Ultimaker guide

How to design for FFF 3D printing

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1. Introduction

When designing a product or part, an engineer or designer always needs to consider the manufacturing process. Fused filament fabrication (FFF) 3D printing is no different, whether you are prototyping or producing end-use parts.

Whatever part you are designing you always need to consider design for manufacturability (DfM) – creating a design that is optimized for the capabilities of your chosen manufacturing process. As an additive manufacturing technology, FFF is no different. Designing for this sort of process is known as design for additive manufacturing (DfAM).

This guide explains how to design effectively for FFF 3D printing. By understanding the principles of effective design for 3D printing, you will achieve:

- Even better performance of 3D printed parts
- Increased print success rate
- Reduced costs through time and material savings
- A faster, more efficient product development cycle

Why choose FFF?

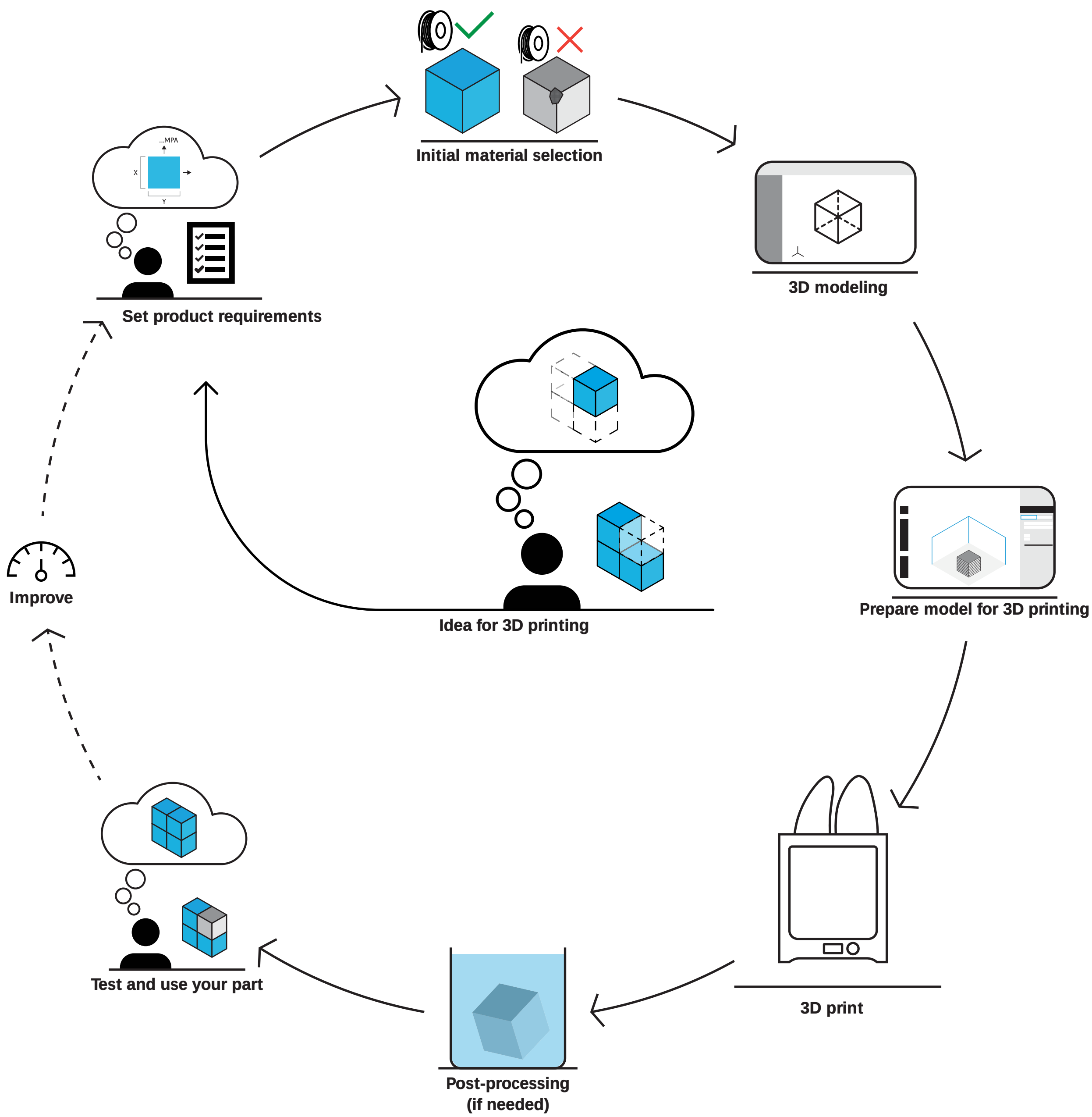
FFF 3D printing gives designers nearly full design freedom. This additive manufacturing technique eliminates the design limitations of many other processes. Compared to injection molding or subtractive manufacturing, FFF 3D printing offers greater design freedom and ease of use.

Highly complex designs can now be realized on accessible, affordable desktop 3D printers. But by understanding the limitations of the technology and the design rules for creating parts with the precise properties you require, you can get the most value from adopting FFF 3D printing.

Optimize your 3D printing process

Anything can be “drawn” in 3D on a digital canvas, but not everything can be 3D printed. The knowledge in this guide will help you approach designing for FFF in a way that ensures the best results from your 3D printers and 3D printed parts.

3D printing workflow



2. Part requirements

As with any other manufacturing process, first you need to think about what goal you want your 3D printed part to achieve and what it should look like.

Do you need fine details or just a simple shape for a rough size assessment? Is your model a prototype or an end-use part? What size will it be? What environment will it be used in? Should it be flexible or rigid? Does it need to withstand impact or friction?

All these questions need to be answered before you start CAD modeling for your 3D printed part.

Aesthetics

- Does aesthetic quality matter?
- Will the part be visible?
- What color will it be?

Strength and wear

- Is there a load on the part?
- Where is the load applied?
- When in use, will the part wear?

Accuracy

- What level of dimensional accuracy is needed?
- Will it be part of a larger assembly?

Operating enviroment

- Will it be exposed to high temperature, sunlight or other conditions?
- Will the part be in contact with oil or chemicals?

Ergonomics

- Does weight or shape matter?
- Who will use the object? What are their needs?

Post-processing

- Should it be easy to paint, grind, or treat with chemicals?
- Are all required surfaces accessible for post-processing?

Assembly

- Is the object bigger than the print build volume?
- How will different parts be assembled?
- What tooling is needed?

Final product

Aesthetics

If you're designing a visual prototype or an end-use part, the requirements for the visible surface are generally higher.

More detail means a longer print time for two reasons. First, you will likely want to choose a smaller layer height – more layers to a print takes longer, but effectively makes it higher "resolution" in its appearance.

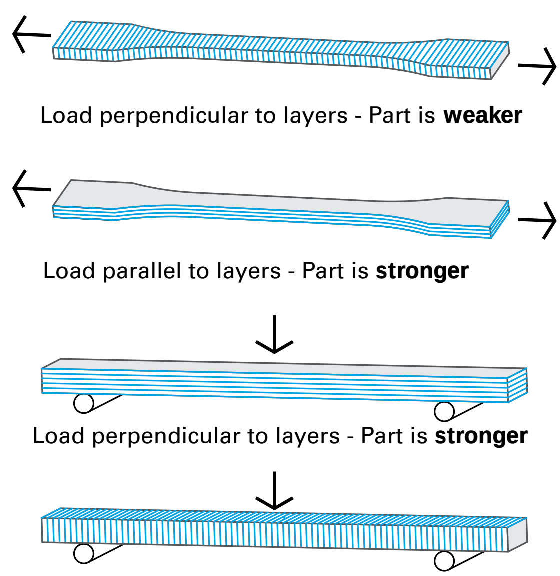
And second, if you choose a smaller nozzle size on your printer in order to achieve more detail, this will also increase print time.

Three examples printed at different layer heights (left: 0.1 mm, center: 0.2 mm, right: 0.3 mm). Model credit: print+

The image above shows three versions of a model printed at different layer heights. The print on the left took seven hours 27 minutes, the center print three hours 46 minutes, and the right only one hour 47 minutes.

Strength, hardness, and wear

As the FFF process builds up prints in layers, 3D printed objects will often have anisotropic mechanical properties. This means a print will be weaker in the direction of the Z axis. If you're designing functional parts, you need to consider the orientation of your model during the design process.



Accuracy

All plastics shrink as they cool. As the FFF process involves extruding heated plastics, this is something you need to consider if you're creating parts that need high levels of accuracy to the original design.

Filaments like PLA shrink a small amount, but others, like nylon and ABS, shrink more extensively. For designs needing a high level of accuracy, it is recommended to do a test print and measure its dimensions using calipers. This can then give you a baseline next time you do a similar print. If you are 3D printing frequently, make a note of the compensation as well as the size of the model and material you used.

Material profiles in Ultimaker Cura include the ideal print settings for the Ultimaker range of materials. Each profile compensates for material shrinkage for each material, to achieve accurate, reliable results.

Ergonomics

With 3D printing you can design end-use parts such as tools that are completely and almost instantly adaptable to the user, allowing more iterations compared to outsourcing.

For example, a tool designed for a right-handed user may cause problems for a left-handed user. Using 3D printing, this tool can be quickly adapted and deployed in a matter of hours.

Volkswagen Autoeuropa use Ultimaker printers to create tooling for the production line

Post-processing

If your 3D printer has multiple extruders, then you can print a secondary support material which is easier to remove than if you simply use support structures made from the same material as your part.

For example, PVA support material dissolves in water and can be safely disposed of down the drain. This not only eliminates the manual labor needed to remove support material, but also ensures a more dimensionally accurate part with an untarnished surface finish. Cutting or sanding away support structures risks damaging fine details and altering the dimensions of your print.

PVA (the white material) dissolves away from the model in water

Assembly

If you need a product made of multiple materials, to be attached to something else, or you want to print something much larger than your 3D printer's build volume, you should consider designing for assembly.

During CAD modeling, design your product in several modular pieces which can then be assembled later. 3D printing materials are compatible with high-strength adhesives, and can be glued together. Alternatively, you can include screw threads or other fastenings in your design.

A 3D printed tool assembled from multiple parts

3. Choosing your material

Today a variety of materials are available for 3D printing, each material possessing different properties. These properties can influence not only the mechanical behavior of your object, but also the printing behavior.

How to choose the right material?

It is important is to think about what material you will use before you start CAD modeling. In this section, we will look at guidelines for each material that will help you understand their basic properties and aspects to take into consideration when printing in certain materials.

With this information you can select the right material for your 3D printing application. As we have the most knowledge and experience of our own materials, this document will focus on Ultimaker materials, which are primarily thermoplastics. The quantity of special filaments such as composite materials and blends make it difficult to fit in a comprehensive guide, but Ultimaker 3D printers use a open filament system, so it is possible to experiment with other materials if desired.

For further information, Ultimaker offers data sheets with technical specifications and online printing guides for each material listed below.

	Printability	**Stiffness**		**Strength**		
	Printing difficulty	Flexural modulus	Tensile modulus	Flexural strength	Tensile stress at yield	Tensile stress at break
PLA	●	●●●	●●●	●●●	●●●	●
Tough PLA	●	●●●	●●●	●●●	●●●	●
ABS	●●	●●	●●●	●●	●●●	●
Nylon	●	●	●	●	●●	●
CPE	●●	●●	●●	●●	●●●	●●●
CPE+	●●●	●●	●●	●●	●●	●
TPU 95A	●●	●	●	●	●	●
PC (transparant)	●●●	●●●	●●●	●●●	-	●●●
PC (black & white)	●●●	●●●	●●●	●●●	●	●●
PP	●●●	●	●	●	●	No break within testing range
PVA	●	-	-	-	-	-
Breakaway	●	-	-	-	-	-

	Ductility	Toughness	Hardness	Temperature resistance
	Elongation at break	Impact strength	Indentation hardness	Environment heat resistance
PLA	●	●	●●●	●
Tough PLA	●	●●	●●●	●
ABS	●	●●	●●	●●
Nylon	●●	●●●	●●	●●
CPE	●●	●	●●	●●
CPE+	●	●	●●	●●●
TPU 95A	●	●●●	●	●●●
PC (transparant)	●●●	●●	●●●	●●●
PC (black & white)	●	●	●●●	●●●
PP	●	●●●	●	●●●
PVA	-	-	-	-
Breakaway	-	-	-	-

This information applies to Ultimaker materials. Similar quality cannot be guaranteed with other filaments

Ultimaker materials

PLA (polylactic acid) is a biodegradable polymer that is ideal for prototyping 3D models with high quality aesthetics. It has good surface quality, is somewhat glossy, and prints details with a high resolution.

PLA is a highly reliable and easy-to-print material that can be printed at low temperatures and shows minimal shrinking when it cools. These properties make it the perfect choice for creating concept models, visualization aids, or for use in education.

Overall, PLA is not as strong as more technical materials but does have a high tensile strength. It is not recommended for functional and mechanical parts. Items printed with PLA can lose their mechanical properties and may become brittle over time.

PLA does not have high heat resistance, so PLA parts are not suitable for use in high-temperature environments. If you print PLA with PVA support material, when dissolving the supports make sure the water temperature does not exceed 35 °C, as this could adversely affect the part.

Tough PLA is a technical PLA (polylactic acid) material with toughness similar to ABS and higher tensile strength than regular PLA. As well as these optimized mechanical properties, Tough PLA is as easy to print as PLA with no delamination or warping, making it a great alternative to ABS for larger prints, and ideal for functional prototypes and tooling.

Tough PLA gives a more matt surface finish than regular PLA, and is also more machinable. However, take care if sanding or threading the material as prolonged friction could result in damage to the part from heat.

It is also compatible with PVA or Breakaway support material, providing easier post-processing than for example using ABS combined with HIPS support structures, which requires limonene to dissolve.

ABS (acrylonitrile butadiene styrene) is a well-known material for mechanical and technical applications.

It has excellent mechanical properties and can be used for objects that require toughness and durability. With a thermal resistance of up to 85 °C, ABS can be used in warm environments. These properties make ABS a good choice for prototyping and fit testing. Ultimaker ABS is specially formulated to minimize warping and ensure consistent interlayer adhesion. This makes it easier to use than standard ABS filaments. Ultimaker ABS has pleasing aesthetics and results in a matt finish when printed.

Nylon (polyamide) is a well-known material used for printing tools, functional prototypes, and end-use parts. It combines strength, impact resistance, and some flexibility. It can handle temperatures up to 80 °C.

Ultimaker Nylon is very durable due to its abrasion resistance and corrosion resistance to alkalis and organic chemicals. Compatibility with PVA and Breakaway support materials ensures design freedom and simple post-processing.

CPE (co-polyester) is another popular material for mechanical applications. It has the same strength as ABS but also has high tensile strength, dimensional stability, and chemical resistance.

This means that CPE can be used in combination with most industrial oils and chemicals without adverse effects. Printing CPE is odorless, and it emits few ultrafine particles and volatile organic compounds. It is compatible with PVA and Breakaway support materials.

CPE+ (co-polyester) is stronger than CPE, which makes it suitable for applications where the strength of the object is key. CPE+ is primarily used for functional prototyping and short-run manufacturing.

It has greater thermal resistance than CPE, so CPE+ parts can be used at temperatures up to 100 °C without deforming (compared to 70 °C for CPE). It is compatible with Breakaway support material.

TPU 95A (thermoplastic polyurethane) is a semi-flexible material for use in applications that demand the qualities of rubber and plastic, such as handle grips or protective surfaces.

TPU 95A has a score of 95 on the Shore A hardness scale, with an elongation at break of up to 580%. It is flexible, strong, and can withstand high impacts without deforming or breaking. It is also resistant to many common industrial oils and chemicals and easily resists normal wear and tear.

Unlike other flexible materials, Ultimaker TPU 95A is easy to use, prints quickly, and does not require a high level of expertise to print and use effectively.

PC (polycarbonate) can be used for a wide range of engineering applications. It's one of the strongest 3D printing materials, making it a perfect choice for printing robust objects.

PC has a high mechanical strength, good UV stability, and high thermal resistance. It retains its form at temperatures up to 110 °C. In addition, PC has a good dimensional stability, is chemical resistant, and has flame-retardant characteristics. These properties make it suitable for lighting, molds, engineering parts, tools, functional prototyping, and short-run manufacturing.

PP (polypropylene), the second most used polymer in the world today, offers many possibilities for both prototypes and end-use parts.

Ultimaker PP is durable with high toughness and fatigue resistance. This means that PP retains its shape after torsion, bending, or flexing. It has very low friction, allowing parts that are in contact with each other to move smoothly over each other.

PP is also semi-flexible. While it's not as flexible as TPU 95A, it can still be a good option if you're looking for a material with slight flexibility. In addition, it has good chemical resistance and high electrical resistance, making it a good electrical insulator. Another key advantage of PP is that it has a low density, making it perfect for the creation of lightweight parts. Furthermore, it has good translucent properties.

PVA (polyvinyl alcohol) is not typically used for printed objects, but it is an ideal material to choose if you're looking for removable support structures. Ultimaker PVA is biodegradable, has good thermal stability, and is less moisture-sensitive than other PVA filaments.

After printing in combination with a build material, PVA support structures can easily be removed by dissolving in water. This gives you complete design freedom when creating parts, allowing models with large overhangs, moving parts, and complex geometries.

Breakaway is a support material for multi-extrusion 3D printing. Breakaway supports are quick to remove and do not need further post-processing for a smooth finish on your 3D print.

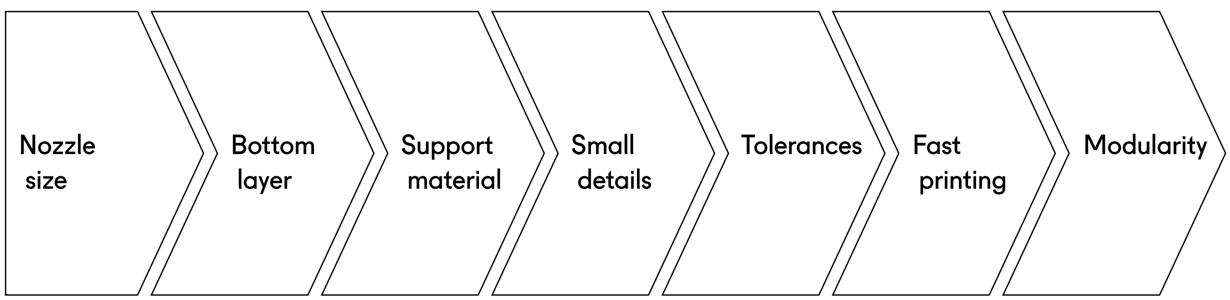
Breakaway support is removed manually, saving considerable time when compared with waiting for dissolvable supports to be removed. But Breakaway still peels cleanly away from the part, ensuring dimensional accuracy. It is also compatible with more build materials than PVA, for example.

4. CAD modeling for FFF

This section provides designers with geometry and design feature guidelines to consider when creating parts in CAD for FFF 3D printing.

We recommend following seven key geometry guidelines when designing for FFF 3D printing. These guidelines depend on your model and should be seen as recommendations. The final outcome will be affected by your model size and its features. However, following these recommendations will result in more successful prints.

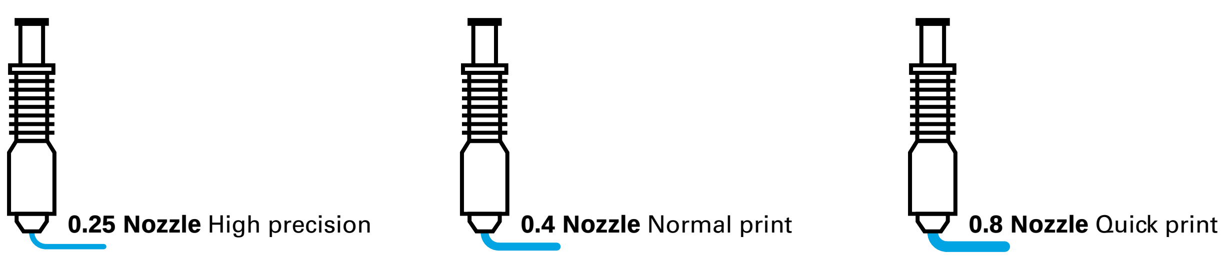
FFF design considerations



1. Select nozzle diameter

Most FFF 3D printers come with a standard nozzle diameter of 0.4 mm. If your printer has the option to replace the nozzle, you can create faster prints with a larger diameter nozzle, or achieve finer detail with a smaller nozzle.

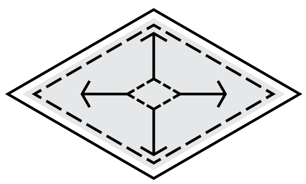
It is important to design for the right nozzle. The minimum wall thickness of your part should be the same or bigger than the diameter of your nozzle.



2. Bottom layer

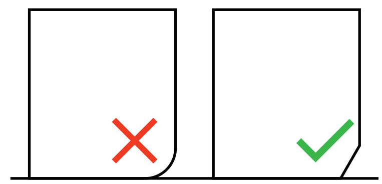
There are three important rules to consider for the bottom layer of your part.

Bottom layer surface



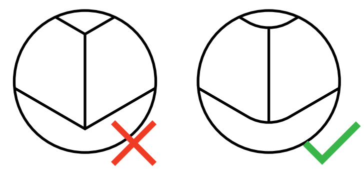
The larger the bottom surface, the better the adhesion to the build plate

Try to avoid fillets on the build plate



Chamfers are recommended

Try to avoid sharp edges



To avoid warping

The bottom layer is the foundation of your 3D print. The larger the bottom layer surface, the better the adhesion to the build plate. A large bottom layer surface is also recommended for materials that are prone to shrinking when cooling, to prevent any distortion. If you are experiencing shrinkage with a particular material or print, try redesigning or orienting it for maximum bottom layer surface area. If needed, you can include an adhesion structure, such as a removable raft or brim at its base, which can be added using slicing software such as Ultimaker Cura.

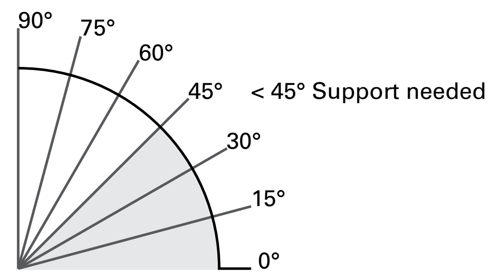
Adding features at the design stage can enhance the print reliability and performance of the part. Fillets or chamfers in areas of a print that will be subject to stress will distribute load more efficiently, reducing the risk of part failure when deployed.

Because an FFF 3D printer nozzle is circular, corners and edges will have a radius that is equal to the size of the nozzle. This means that these features will never be perfectly angled. A smaller nozzle size can help to create sharper corners. Sharp edges on the bottom surface are liable to warp, but a rounded edge on each corner will reduce the risk of this.

3. Save on support material

If you want to save material or your printer can only print with limited materials for creating the support structure (like PLA or ABS which can be hard to remove), you can adapt your design. Even if you have a multi-extrusion 3D printer that prints specialist support materials, then you may still want to design or orient a part so that it minimizes the use of support structures, which can save time and costs.

The common guideline when designing for FFF 3D printing is the "45-degree rule".



In general, overhangs less than 45 degrees from a vertical surface will require support material.

Bridging is when your design requires a 3D printer to print a flat, horizontal part of the model in mid-air – "bridging" two parts of your design.

The printer has to quickly drag lines of plastic across a gap in a way that the plastic won't fall down when being printed.

We recommend you try to avoid bridging, but if you do need to use it then the shorter the distance, the better the results. If a bridge is too big, use support material instead.

The effects of bridging on different sized prints

4. Small details

Depending on your 3D printer, printing small details can be a challenge. Be aware that your digital design will have to consider the physical capabilities of your FFF 3D printer.

For better results when printing parts with small details, we recommend:

- Using a smaller nozzle diameter
- Ensure small details have enough time to cool before the next layer
- Adding a "prime tower" – a nozzle-priming feature in Ultimaker Cura

How does a smaller nozzle size help? There are two physical properties that influence the details which can be printed. The minimum layer height (for Z axis) and the minimal wall thickness (X and Y axes). The smaller the nozzle, the finer the details that can be printed in X and Y directions.

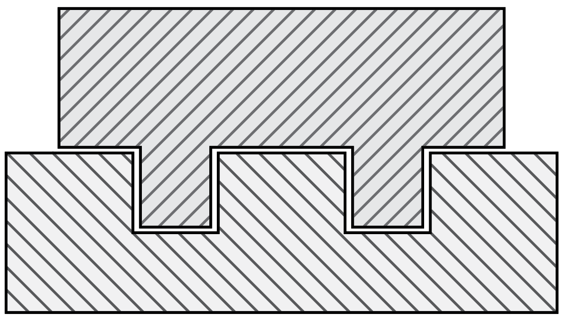
Reducing print speed gives each layer more time to cool and set before the next layer is printed, which makes features much more accurate. You can adjust print speed using settings in your print preparation software, such as Ultimaker Cura.

If printing in dual extrusion, another feature you can use while preparing your print in Ultimaker Cura is a prime tower. This is an extra tower on the build plate to prime the nozzle properly before printing the next layer. It reduces oozing, under-extrusion, and enhances overall printing quality.

A detailed model printed with a 0.25 mm nozzle. Model dimensions: 165 x 107 x 40 mm

5. Tolerances

As we saw in the product requirements section of this guide, plastic polymers shrink when they are heated and then cooled. This needs to be taken into consideration when designing parts that need specific tolerances.



When exact dimensions are important, we recommend you perform printing tests beforehand to determine how much you need to compensate for. One method of doing this is to measure a test print with calipers and compare these dimensions to your original design.

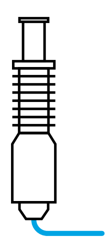
Test prints can be measured against the original design dimensions

6. Fast printing

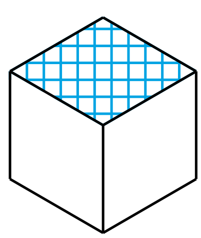
When you need a print quickly, there is a number of things you can do to speed up the process. We have already looked at the effect of nozzle size – so choose a larger nozzle for a faster print.

Reducing the thickness of the bottom or the walls of your print can save significant time, as these layers often have the largest surface area. If you are printing a model as a rough draft or quick prototype, there is no need to print with very thick walls.

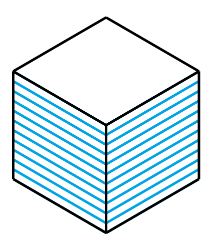
Ultimaker Cura shows you the expected duration of each print, so you can use this to test your changes before printing. You can also reduce the amount of material in your print in Ultimaker Cura, for example by using gradual infill.



Use a different nozzle diameter



Use a lower infill density



Set a larger layer height in Ultimaker Cura

7. Modularity

Combining FFF 3D printing with modular design enables you to do more with your 3D printers. Assembling multiple parts means you are no longer limited by your printer's build volume, and when you print these parts across several printers you also get your finished product faster, enabling more iterations of your design.

Creating a modular design from multiple 3D printed parts has other advantages too. If part of a tool is regularly subjected to wear and needs replacing, you do not need to keep stock or wait for order fulfilment. Just print it when you need it. You can also combine different materials with different properties to create a more complete product.

Printing multiple parts and assembling avoids long print times for large designs

5. Case study: Volkswagen Autoeuropa

By designing 3D printed tools, jigs, and fixtures for the assembly line, Volkswagen Autoeuropa managed to reduce cycle time operation, labor, and the need for reworking, while improving tool ergonomics, all at a tenth of the usual cost. The company estimated that they were able to save €325,000 by the end of 2017.

Wheel protector

Used during wheel assembly to prevent damage, reducing the risk of scrap costs

External suppliers	
Cost per part	€800
Project duration	56 days

Ultimaker 3D printers	
Cost per part	€21
Project duration	10 days

Liftgate badge

Ensures the correct placement of the car model emblems, repeatedly and efficiently

External suppliers	
Cost per part	€400
Project duration	35 days

Ultimaker 3D printers	
Cost per part	€10
Project duration	4 days

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About Ultimaker

Ultimaker has been in operation since 2011, and over the years has grown to become a market-leader; creating powerful, professional, and accessible desktop 3D printers with offices in the Netherlands, New York, Boston, and Singapore plus production facilities in Europe and the US. Ultimaker's team of over 300 employees continually strives to offer the highest-quality 3D printers, software, and materials on the market to accelerate the world's transition to local digital manufacturing.

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