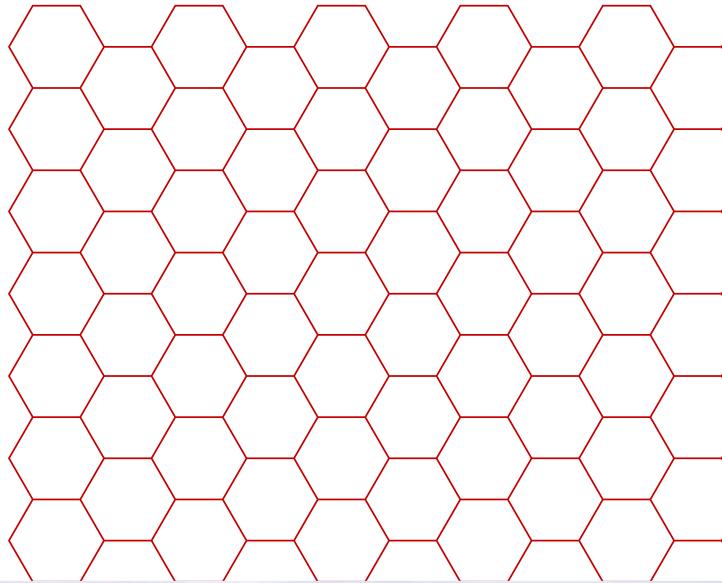




Ultimaker guide

How to design for FFF 3D printing



Ultimaker

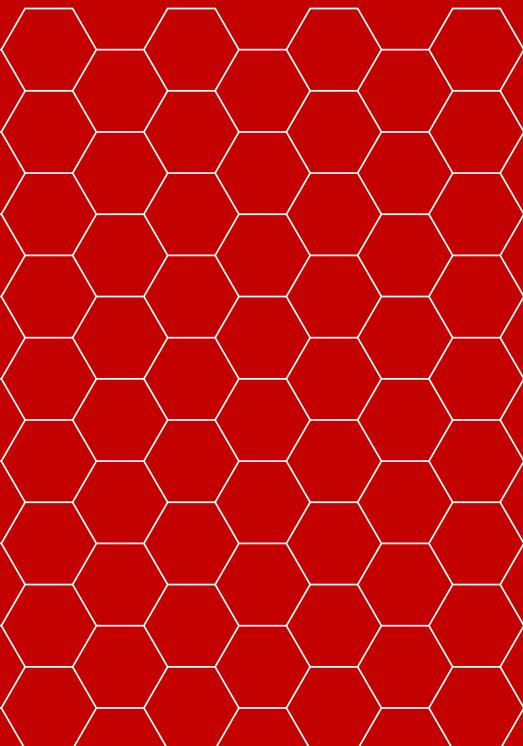


Introduction to FFF 3D printing



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Introduction

Form may follow function, but designing for manufacturability (DfM) means that how a product is fabricated is equally important. This is true of fused filament fabrication (FFF) 3D printing, whether you are prototyping or producing end-use parts. Designing for this process is known as design for additive manufacturing (DfAM).

This guide explains how to effectively design for FFF 3D printing and will help you improve:

- The performance of 3D printed parts
- Your 3D print success rate
- Production costs, through time and material savings
- The speed and efficiency of your product development cycle

Why choose FFF?

Additive manufacturing eliminates the design limitations of other processes, offering design freedom and ease of use. Highly complex designs can now be created on affordable desktop 3D printers. And by understanding the design best practices for FFF 3D printing, you can get the most value from your 3D printer.

Optimize your 3D printing

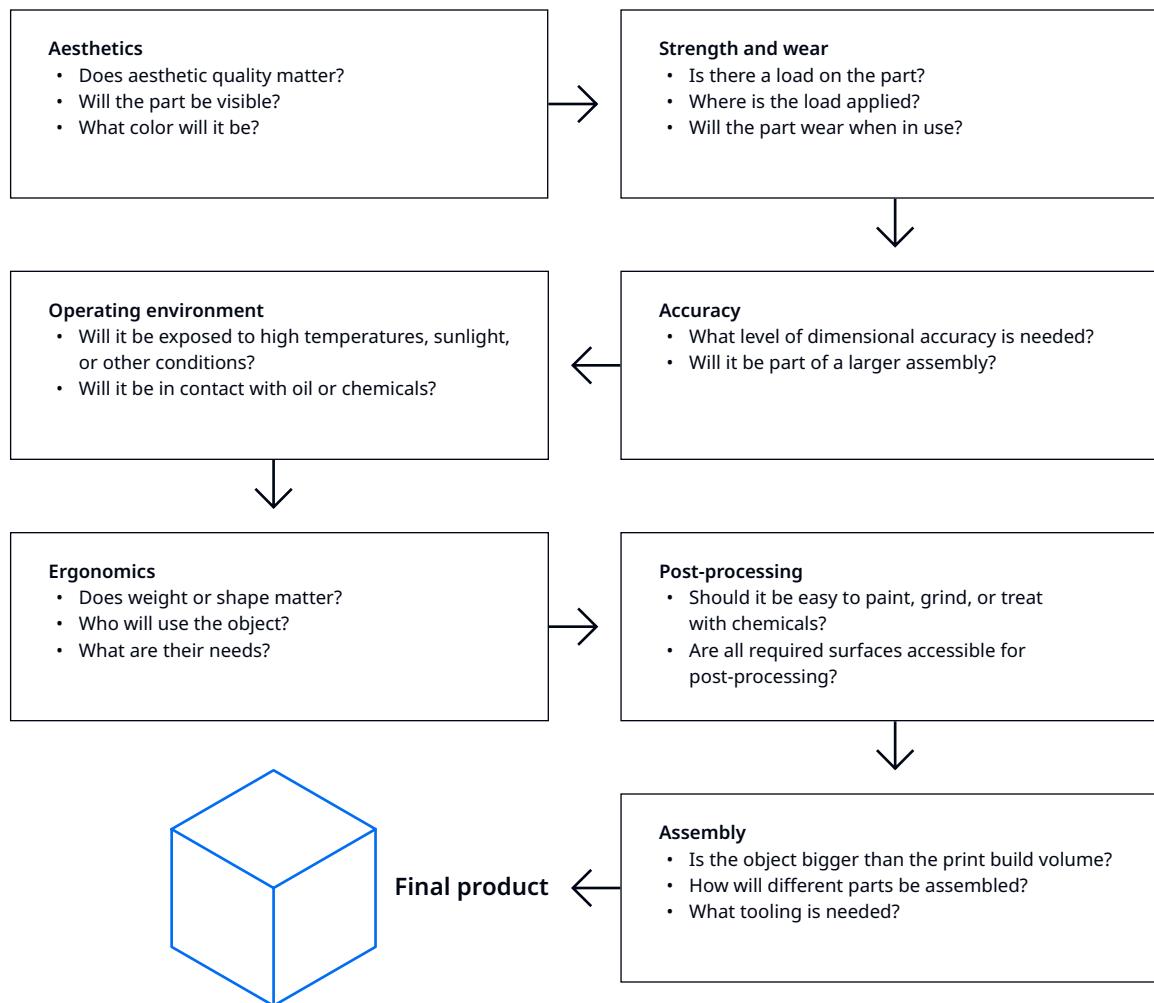
Anything can be 'drawn' in 3D on a digital canvas, but not everything can be 3D printed. The knowledge in this guide will help you design for FFF to ensure the best results from your 3D printers and 3D printed parts.

Part requirements

When designing for additive manufacturing, your first task is to outline your part's specifications. To do so, you'll need to know how it will be used and what it should look like.

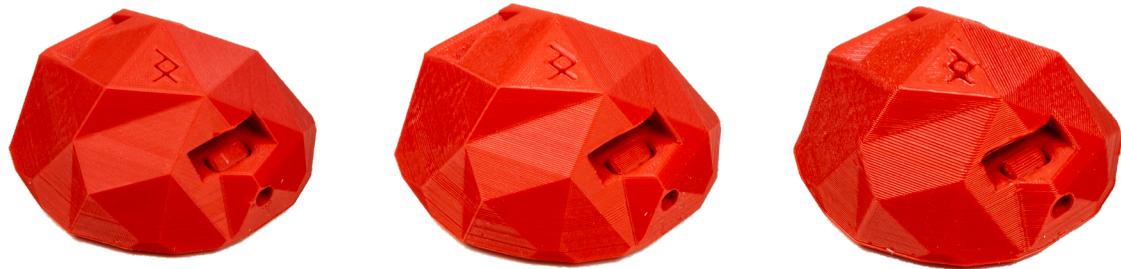
Do you need fine details or a simple shape for size assessment? Is your model a prototype or an end-use part? What environment will it be used in? Should it be flexible or rigid? Does it need to withstand impact or friction?

All these questions need to be answered before you start CAD modeling.



Aesthetics

Visual prototypes and end-use parts usually have higher aesthetic requirements. But more detail means longer print times. You will need to choose a smaller layer height – and more layers mean more time. Choosing a smaller nozzle size will allow you to achieve more detail, but will also increase print time.

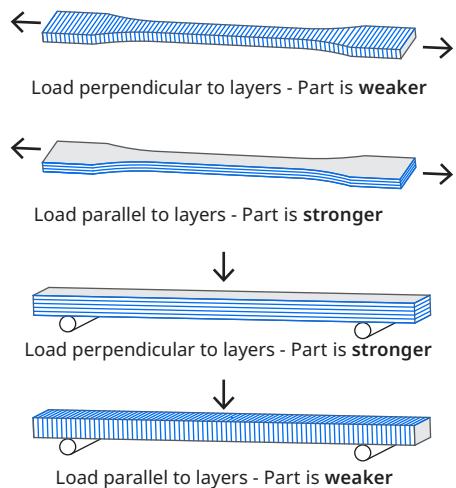


Three examples printed at different layer heights (left: 0.1 mm, center: 0.2 mm, right: 0.3 mm). Model credit: print+

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 prints in layers, 3D printed objects will often 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 extrudes heated plastics, this should be considered when creating parts that require dimensional accuracy.

For example, PLA shrinks a small amount, while nylon and ABS shrink more extensively. For designs that need accuracy, it is best to do a test print and measure it with calipers. This provides a baseline for future prints. If you are 3D printing frequently, make a note of the compensation, the size of the model, and the material used.

Material profiles in Ultimaker Cura include the ideal print settings for the Ultimaker range of materials. These profiles compensate for the material shrinkage of each material, for accurate, reliable results.

Ergonomics

With 3D printing, you can design end-use parts that are completely adaptable to the user. For example, a tool designed for a right-handed user can be adapted for a left-handed user in a matter of hours.



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

Post-processing

Using a 3D printer with multiple extruders enables you to print a secondary support material. This is easier to remove than support structures made from the same material as your part.

PVA support material dissolves in water and can be safely disposed of down the drain. This eliminates the manual labor needed to remove support material and ensures a more accurate part with an unmarked surface finish. Cutting or sanding support structures risks damaging fine details and altering the dimensions of your print.

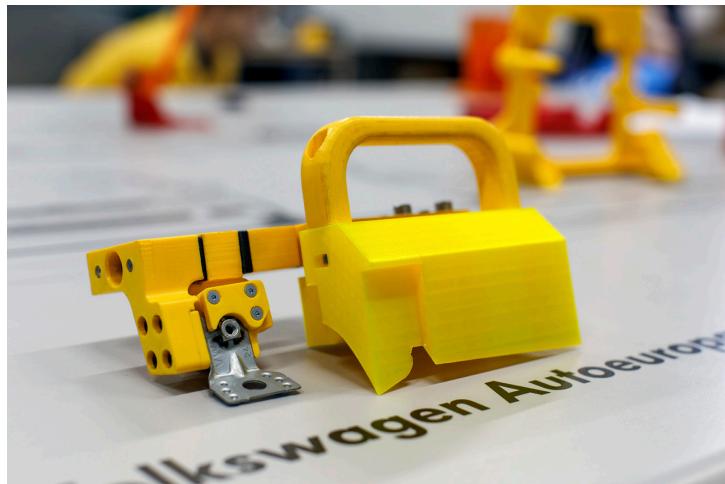


PVA (the white material) dissolves in water

Assembly

For items larger than your 3D printer's build volume, you should consider designing for assembly. This is also useful for products made of multiple materials, or that need to be attached to something else.

During CAD modeling, design your product in several modular pieces for later assembly. 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

Choosing your material

A variety of materials are available for 3D printing, each possessing different properties which can influence the mechanical and printing behavior of your object. This makes it important to consider material selection before CAD modeling, as the material used will determine the properties of the item being printed.

By understanding the properties of the available materials, you can select the right material for your 3D printing application. While this document focuses on Ultimaker materials, Ultimaker 3D printers use an open filament system. This makes it possible for you to experiment with other materials if necessary.

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 (transparent)	●●●	●●●	●●●	●●●	-	●●●
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 (transparent)	●●●	●●	●●●	●●●
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 highly reliable and easy to print. It can be printed at low temperatures, with minimal shrinkage. These properties make it the perfect choice for creating concept models, visualization aids, or for use in education.

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 is not suitable for use in high-temperature environments. If you print PLA with PVA support material, make sure the water temperature does not exceed 35 °C when dissolving the supports, 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. It is as easy to print as PLA, with no delamination or warping. This makes Tough PLA a great alternative to ABS for larger prints, and ideal for functional prototypes and tooling.

Tough PLA's finish is more matt than regular PLA, and is also more machinable. Take care if sanding or threading the material, as prolonged friction could result in heat damage.

It is also compatible with PVA or Breakaway support material, providing easier post-processing than ABS combined with HIPS support structures, which require 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, so is easier to use than standard ABS filaments. Ultimaker ABS has pleasing aesthetics and a matt finish.



Nylon (polyamide) is often used for printing tools, functional prototypes, and end-use parts. It combines strength, impact resistance, and some flexibility. It can handle temperatures of 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.

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



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

It has greater thermal resistance than CPE, and 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 applications requiring 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. 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 of up to 110 °C.

In addition, PC has good dimensional stability, is chemical resistant, and is flame-retardant. These properties make it suitable for lighting, molds, engineering parts, tools, functional prototyping, and short-run manufacturing.

PP (polypropylene) offers many possibilities for prototypes and end-use parts, and ranks second among the world's most-used polymers.

Ultimaker PP is durable, tough, and fatigue resistant, so it retains its shape after torsion, bending, or flexing. It has very low friction, allowing parts that are in contact to move smoothly over each other.



PP is semi-flexible, and translucent. While not as flexible as TPU 95A, it is a good option for items that require slight flexibility. It also has good chemical resistance and high electrical resistance, making it a good electrical insulator. Another key advantage of PP is its low density, making it perfect for the creation of lightweight parts.



PVA (polyvinyl alcohol) is not typically used for printed objects, but is perfectly suited to removable support structures. Ultimaker PVA is biodegradable, has good thermal stability, and is less moisture-sensitive than other PVA filaments.

Dissolvable in water, PVA support structures can be easily removed after printing. This provides complete design freedom, allowing models with large overhangs, moving parts, and complex geometries.

Breakaway is a support material for multi-extrusion 3D printing. It is quick to remove and doesn't need further post-processing for a smooth finish.



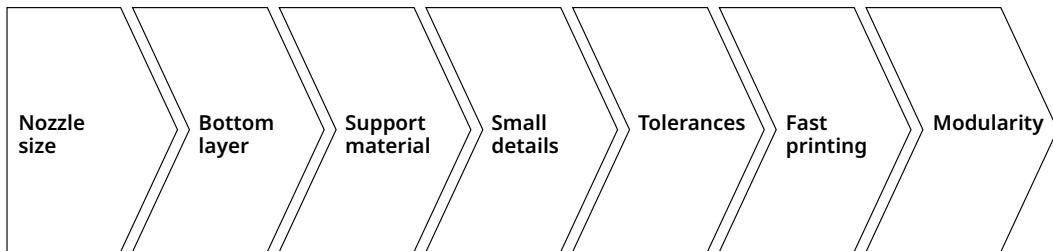
Unlike waiting for PVA to dissolve, breakaway support peels cleanly away, saving time and ensuring dimensional accuracy. It is also compatible with more build materials than PVA.

CAD modeling for FFF

This section provides geometry and design feature guidelines for creating FFF 3D parts in CAD.

We suggest focusing on seven key geometry considerations to successfully design for FFF 3D printing. These are recommendations, as the final design and outcome will depend on your model size and its features.

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 nozzle or achieve finer detail with a smaller nozzle.

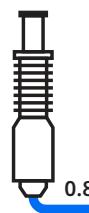
It is important to design for the right nozzle. The minimum wall thickness of your part should be the same or larger than the diameter of your nozzle.



0.25 Nozzle High precision



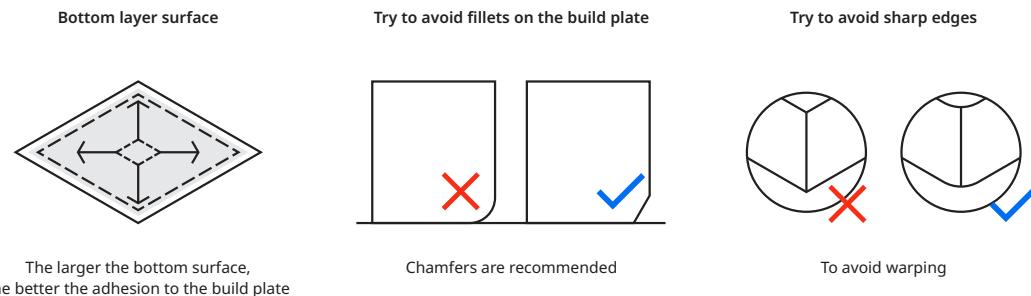
0.4 Nozzle Normal print



0.8 Nozzle Quick print

2. Bottom layer

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

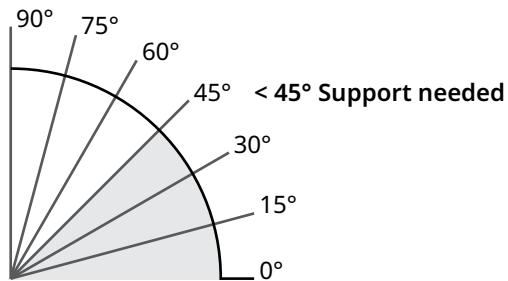


The bottom layer is the foundation of your 3D print. The greater its surface area, the better the adhesion to the build plate. For materials prone to shrinkage, a large bottom layer is recommended to prevent distortion. If your 3D print is shrinking, try redesigning or orienting it for maximum bottom layer surface area. You can also include an adhesion structure, such as a removable raft or brim, at its base. This can be added using slicing software such as Ultimaker Cura. These features can enhance print reliability and part performance.

Using fillets or chamfers in stress prone areas also reduces part failure, by distributing load more efficiently. Because FFF 3D printer nozzles are circular, corners and edges have a radius that equals the size of the nozzle. While these features will never be perfectly angled, a smaller nozzle size can create sharper corners. Sharp edges on the bottom surface are liable to warp, but a rounded edge on each corner will reduce this risk.

3. Save on support material

You can adapt your design to save material, or if your printer can only use limited support materials (like PLA or ABS, which can be hard to remove). Even if you have a multi-extrusion 3D printer that prints specialist support materials, you can minimize the use of support structures to save time and money.



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.

We recommend that you avoid bridging, which is when your 3D printer needs to print a flat, horizontal part of the model in mid-air — 'bridging' two parts of the design. This means that the printer has to quickly drag lines of plastic across a gap, to prevent collapse during printing.

In cases where it is necessary to use a 'bridge', the shorter the distance, the better the results. For longer 'bridges', use support material.



The effects of bridging on different sized prints

4. Small details

Printing small details can be challenging, so your design should account for the physical capabilities of your FFF 3D printer.

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

- Using a smaller nozzle diameter
- Ensuring small details have enough time to cool before the next layer is added
- 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 (Z axis) and the minimal wall thickness (X and Y axes). The smaller the nozzle, the finer the details that can be printed in the X and Y directions.

Reducing print speed gives each layer more time to cool and set before the next layer is printed, making features more accurate. You can adjust print speed settings in your print preparation software, such as [Ultimaker Cura](#).

If printing in dual extrusion, you can elect to print a prime tower when preparing your print in Ultimaker Cura. This is an extra tower that ensures the nozzle is properly primed before printing the next layer. It reduces oozing and under-extrusion, and enhances overall print quality.

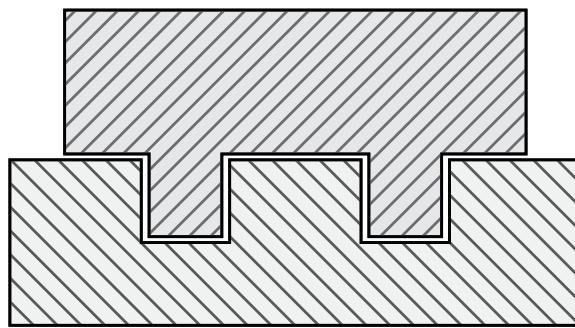


A detailed model printed with a 0.25 mm nozzle. Model dimensions: 165 x 107 x 40 mm

5. Tolerances

Plastic polymers shrink when heated, and then cooled.

When exact dimensions are important, we recommend you perform printing tests beforehand. This enables you to determine the level of variance. One method of doing this is to measure a test print with calipers and compare these dimensions to your original design.



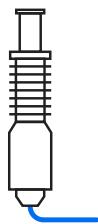
Test prints can be measured against the original design dimensions

6. Fast printing

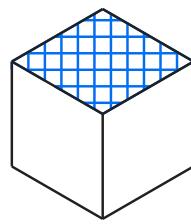
When you need a print quickly, there are a number of ways to speed up the process, like choosing a larger nozzle.

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

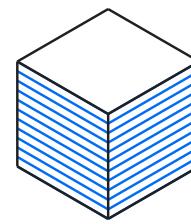
Ultimaker Cura shows you the expected duration of each print, so you can use this to test your changes before printing. You can also reduce the amount of material in your print in Ultimaker Cura by reducing the infill density.



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. Printing across several printers is even 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 subject to wear and regularly needs replacing, you need only replace that part and not the entire tool. And you don't need to keep stock of it – just print it when you need it. You can also combine different materials with different properties to create a more complex product.



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

Case study: Volkswagen Autoeuropa

By designing 3D printed tools, jigs, and fixtures for the assembly line, [Volkswagen Autoeuropa](#) reduced cycle time operation, labor, and the need for reworking – all while improving tool ergonomics, and at a tenth of the usual cost. The company estimated that it was able to save €325,000 within the first year of introducing Ultimaker 3D printers.

Wheel protector

Used during wheel assembly to prevent damage, reducing scrap costs

External suppliers

Cost per part	€800
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Project duration	56 days
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Ultimaker 3D printers

Cost per part	€21
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Project duration	10 days
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Liftgate badge

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

External suppliers

Cost per part	€400
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Project duration	35 days
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Ultimaker 3D printers

Cost per part	€10
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Project duration	4 days
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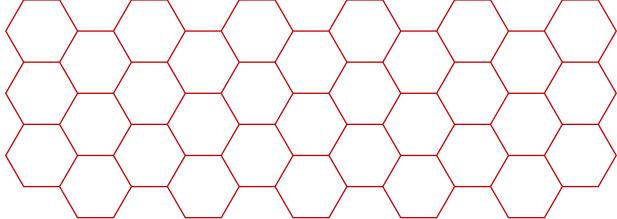


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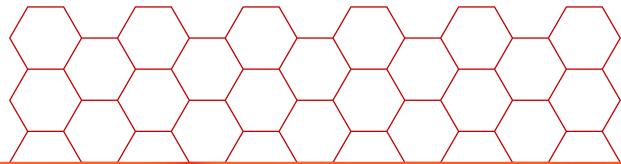
Since 2011, Ultimaker has built an open and easy-to-use solution of 3D printers, software, and materials that enables professional designers and engineers to innovate every day.

Today, Ultimaker is the market leader in desktop 3D printing. From offices in the Netherlands, New York, Boston, and Singapore – plus production facilities in Europe and the US – its global team of over 400 employees work together to accelerate the world's transition to local, digital manufacturing.

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