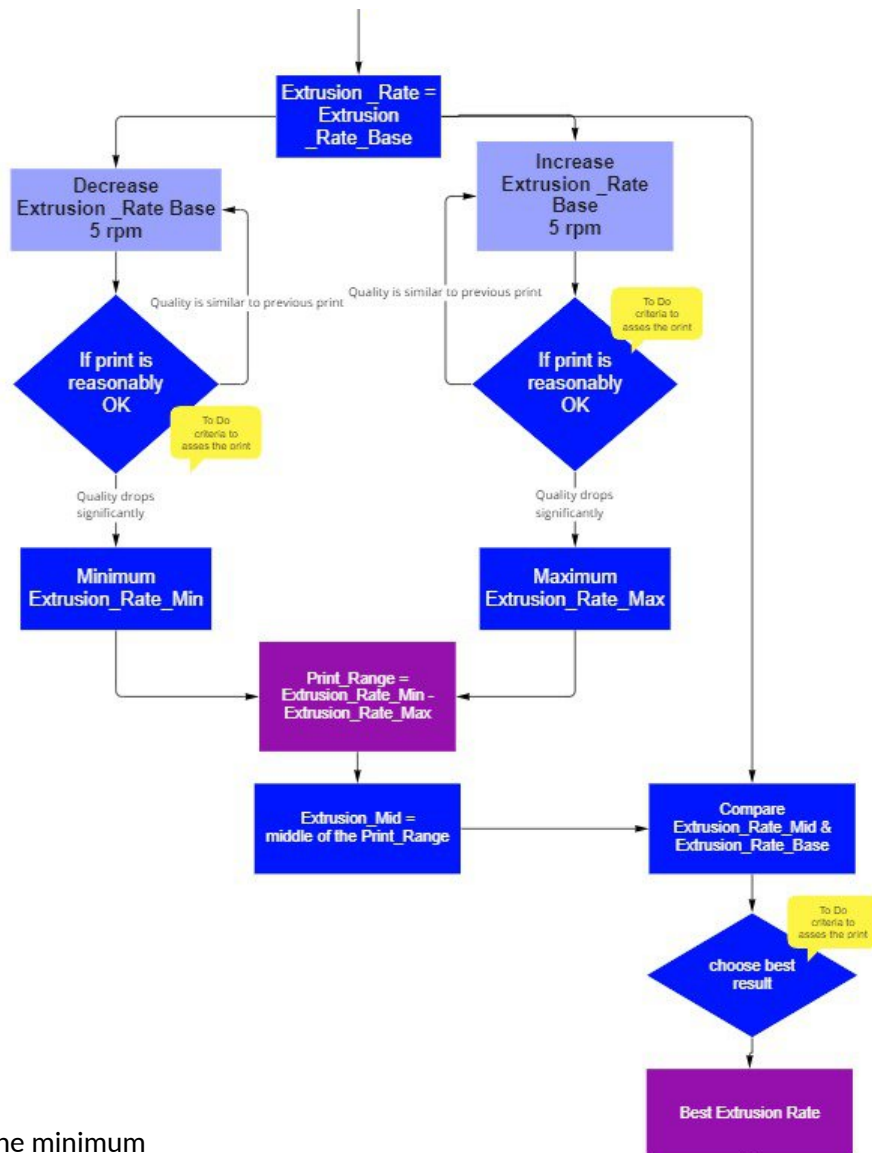
The default extrusion ratio will be now set to 0.6 (15 mm/s : 25 rpm)

04 – Find Minimum Extrusion Ratio

The minimum extrusion ratios is lower bound of the possible range of extrusion ratio that the printer can print with a plastic.

Why minimum extrusion ratio?

To maximize customization capacity, using 6-axis robotic printing, it is important to enable various printing settings such as variable layer-height. To facilitate consistent print quality in different layer heights, the extrusion ratio has to be adjusted accordingly. For lower layer heights usually this ratio is smaller, whereas in the case of higher layer heights, the ratio will be larger.



Image_05. Finding the minimum extrusion ratio

Example:

Print_A layer height = 3.5 mm

Print_B layer height = 2.5 mm

Print_C layer height = 1.5 mm

*Extrusion ratio of **Print_A** > Extrusion ratio of **Print_B** > Extrusion ratio of **Print_C***

Starting point

The goal is to find the what is the minimum possible (rpm) value to print while having the print speed as a constant value. Set the initial extrusion ratio to the default extrusion ratio value.

Example:

Diameter of the nozzle = 5 mm

The initial layer height will be set to 2.5 mm

The default extrusion ratio = 1 (assuming the default extrusion ratio is 1 for this example)

25 mm /s :25 rpm

Decreased ratio = 20 rpm

First print test extrusion ratio = 20:25 → 0.8

Finding minimum extrusion ratio:

1. **Decrease** the rpm value by 5 from the default extrusion ratio and print the first sample
2. Evaluate the result
3. While the print quality is approved after evaluation, repeat the same step

If the print quality is NOT approved after evaluation:

The last registered successful extrusion ratio shall be entered as the minimum extrusion value

05 – Find Maximum Extrusion Ratio

The minimum extrusion ratios is lower bound of the possible range of extrusion ratio that the printer can print with a plastic.

Why Maximum extrusion ratio?

To maximize customization capacity, using 6-axis robotic printing, it is important to enable various printing settings such as variable layer-height. To facilitate consistent print quality in

different layer heights, the extrusion ratio has to be adjusted accordingly. For higher layer heights usually this ratio is larger, whereas in the case of lower layer heights, the ratio will be smaller.

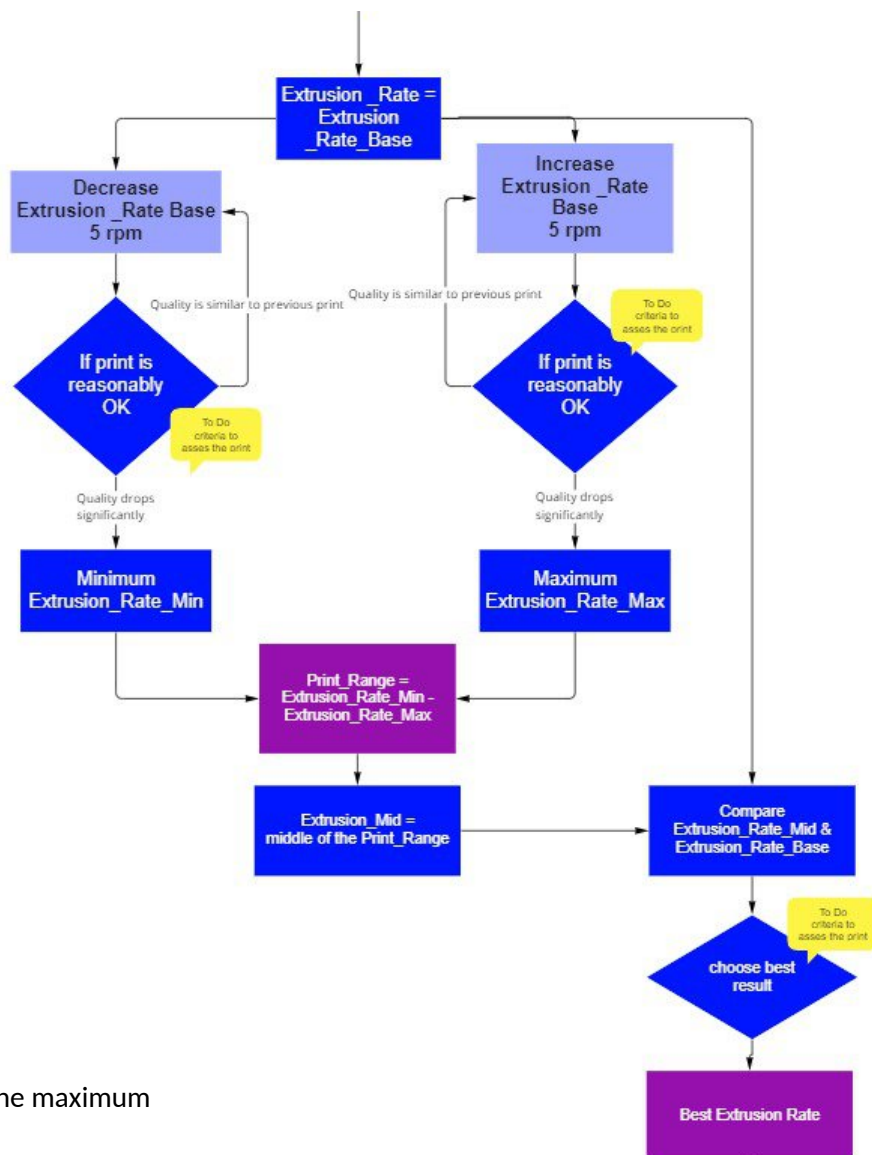
Example:

Print_A layer height = 3.5 mm

Print_B layer height = 2.5 mm

Print_C layer height = 1.5 mm

Extrusion ratio of **Print_A** > Extrusion ratio of **Print_B** > Extrusion ratio of **Print_C**



Image_06. Finding the maximum extrusion ratio

Starting point

The goal is to find the what is the maximum possible (rpm) value to print while having the print speed as a constant value. Set the initial extrusion ratio to the default extrusion ratio value.

Example:

Diameter of the nozzle = 5 mm

The initial layer height will be set to 2.5 mm

The default extrusion ratio = 1 (assuming the default extrusion ratio is 1 for this example)

25 mm /s :25 rpm

Decreased ratio = 20 rpm

First print test extrusion ratio = 30:25 → 1.2

Finding maximum extrusion ratio:

1. **Increase** the rpm value by 5 from the default extrusion ratio and print the first sample
2. Evaluate and record the result
3. While the print quality is approved after evaluation, repeat the same step

If the print quality is NOT approved after evaluation:

The last registered successful extrusion ratio shall be entered as the maximum extrusion value

06 – Find Minimum Layer Height

The layer height is one of the key print settings that can be adjusted in 6-axis 3d printing. This specific parameter is directly correlated to the size of the printing nozzle and the extrusion ratio. The steps are straight forward. The goal is to find the minimum possible layer height that the nozzle size can print.

Starting point

Set the initial layer height value to half of the printing nozzle diameter.

Example:

If the nozzle diameter is 7 mm

The layer height shall be set to 3.5 mm

Finding minimum layer height:

1. **Decrease** the layer height value by 0.5 mm from the base layer height and print the first sample
2. Evaluate and record the result
3. While the print quality is approved after evaluation, repeat the step 1 and 2
4. If the the result is not approved after evaluation, **reduce** the extrusion ratio within the available valid range of extrusion ratio. Print the sample using the **same** layer height value.
5. Repeat this cycle until the results are not within the approved quality after evaluation.
6. Enter the final successful layer height value as the minimum layer height.

Example:

Given parameters for the example:

Nozzle size = 5 mm

Initial layer height = Nozzle size / 2 = 2.5 mm

Print speed = 25 mm/s

Extrusion rate = 25 rpm

Default extrusion ratio = 25:25 → 1

Minimum extrusion ratio = 12:25 → 0.48

New layer height to start = 2.5 mm - 0.5 mm → **2.0 mm**

Print the sample

If last printed result is approved:

New layer height = 2.0 mm - 0.5 mm → **1.5 mm**

Extrusion ratio = default ratio (for this example the ratio of 1)

Print the sample

If last printed result is NOT approved:

Layer height remains the **same** as the previous settings, The layer height = 1.5 mm

New extrusion ratio shall be **decreased** as long as it is larger than or equal to the minimum extrusion ratio. New extrusion ratio = **0.8**

(0.8 is larger than 0.48, therefore, it is a valid ratio to use)

Print the sample

If last printed result is approved:

New layer height = 1.5 mm - 0.5 mm → **1.0 mm**

Extrusion ratio shall remain the **same** as the last used value. Extrusion ratio = 0.8

Print the sample

If last printed result is NOT approved:

Layer height remains the **same** as the previous settings, The layer height = 1.0 mm

New extrusion ratio shall be **decreased** as long as it is larger than or equal to the minimum extrusion ratio. New extrusion ratio = **0.6**

(0.6 is larger than 0.48, therefore, it is a valid ratio to use)

Print the sample

If last printed result is NOT approved:

Layer height remains the **same** as the previous settings, The layer height = 1.0 mm

New extrusion ratio shall be **decreased** as long as it is larger than or equal to the minimum extrusion ratio. New extrusion ratio = **0.4**

(0.4 is NOT larger than 0.48, therefore, it is NOT a valid ratio to use)

The printing process shall be stopped at this point.

The minimum possible printing layer height will be entered from the last successful result.

The minimum layer height = **1.5 mm**

07 – Find Maximum Layer Height

The layer height is one of the key print settings that can be adjusted in 6-axis 3d printing.

This specific parameter is directly correlated to the size of the printing nozzle and the extrusion ratio. The steps are straight forward. The goal is to find the maximum possible layer height that the nozzle size can print.

Starting point

Set the initial layer height value to half of the printing nozzle diameter.

Example:

If the nozzle diameter is 7 mm

The layer height shall be set to 3.5 mm

Finding minimum layer height:

1. **Increase** the layer height value by 0.5 mm from the base layer height and print the first sample
2. Evaluate and record the result

3. While the print quality is approved after evaluation, repeat the step 1 and 2
4. If the the result is not approved after evaluation, **increase** the extrusion ratio within the available valid range of extrusion ratio. Print the sample using the **same** layer height value.
5. Repeat this cycle until the results are not within the approved quality after evaluation.
6. Enter the final successful layer height value as the maximum layer height.

Example:

Given parameters for the example:

Nozzle size = 5 mm

Initial layer height = Nozzle size / 2 = 2.5 mm

Print speed = 25 mm/s

Extrusion rate = 25 rpm

Default extrusion ratio = 25:25 → 1

Maximum extrusion ratio = 35:25 → 1.4

New layer height to start = 2.5 mm + 0.5 mm → **3.0 mm**

Print the sample

If last printed result is approved:

New layer height = 3.0 mm + 0.5 mm → **3.5 mm**

Extrusion ratio = default ratio (for this example the ratio of 1)

Print the sample

If last printed result is NOT approved:

Layer height remains the **same** as the previous settings, The layer height = 3.5 mm

New extrusion ratio shall be **increased** as long as it is smaller than or equal to the maximum extrusion ratio. New extrusion ratio = **1.2**

(1.2 is smaller than 1.4, therefore, it is a valid ratio to use)

Print the sample

If last printed result is approved:

New layer height = 3.5 mm + 0.5 mm → **4.0 mm**

Extrusion ratio shall remain the **same** as the last used value. Extrusion ratio = 1.2

Print the sample

If last printed result is NOT approved:

Layer height remains the **same** as the previous settings, The layer height = 4.0 mm

New extrusion ratio shall be **increased** as long as it is smaller than or equal to the maximum extrusion ratio. New extrusion ratio = **1.4**
(1.4 is equal to 1.4, therefore, it is a valid ratio to use)

Print the sample

If last printed result is NOT approved:

Layer height remains the **same** as the previous settings, The layer height = 4.0 mm

New extrusion ratio shall be **increased** as long as it is smaller than or equal to the maximum extrusion ratio. New extrusion ratio = **1.6**

(1.6 is NOT smaller than 1.4, therefore, it is NOT a valid ratio to use)

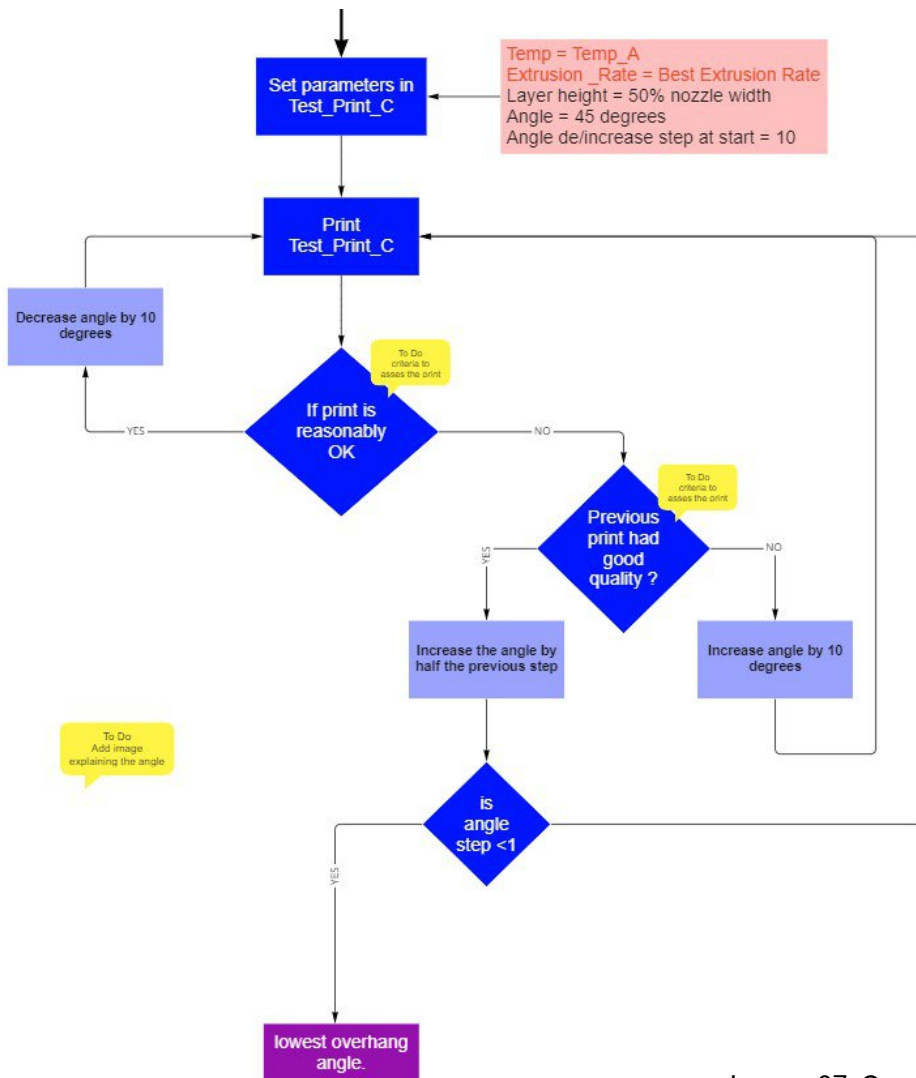
The printing process shall be stopped at this point.

The maximum possible printing layer height will be entered from the last successful result.

The minimum layer height = **3.5 mm**

08 – Overhang Tests

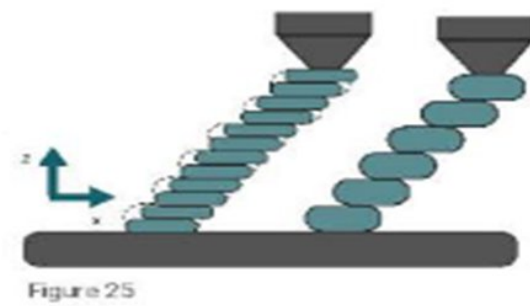
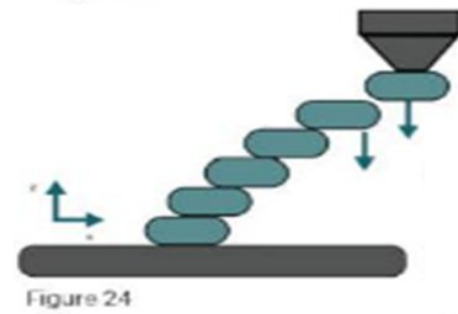
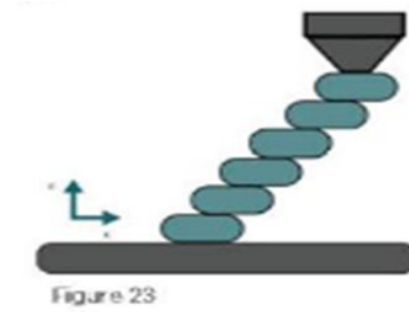
After finding the suitable print settings, in order to validate possibility of printing basic geometries, It is important to proceed with overhang tests. This test is the first indicator that how far the selected polymer allows for geometrical freedom in the printing process. The overhang test in this protocol is simplified to a fixed orientation of printing only. Also, other factors that affect the overhang besides the angle of the overhang are not considered in this protocol. One of the important parameters that can be experimented with in order to optimize the overhang angle is layer height. As a rule of thumb, the lower the layer height the higher possibility of overhang angle. The aim is to have the protocol enabling the basic geometrical features. In the future there will be other geometrical related test designs curated to contribute to a more extensive knowledge base.



Image_07. Overhang tests flowchart



Image_08. Overhang tests

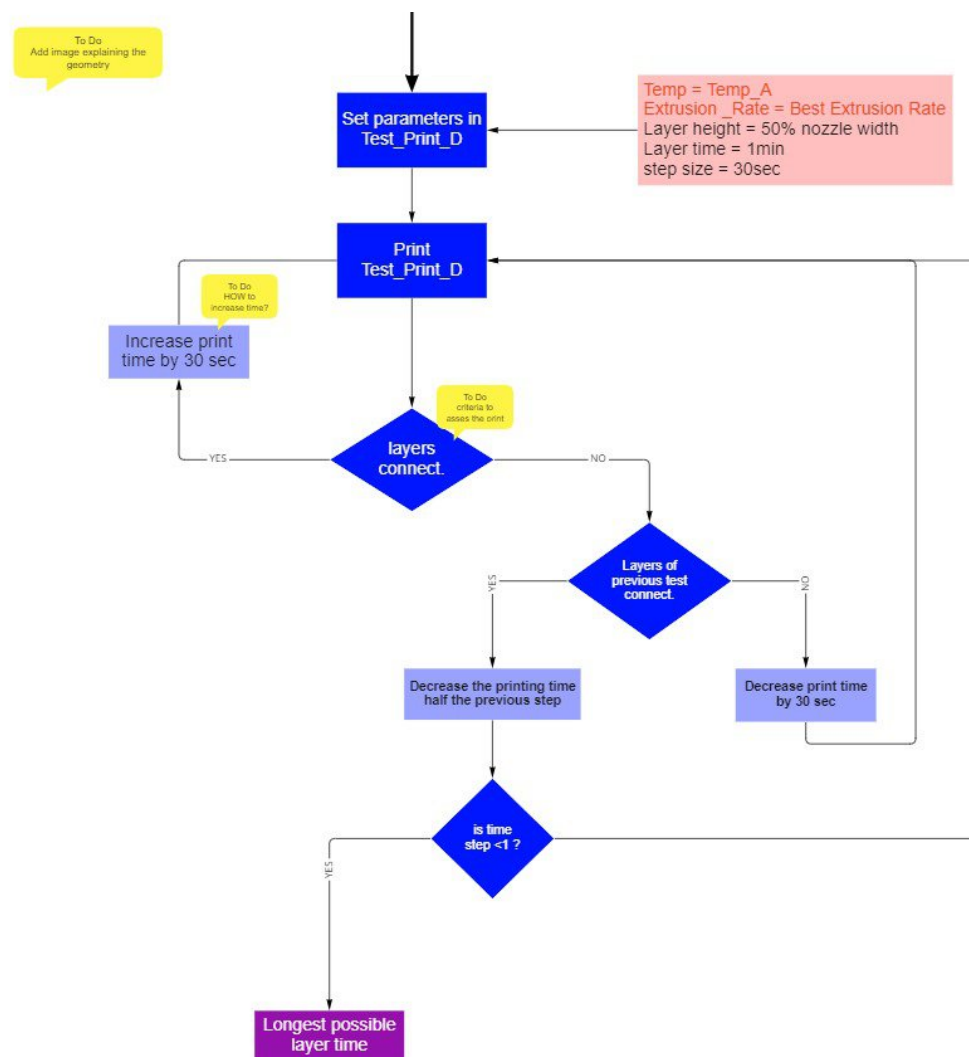


Image_09. Overhang tests diagrams

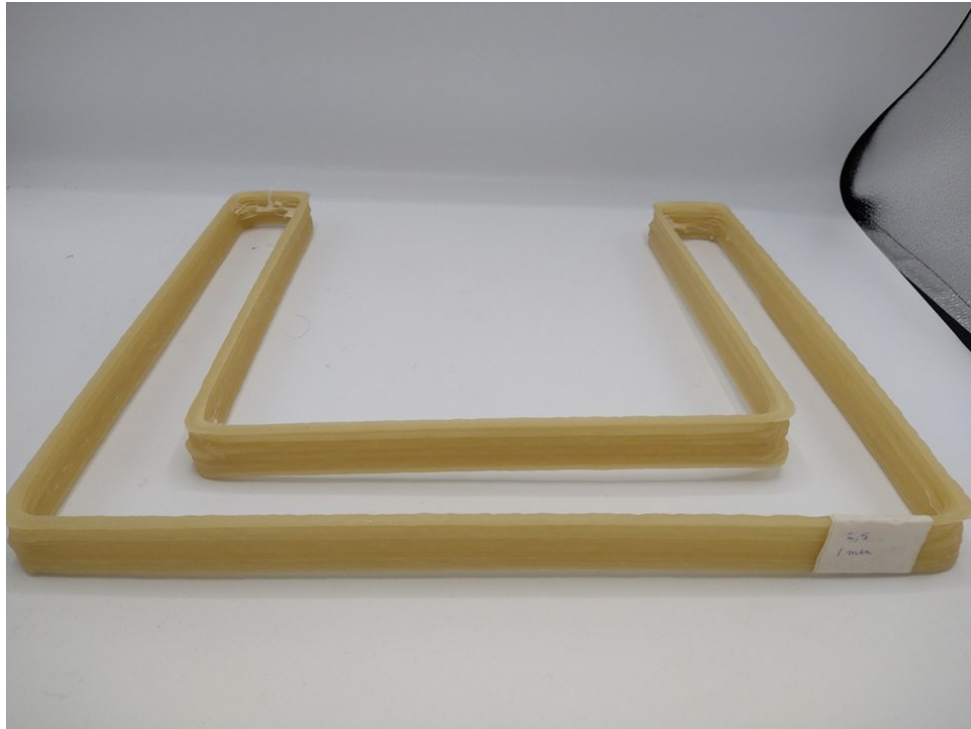
09 – Layer Time Tests

This test is one of the most crucial tests when exploring possible geometrical aspects of 3d printing. This test aims to measure the effective time per unit of length in the printing process. In other words, to measure how long would it take for the printed layer to be still bonding with the next layers that will be deposited on top. The layer time is correlated to the speed of printing, the thermal capacity of the polymer and the length of each printed layer.

The length of the layers are directly derived from the geometry of the print. Therefore, it remains crucial to understand this particular parameter in this protocol. The way to perform this test is shown in the following flowchart.



Image_10. Layer time tests flowchart



Image_11. Layer time tests