

Multi Jet Fusion printing tips and tricks for the 500 3D printer series



January 2019

The purpose of this document is to provide a summary of the actions that can be taken to maximize part quality when printing with a Multi Jet Fusion 500 series printer. It includes a collection of best practices to keep the system in optimal conditions, recommendations on how to place and orient parts in the building chamber and guidance for choosing the most appropriate printing and cooling profiles for different application scenarios. Specific tips are provided to improve look and feel, mechanical properties and dimensional accuracy. Finally, a compilation of part quality artifacts is given as an appendix, where the cases are discussed, and specific mitigation methods are shown.

This guide is divided into the following sections:

- *Executive summary - Orientation workflows*
- *General Considerations*
- *Optimizing Look & Feel & Color*
- *Optimizing Dimensional Accuracy*
- *Optimizing Mechanical Properties*
- *Appendix: Design Optimization Strategies*
- *Appendix: Part Quality Artifacts*



Executive summary - Orientation workflows.

The orientation of parts is critical to getting the best quality and this orientation depends on the requirements and the purpose or final application of each of the parts. In general terms, there are 2 main ways to orient a part: to maximize its look and feel and to maximize its dimensional accuracy.

The workflows recommended to get the best printing quality in each of the above scenarios is included below:

Workflow to optimize look & feel

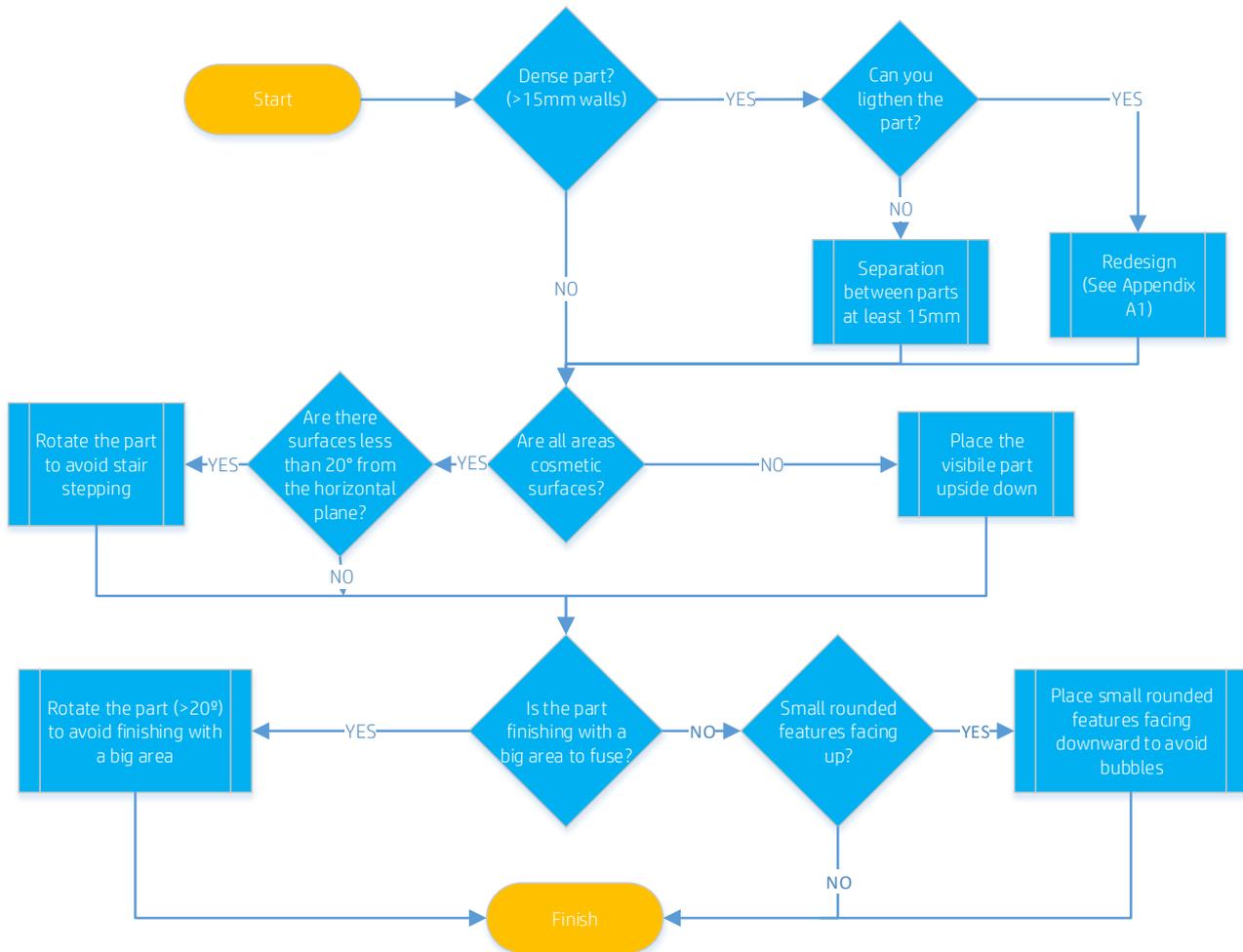


Figure 1: Flowchart for an appropriate process-parameter selection based on the geometry and functionality of a part in order to maximize its look and feel.

Workflow to optimize dimensional accuracy

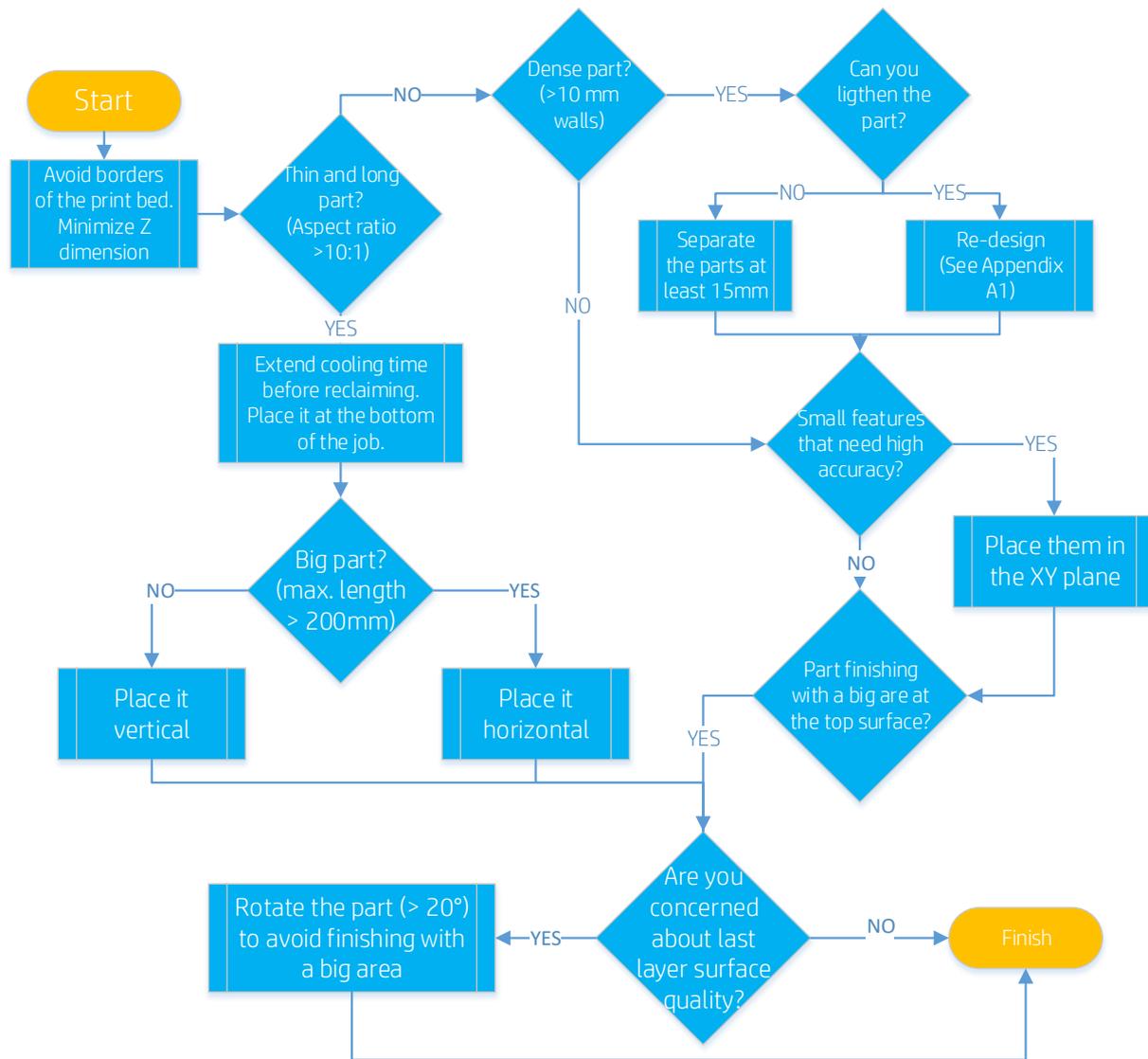


Figure 2: Flowchart for appropriate process-parameter selection based on the geometry and functionality of a part in order to maximize its dimensional accuracy.



General Considerations

1. To achieve optimal part quality, it is necessary to have the site prepared according to the requirements listed in the Site Preparation Guide [13]:
 - The operating temperature of the equipment should be between 15-30°C (59-86°F). Going further than these limits could have adverse effects on part quality. Try to prevent big thermal fluctuations, even when being within the limits.
 - Printer operating relative humidity should be between 20-80%, without condensation. Ensure this range for optimal system usage and performance.
 - Power line quality is important. If you suspect that the power installation at the site will suffer from variability or alterations, we recommend installing a UPS system.
 - Be sure that the set-up altitude is the right one according to the location of your facility. A wrong selection could directly affect the cooling system and pressure parameters.
 - Extremely high packing-density jobs, non-recommended powder mix ratios, and bad system maintenance may lead to some part quality issues.
2. To ensure part quality, strictly observe the User Guide's [1] cleaning, maintenance and calibration practices of the printer. For details on how to properly maintain the printer, please check chapter **14 – Maintenance**.
3. Some problems may be caused by printhead issues. Make sure the printheads are correctly aligned and in good condition. There are different actions to be taken to detect cross-contamination and to help the printer recover from nozzles being out.

1. Optimizing Look and Feel

MJF is a layer-by-layer manufacturing technology and, consequently, every dimension in the Z-direction is discretized according to the layer thickness (80 μm). The disposition of these layers is not noticed in many situations due to their small size and good inter-layer cohesion, but this ultimately depends on the angle of the part with respect to the building reference system. Therefore, it is recommended to **avoid angles below 20°** between big, flat areas and the XY-plane. Moreover, heat distribution under parts has been observed to smoothen the transition between layers. Thus, placing curved and cosmetic features upside down is recommended, as shown in **Figure 3**.

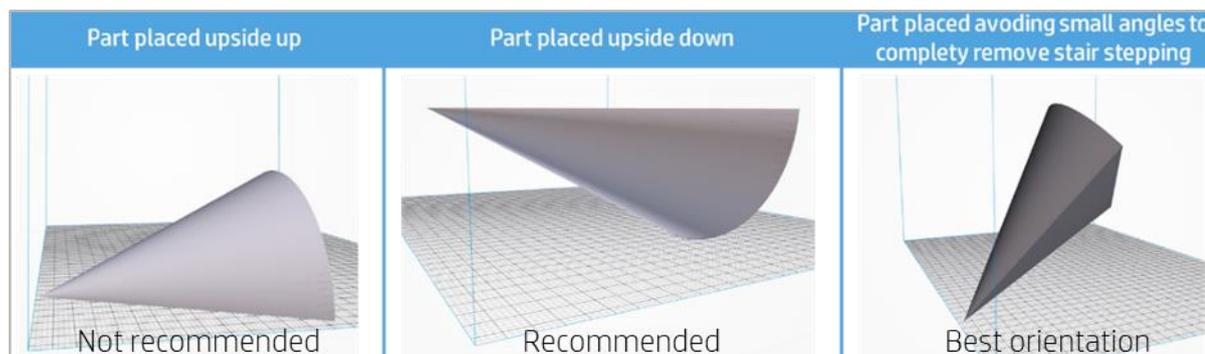


Figure 3: Orientation strategies for parts displaying curved areas in order to minimize the appearance of excessive layer discretization.

To maximize **color homogeneity**, it is advisable to avoid situations wherein parts are exposed to excessive or non-homogeneous heat during printing. Some ways to ensure this are:

- Make sure that the **cover glasses of both the fusing lamps and the thermal camera are clean**.
- The recommended **minimum distance between parts** is 5 mm.
- Leave **enough separation** (approx. >15 mm) between dense parts (wall thickness approx. >15 mm) to prevent bigger objects from heating smaller neighboring parts. This, however, does not mean that the separation between all the parts in the job needs to be set to >15 mm, since there is specialized software (like Materialise Magics [2]) that allows for different separations for different kinds of parts, as shown in **Figure 4**.
- Distribute the **parts as homogeneously as possible on the XY-plane** to facilitate similar energy absorption across the printing bed. The reason for this is that, at equal irradiance, sections with lower printed areas receive significantly more energy than zones with higher packing densities due to the radiation reflection of the unfused powder and the lamps' cover glasses (**Figure 6**). Consequently, lower packing densities effectively receive more energy per part than higher packing densities with the same material, print profile, fine-tuning and type of parts.
- Place the **parts as centered on the platform as possible** and avoid placing dense parts close to the walls of the build chamber.

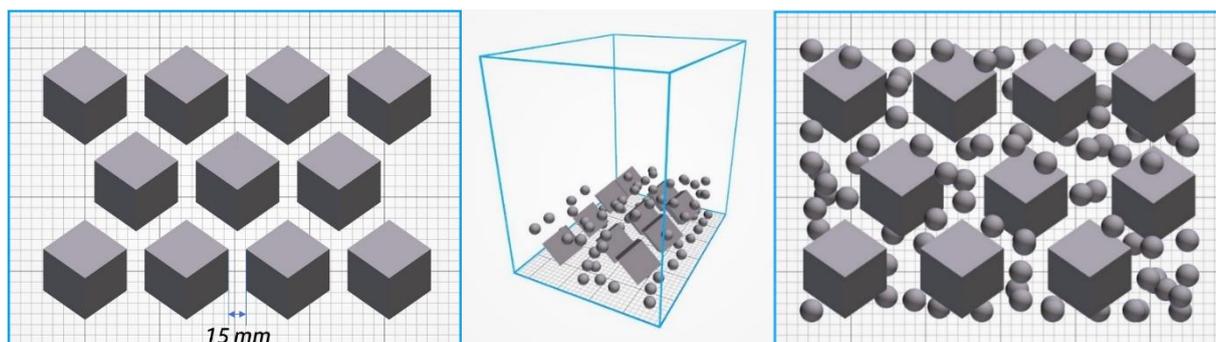


Figure 4: *Left*) Top view of a job with big dense parts that need to be separated at least 15 mm from each other to minimize part quality issues. Note that an empty margin is kept minimizing the possibilities of obtaining rough irregularities (elephant skin) on big parts located near the walls. **Middle and right**) General and top views of a print job with a mix of both small and big parts, showing that it is possible to use different part separation values depending on the size of the objects, which increases packing density.

- Similarly, placing parts in the building chamber while **avoiding drastic changes of the printed areas per layer** (Z-direction), as also shown in **Figure 6**, is a good idea. This information about the printed area distribution along the Z-axis is provided by some professional suites like Materialise Magics [2].
- **Re-designing dense parts by hollowing them or introducing internal lattices** in them (see [Appendix A1](#) for further information) reduces the amount of melted material and therefore the overall temperature in the surrounding area. This is clear from the noticeable difference in printed areas between the last 2 scenarios in **Figure 6**, which is reduced to almost half by hollowing the cubes and leaving a 5 mm wall thickness. These strategies also save both fluid agent and powder compared to fully solid designs.

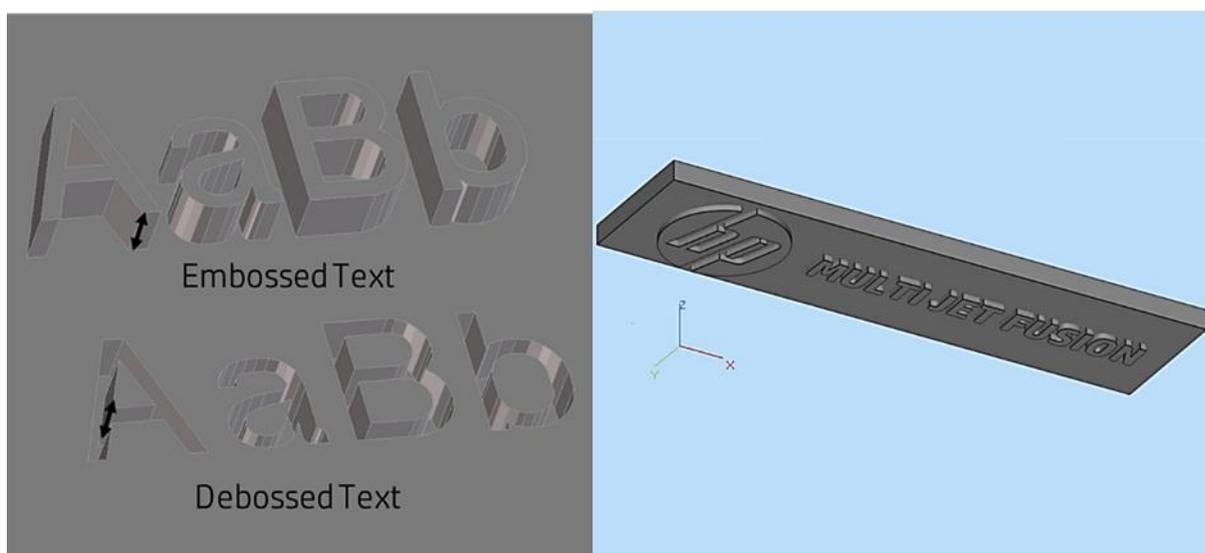


Figure 5: *The recommended orientation for embossed and debossed text on Multi Jet Fusion parts is facing down.*

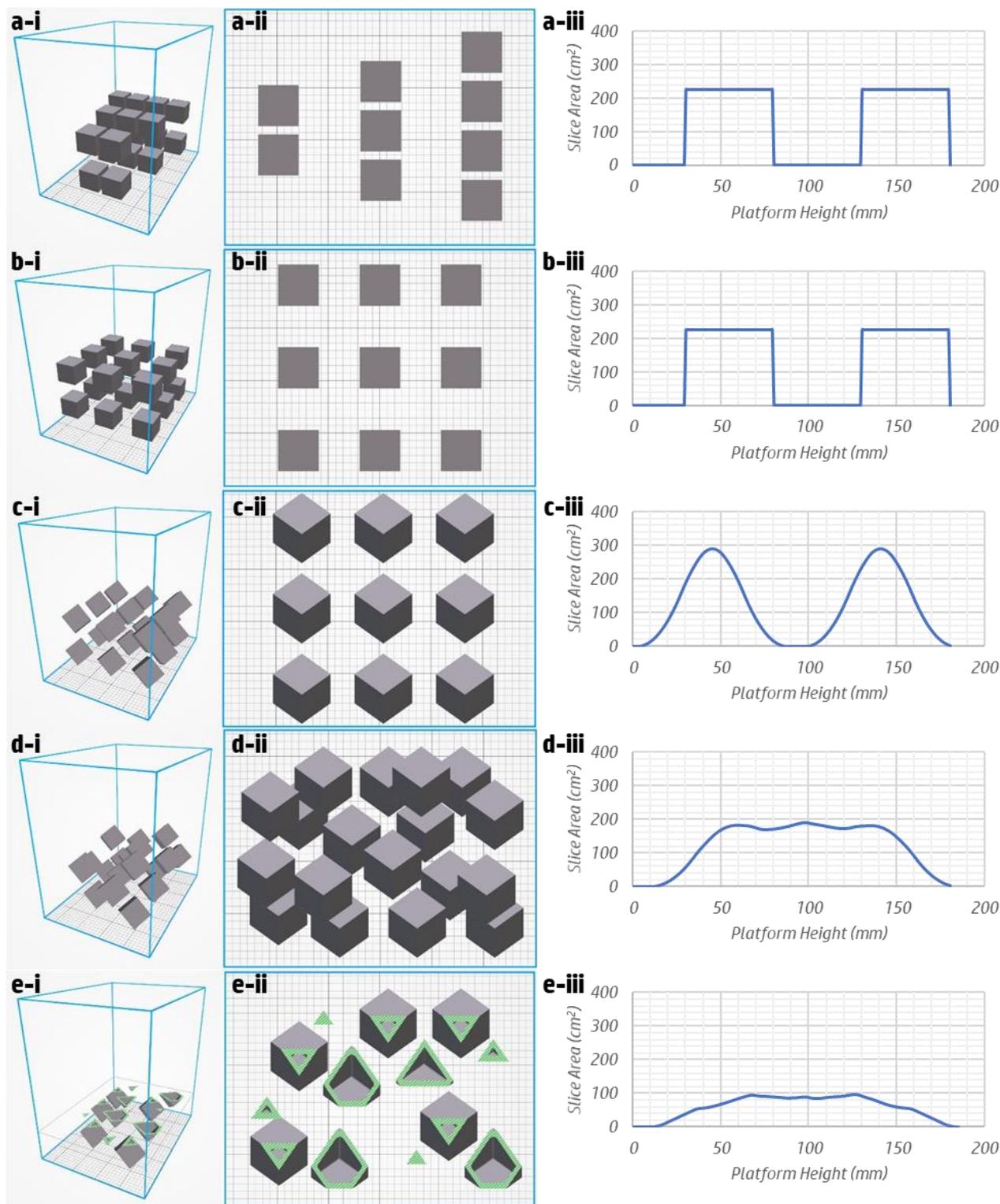


Figure 6: Depictions of general (left column) and top (middle column) views of different print jobs during different stages of look and feel optimization. The printed area per layer distribution (right column) is used as an indicator of homogeneity in the Z-direction to prevent big differences in the energy absorption of parts. **a)** An example of a non-recommended job configuration displaying non-homogeneity in the 3 dimensions. **b)** A job that's homogeneous on the XY-plane but with a distinct and potentially problematic gap along the Z-axis. **c)** The gap along the Z-axis is smoother after rotating the cubes in order to avoid exposing large areas to the last layers to be printed. **d)** Using automatic packing, the printed area distribution is smoothed even further, minimizing adverse thermal effects. This is a recommended configuration. **e)** The optimum solution, whereby the printed area is reduced by half by hollowing the cubes (to 5 mm-thick walls). The images show cross-sections of the parts for illustrative purposes.



Some geometries may display position- and orientation-dependent artifacts, such as capillarity, sinks, abraded tops or bubbles (more information in [Appendix A2](#)) that can be reduced by keeping the following advice in mind during the creation of the printing job:

- Since many of these artifacts mainly affect the last printed layer, it is recommended to rotate the part so that the top layers have a reduced cross-section, **avoiding flat areas as much as possible (Figure 6)**.
- Place **small features** such as pins and thin walls **upside down** to improve their look and feel and strength. This also applies to embossed or debossed text, which should be printed along the XY-plane for maximum resolution, as shown in **Figure 6**.
- **Small rounded features** may be prone to collecting small bubbles and should be positioned **facing downward** to avoid this effect.

Look and feel flowchart and examples

To further illustrate the recommendations provided for cosmetic parts, an **example involving a toy sailboat** is shown in **Figure 7**. Since the most visible area of the object is the inside of the boat, it is immediately clear that the part needs to be placed facing downwards to provide a better finish in that section. A first approach would be to leave it flat (**Figure 7b**), but the printed area distribution of this orientation (especially in the collective case with 50 parts, as shown in **Figure 7c & d**) ends sharply after a maximum peak, which is recommended to avoid in order to minimize surface artifacts such as capillarity, abraded tops and sinks. Consequently, the boat should be angled, but always at more than 20° in order to minimize the visibility of the individual layers (**Figure 7e**). Please note that this rotation can be performed around a different axis or a combination of them. The rotation axis along the boat's length is chosen to minimize the required Z-dimension printing and distribute the printed area across the many layers.

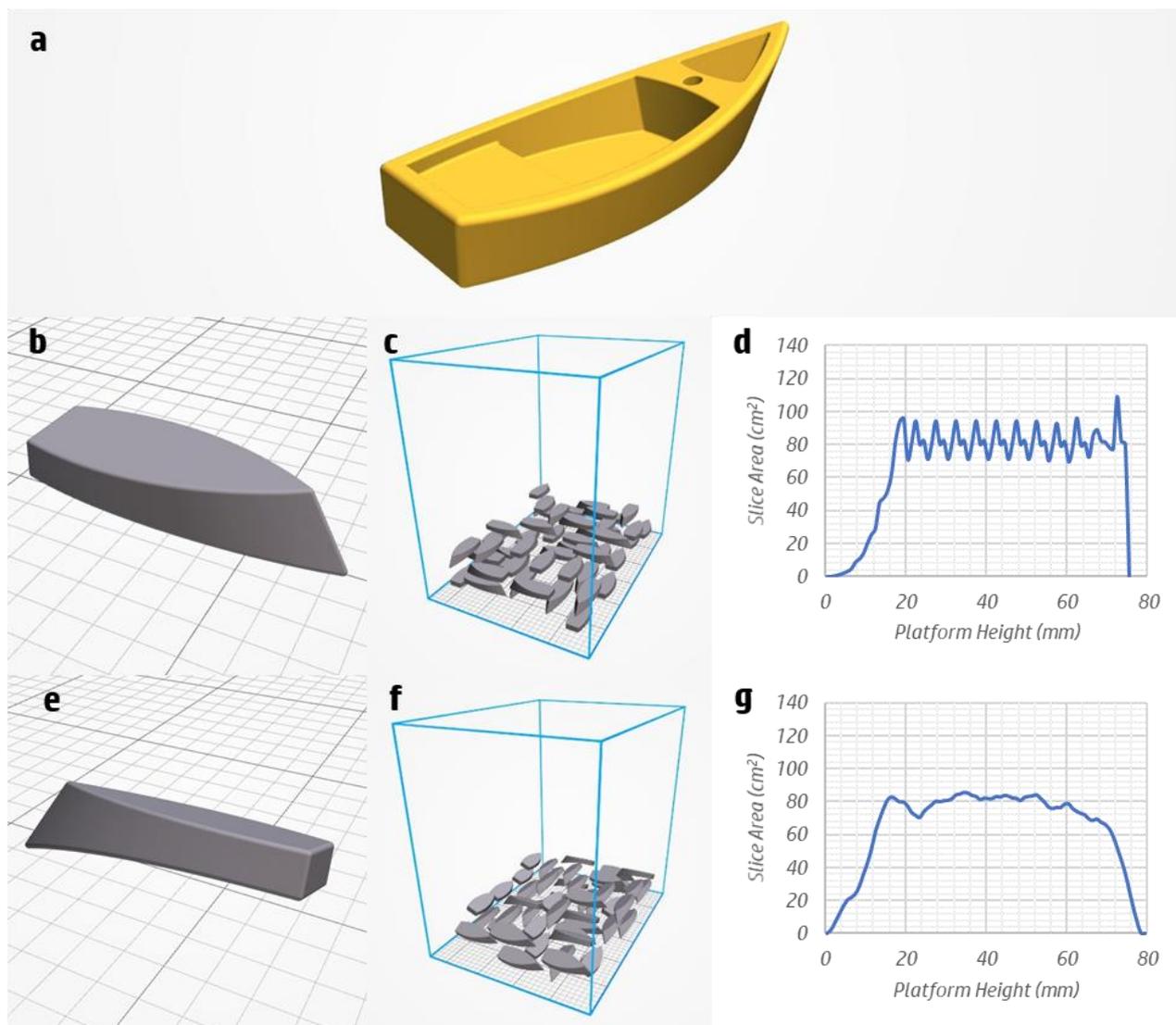


Figure 7: An example of part orientation focusing on maximizing the look and feel of a toy sailboat (a). b-d) Initial orientation stage wherein the part has a large area parallel to the XY-plane, increasing the effect of artifacts such as capillarity. 50 parts were placed, allowing rotation around the Z-axis. The area-per-layer distribution fluctuates and ends abruptly. e-g) A boat rotated 25° around its own axis in order to prevent capillarity and excessive layer-stepping. The collective area distribution with 50 boats is smoother than in the previous scenario.

In terms of the position of the parts in the build chamber, it is best to look for the center of the platform, but there is not a significant difference in the result if orienting the parts along the printing axis (X) or axis (Y). Thus, in the collective scenarios where 50 boats are printed in the same job, rotations around the Z-axis are allowed, which can increase packing density (depending on the geometry of the parts) and, more importantly, helps the required droplets to be shared across more printing elements. This homogeneous distribution of the printing load is critical to avoiding the over-stress of a small set of dies while leaving others idle for long periods of time.

The advice provided in this section is summarized in the flowchart shown in **Figure 8**, which can be used as a guide to maximize the look and feel of printed parts.

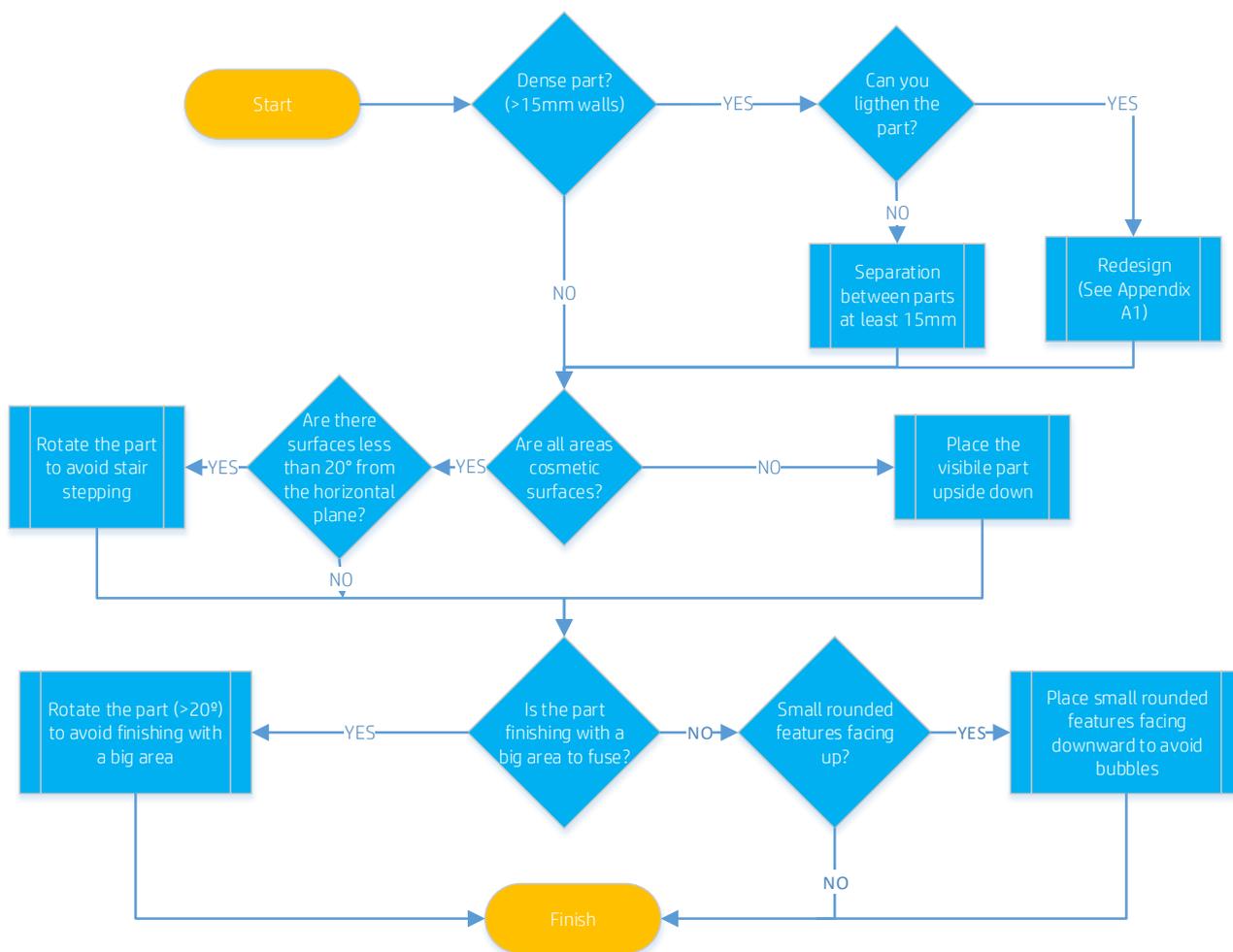


Figure 8: Flowchart for an appropriate process-parameter selection based on the geometry and functionality of a part in order to maximize its look and feel.

2. Optimizing Dimensional Accuracy

To maximize accuracy, the system needs to operate at voxel level with adequate energy delivered to properly fuse the intended sections layer-by-layer. To achieve this goal, please consider the following:

- Make sure that the **cover glasses of both the fusing lamps and the thermal camera are clean**.
- Make sure that the **file is printable** and that the dimensions are within the capabilities of the system. For more information on this, check the “Design and Printing Guidelines” [3].
- Orient each part placing its **critical features on the horizontal plane**, since it provides the highest resolution. As such, pins and holes should ideally have their diameters contained on the XY-plane (**Figure 9**). For flat and thin parts (with an aspect ratio higher than 10:1), see the following section for additional tips on preventing shrinkage-related deformations.
- Place **small features** such as pins and thin walls **upside down** to improve their look and feel and strength. This also applies to embossed or raised texts, which should be printed on the XY-plane for maximum resolution, as shown in **Figure 6**.
- The recommended **minimum distance between parts** is 5 mm.
- Leave **enough separation** (approx. >15 mm) between dense parts (wall thickness approx. >15 mm) to stop bigger objects from heating neighboring parts. This does not mean that the separation between all parts in the job needs to be set to >15 mm, as there is specialized software (like Materialise Magics [2]) that allows for different separations for different kinds of parts, as is shown in **Figure 4**.
- Place the parts with the **highest dimensional requirements**, especially on the Z-axis, as **centered and as low** on the printing platform as possible (**Figure 9**). For optimum results, leave a margin between the parts and the Build Unit chamber walls. It is noteworthy to know, however, that the area outside this optimum region is still valid and can still be used for parts with lower dimensional requirements, particularly in the Z-direction.

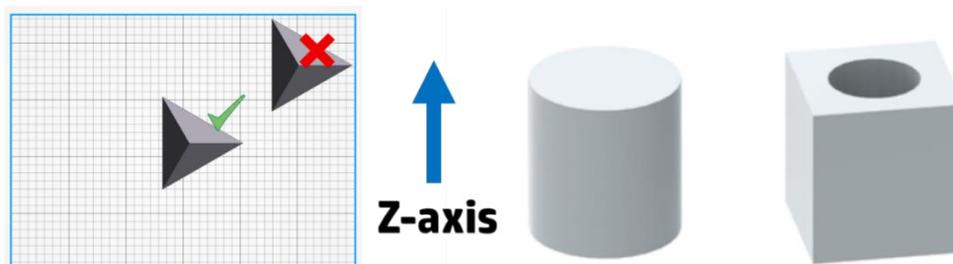


Figure 9: Left) Avoid placing parts with high dimensional requirements (especially in the Z-direction) near the borders of the platform, since these regions are more susceptible to warpage on flat parts and elephant skin on denser objects. **Right)** Orientation recommendation for pins and holes when their diameters are the most critical dimensions and are therefore placed on the XY-plane, where the highest resolution is achieved in MJF.

- **Distribute the parts as homogeneously as possible on the XY-plane** to facilitate similar energy absorption across the printing bed. The reason for this is that at equal irradiance, sections with lower printed areas receive significantly more energy than zones with higher packing densities due to the radiation reflection of the unfused powder and the lamps’ cover glasses (**Figure 6**). Consequently, lower packing densities effectively receive more energy per part than higher packing densities with the same material, print profile, fine-tuning and type of parts.
- Place the parts in the building chamber **avoiding drastic changes in the printed areas per layer** (in the Z-direction), as is shown in **Figure 6**. This information about the printed area distribution along the Z-axis is also provided by some professional suites like Materialise Magics [2].

- **Re-designing dense parts by hollowing them or introducing internal lattices** in them (see [Appendix A1](#) for further information) reduces the amount of melted material and therefore the overall temperature of the surrounding areas. These strategies also save both fluid agent and powder compared to fully-solid designs.
- Once printed, **thorough cleaning by bead-blasting** [4] is required to remove all the unfused powder that may have accumulated within small cavities. This is crucial before measuring the parts to obtain reliable results.
- Keep in mind that **post-processes** like machining [5] and insert additions [6] are possible with MJF parts, which allow you to increase the resolution of their localized features beyond the capabilities of the system alone. When the parts are machined, it's possible to end up seeing the internal core of the part, which is black, depending on the quantity of material removed.

Thin and long parts

Long and thin parts are susceptible to non-uniform cooling, which may cause uneven shrinkage along the printed part, creating a distortion in a certain direction that deviates from the nominal shape (**Figure 10**). As a rule of thumb, any part with an aspect **ratio higher than 10:1**, an **abrupt change in its cross-section** or a predominantly **long and thin curved segment** is susceptible to showing warpage (**Figure 10**). The following actions can be considered to minimize the possibility of this deformation:

- **Increase the thickness** of long walls to reduce their aspect ratios. The thicker the part, the stiffer it will be, and the more internal stresses it can withstand.

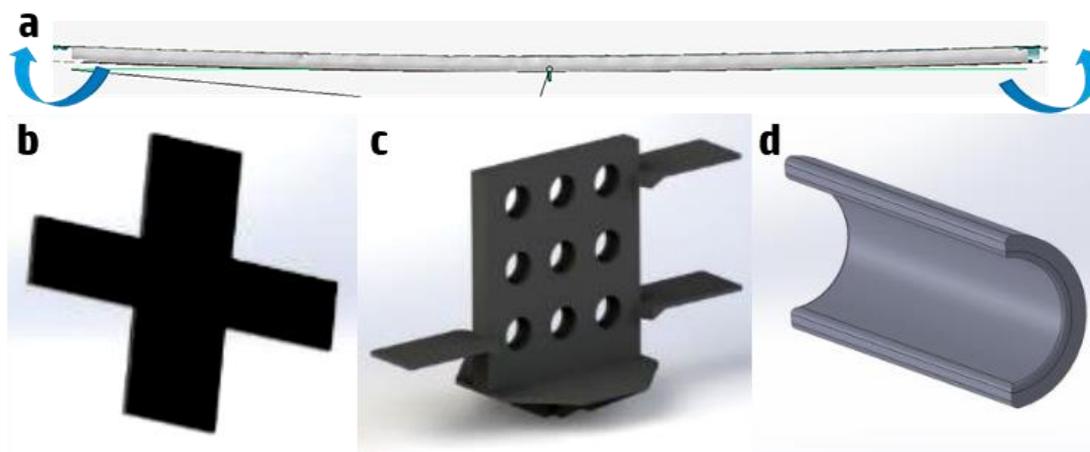


Figure 10: Part categories susceptible to shrinkage-induced warpage (a) include: long and thin parts (b), parts with abrupt changes in cross-sections (c), and thin curved surfaces (d).

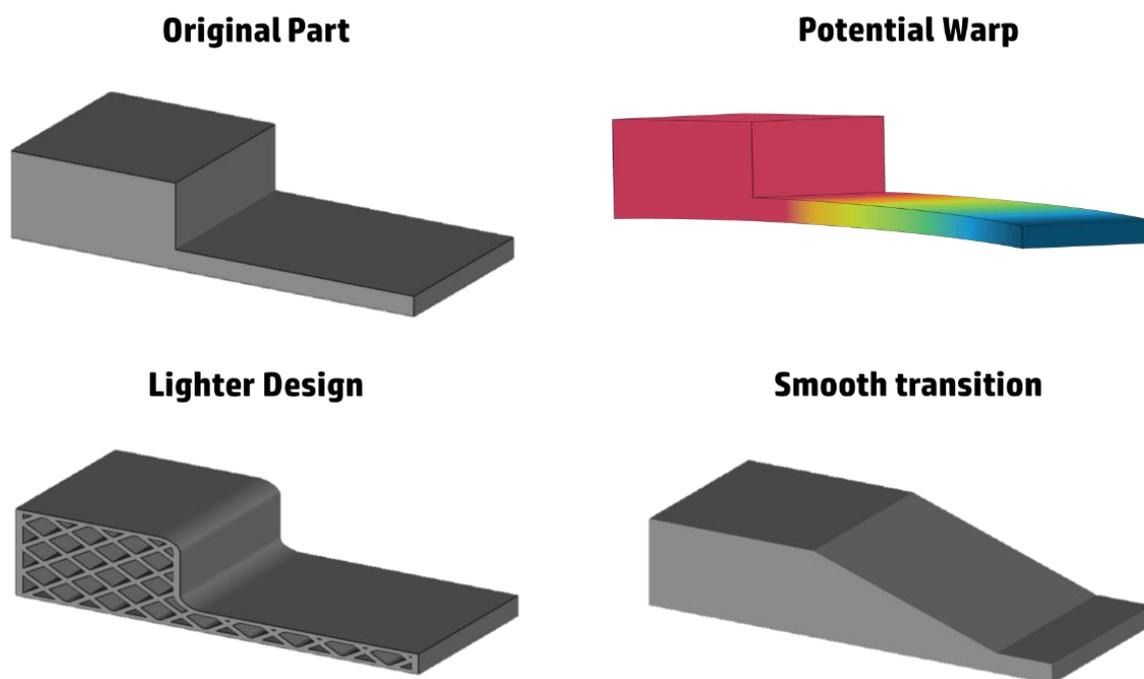


Figure 11: A part with a sharp variation in its cross-section that would potentially display warpage due to different contraction rates. Two potential re-designs are shown: one reducing the volume of the part by using a lattice and another one including a ramp to smoothen the transition and reduce stresses.

- Re-design parts with high potential stresses and **smoothen their cross-section transitions**, as is shown in **Figure 11**.
- **Lighten the parts** by hollowing them or by adding internal lattices to them (see [Appendix A1](#) for more details) as is also displayed in **Figure 11**.
- **Sacrificial supports** may keep thin parts from deforming, but these should be carefully applied to keep from inducing even greater stresses. These scaffolds should be light and should not come in contact with the part at too many points.
- **Avoid ridges and ribs** on large, flat areas, because they generate thermal gradients due to their non-uniform cooling. If they cannot be removed, **place them upside down** to allow them to start cooling before the thicker planes do. This reduces the stress on the part. See **Figure 12** for your reference.
- Print **short buckets**, which accumulate less heat and cool down faster but in a controlled way.

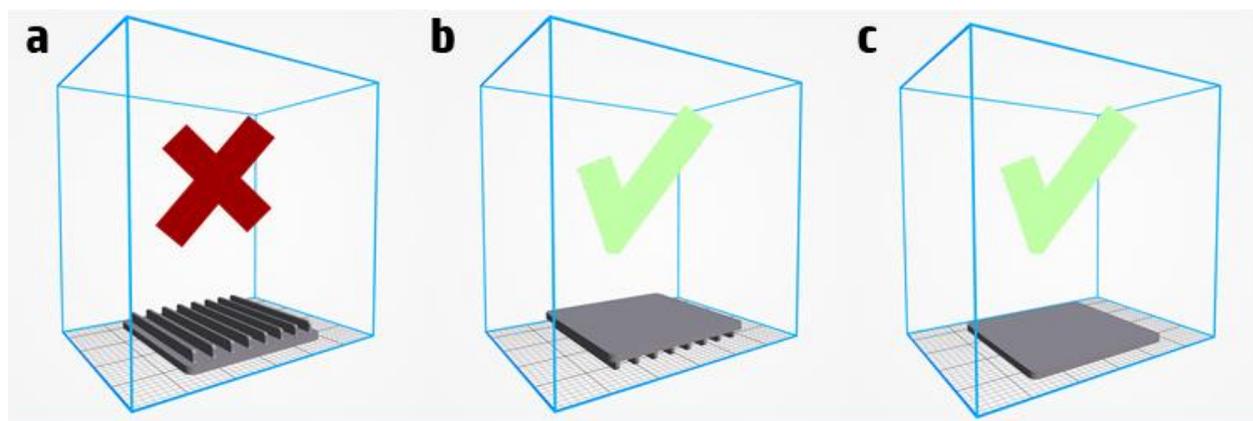


Figure 12: Parts with ribs should not be placed with smaller features facing up (a), but rather upside down (b). Removing the ribs is a valid option to prevent warpage if the application allows for it (c).

- Keep in mind that the stiffness of thin polyamide parts is low, which means that most warped parts can be effortlessly re-shaped once they are mounted in their designated place. Furthermore, thermal post-treatments can be applied to conform the material into a different shape after printing, allowing for fine-tuning of finished parts.

Big and/or massive parts

Dense parts are those with a **substantial mass concentrated in a reduced volume**, so they do not have many cavities or have walls thicker than 15 mm. These massive objects accumulate more heat than the average part and require a special heat management approach that is built-in the system own printing algorithm. However, when many of said objects are printed in the same session, the generated heat may exceed the dissipation achieved following the standard recommendations provided in other sections of this document. Thus, for these cases, the following recommendations are suggested (see **Figure 13** for a graphical example):

- Favorable **orientation** is critical for parts that do not have their mass distributed homogeneously. It is recommended to print the thinner features facing down with the more massive section in the upper position to prevent thermal bleeding (**Figure 20**) due to excessive heat transfer.
- Make sure that the parts are **appropriately separated** (> 10-15 mm) and that the **packing density** is not excessive. The range between 8 and 10 % is a good reference point, while higher than 20 % is strongly discouraged.
- A way of decreasing packing density without drastically reducing the number of parts is to **hollow** them (see [Appendix A1](#) for more details). However, depending on the thickness of the external walls and the design of the part, it is possible that hollowing results in sinks due to slightly different shrinkage rates in different sections (see [Appendix A2](#) for an explanation of this artifact). In this case an **internal lattice** is recommended to reduce the mass of the object while keeping structural integrity.
- Print jobs containing a fairly high density of massive parts are likely to generate inhomogeneous layer distributions. In other words, some layers would contain a big printed area while others would be almost blank. To avoid heating irregularities, it is encouraged to follow previous advice on print job design (see **Figure 6**).
- **Short buckets** help reduce the time that the parts spend at high temperature, which improves the general output.

- High packing density print jobs with dense parts can result in **powder yellowing**. This would not normally affect dimensional accuracy but can weaken the mechanical properties of thinner parts.

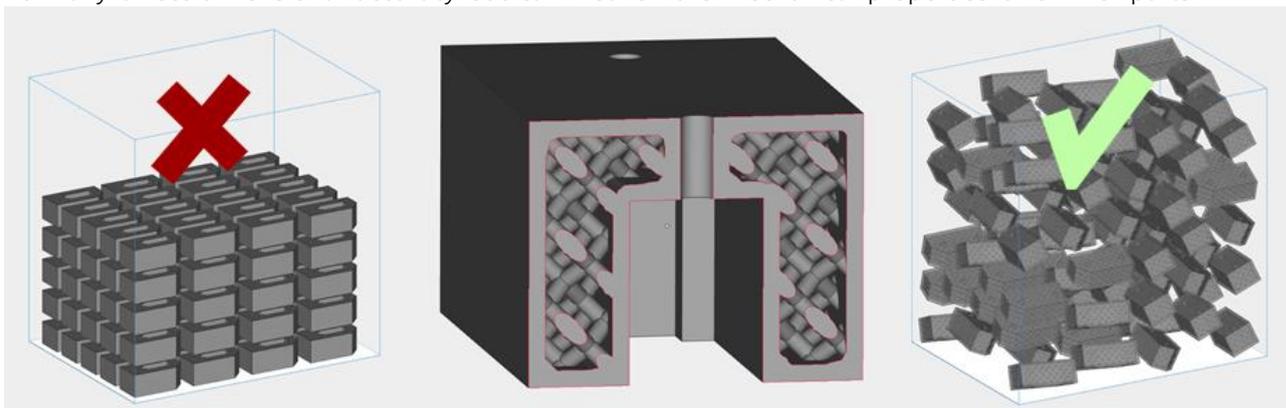


Figure 13: *Left*) Print job design not recommended due to excessive packing density, dense parts, array configuration and flat orientation. *Middle*) Section of a dense part that has been lightened applying internal lattices. *Right*) Recommended print job configuration with lightened parts with increased part separation, tilted orientation and more degrees of freedom during automatic packing.

Dimensional accuracy flowchart and examples

The first example involves the printing of a **honeycomb plate** with the intention of maximizing dimensional accuracy (**Figure 14**). For this part, the first thing to notice is that it is very similar to a big, flat plane, and therefore the object is moderately susceptible to suffering from warpage. However, thanks to its light honeycomb design, this deformation is not expected to be as severe as on a fully-dense plate.

To maximize the accuracy and circularity of positioning holes, it is recommended to orient the part so that these features are contained on the XY-plane. Furthermore, this orientation minimizes the height of the part, which is compatible with the recommendations for reducing warpage and bowing. To preserve the flatness of a part, center it as much as possible on the platform, place it in the lowest quarter and use **Slow Cooling** and wait at least 50% longer than the default cooling time before retrieving the parts. Keep in mind that placing a part flat can induce capillarity on its top face, so angle the part slightly to prevent it if this is more critical than obtaining maximum accuracy of its holes.

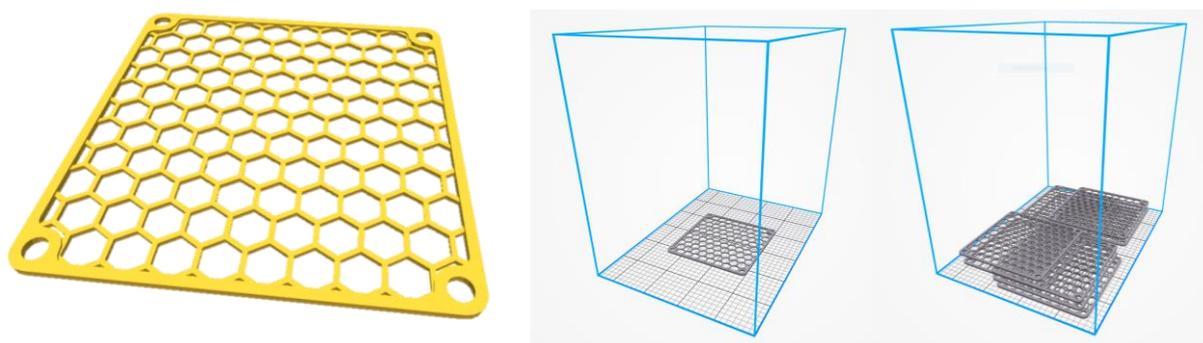


Figure 14: A honeycomb plate (*left*) oriented to maximize dimensional accuracy and minimize warpage. Critical features such as the positioning holes are contained on the XY-plane (*middle*). *Right*) A bucket with 10 plates in the same orientation.

In a collective scenario where several plates of this type are required (**Figure 14**), the following are recommended:

- Print **short buckets**.
- **Center the parts** as much as possible.

- Make sure that a **similar number of parts are being printed at each level**. In the example there are either 2 parts or none.
- **Shuffle the parts** so that they do not line up along the same XY coordinates. This makes the printing load be shared across more printheads, extending their lifespans.
- Use **extended cooling time before reclaiming**.

The advice provided in this section is summarized in the flowchart shown in **Figure 15**, which can be used as a guide for maximizing the dimensional accuracy of MJF-printed parts.

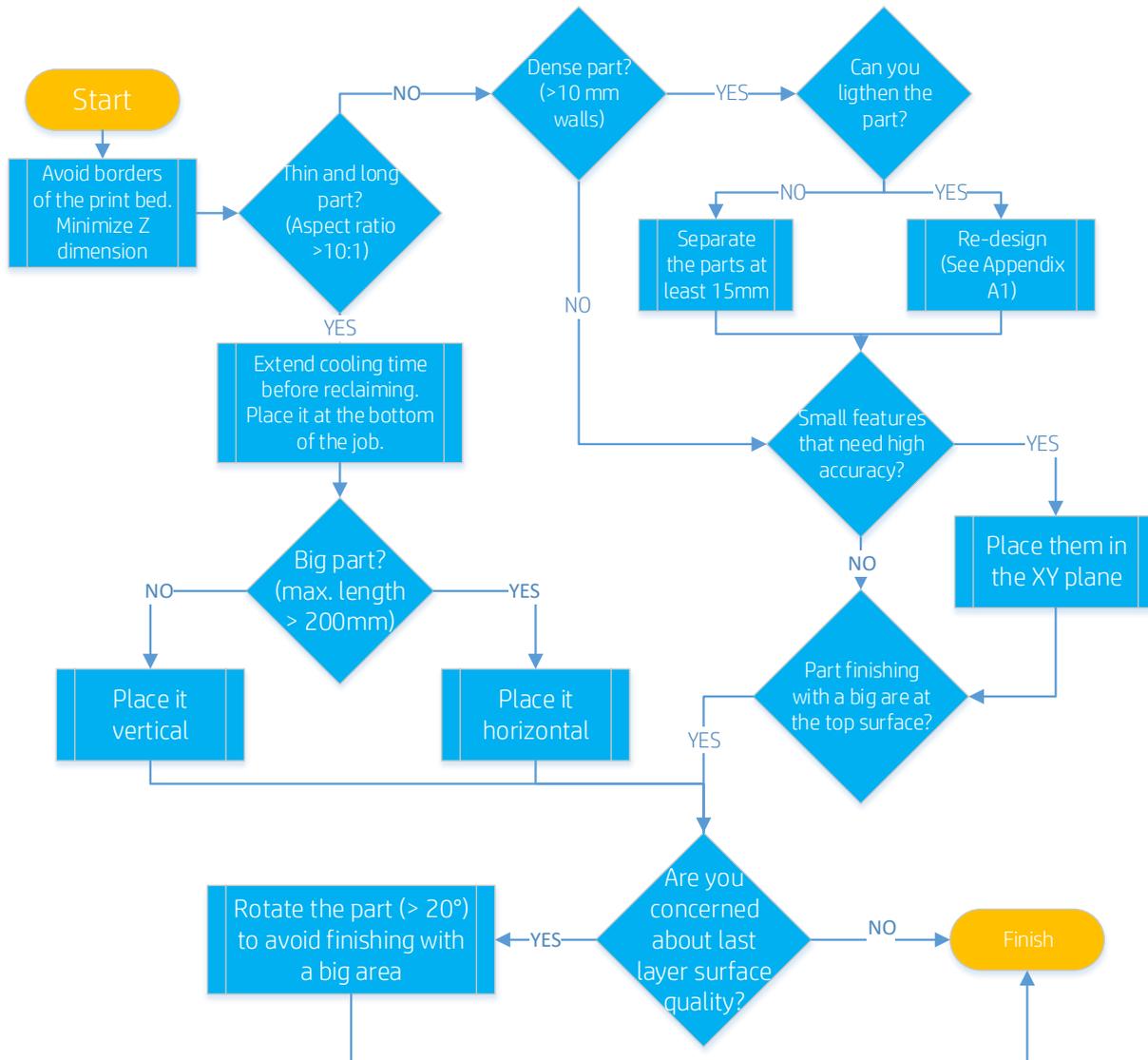


Figure 15: Flowchart for appropriate process-parameter selection based on the geometry and functionality of a part in order to maximize dimensional accuracy.



3. Optimizing Mechanical Properties

The following points should be considered in order to increase the performance of the parts:

- Make sure that the **cover glasses of both the fusing lamps and the thermal camera are clean**.
- Best mechanical results are obtained when printing on **white powder**, so it is advised not to re-use material that is showing distinctive yellowing.
- The recommended **minimum distance between parts** is 5 mm.
- Leave **enough separation** (approx. >15 mm) between dense parts (wall thickness approx. >15 mm) to stop bigger objects from heating their nearby neighbors. This, however, does not mean that the separation between all parts in the job needs to be set to >15 mm, as there is specialized software (like Materialise Magics [2]) that allows for different separations for different kinds of parts, as shown in **Figure 4**.
- **Distribute the parts as homogeneously as possible in all directions, XYZ**, to facilitate similar energy absorption across the printing bed. The reason for this is that at equal irradiances, sections with lower printed areas receive significantly more energy than zones with higher printed areas due to the radiation reflection of the unfused powder and the lamps' cover glass (**Figure 6**). Consequently, lower packing densities effectively receive more energy per part than do higher packing densities with the same material, print profile, fine-tuning and type of part.
- Place the parts in the bucket **avoiding drastic changes in the printed areas per layer** (in the Z-direction), as also shown in **Figure 6**.
- **Print short jobs**, minimizing the number of layers, which allows faster printing and cooling stages. This has been observed to increase the elongation at breakpoints and impact resistance of parts due to faster re-crystallization of the polyamide.
- **Place mechanically important features in the XY-plane** since tensile and Impact properties tend to be slightly higher than in the Z direction.
- **Avoid placing parts close to the walls** of the build chamber, especially if oriented in the Z direction.

Mechanical examples

An example of a part orientation for a part that requires **increased elongation and impact** resistance in its thinner features is shown in **Figure 16**. However, as was discussed previously, for better mechanical properties, other process factors such as job heights and density are also key factors. Thus, to obtain high **elongation and impact resistance values**, it is recommended to cool the parts using the default cooling settings, and to print shorter jobs (minimizing Z-height) with low packing densities.

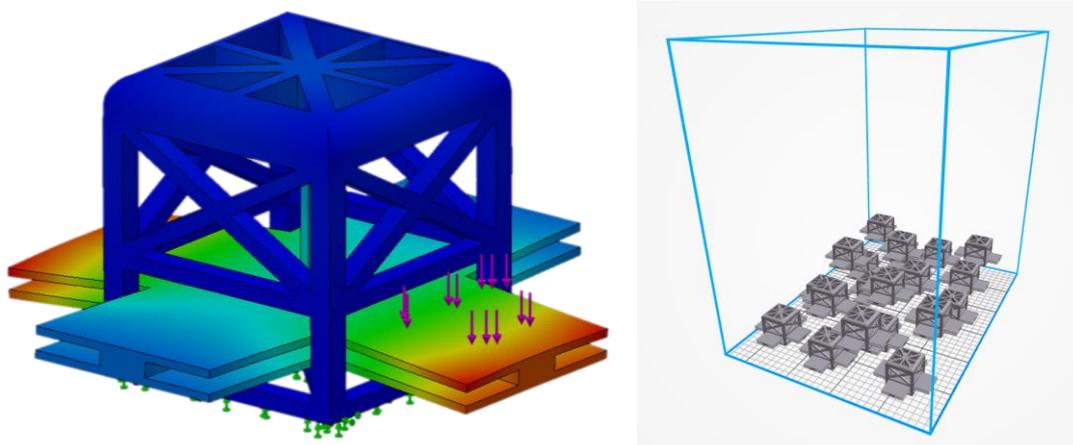


Figure 16: *Left)* A mechanical part with high elongation requirements on its thinner features. *Right)* A short bucket containing 20 iterations of the same part.

A1. Appendix: Design Optimization Strategies

Decreasing the overall mass and wall thickness of printed parts helps to reduce the amount of material used, which has an associated cost reduction. Furthermore, thinner sections accumulate and re-radiate less heat, improving the dimensional accuracy and general look and feel of the parts. The most obvious re-design route is to alter the CAD manually, trying to remove any unnecessary features and sections, as is done for other manufacturing technologies. However, Additive Manufacturing allows the designer to create more complex structures than ever before, enabling substantial savings in time, material, and assembly time.

Semi-automatic re-design routes can be followed to achieve similar or even greater part optimizations, such as hollowing the objects, inserting internal lattices in them or applying topology optimization algorithms. These strategies are summarized in **Figure 17** and are briefly described in the following sections, but for a deeper explanation of their use in Multi Jet Fusion, see “Design Optimization Strategies” [7]. Please note that they can be combined for even more significant mass reduction.

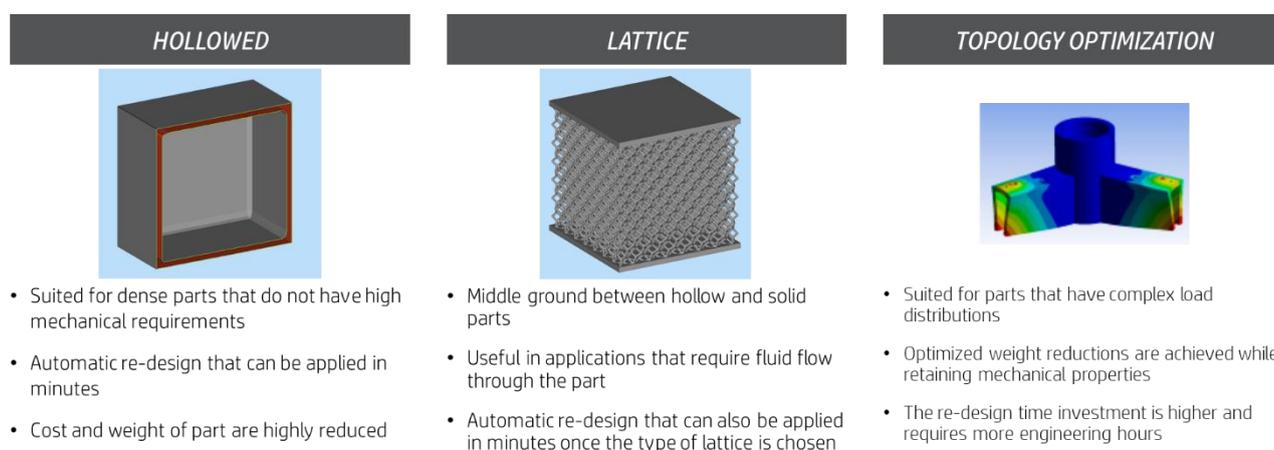


Figure 17: Description of the main semi-automatic re-design approaches for parts printed with Multi Jet Fusion.

Hollowing

This method consists of hollowing the CAD file through an automatic process (professional software such as SmartStream[16] SolidWorks [9], Materialise Magics [2] or Autodesk Netfabb [15] have it built-in). This is very fast and simple, reducing the mass of a part significantly, but at the expense of its mechanical integrity, as the amount of melted material is diminished. However, the performance of the part compared with the fully solid design is ultimately linked to the remaining wall thickness and the amount of unfused powder left within the part.

- The minimum recommended **wall thickness** is 2 mm, but higher mechanical properties are achieved with thicker walls. The optimum choice is application-dependent.
- At least two **drain holes** with a minimum diameter of 5 mm in opposite faces of the part are recommended for efficient powder removal, which is critical to obtaining the highest weight reduction.
- **Trapped unfused powder** can be left within the part if no drain holes are included. This results in heavier and more resistant parts compared with the fully hollow option, however. While the part is still light, it is weaker than the non-hollowed version. The difference in weight stems from the different density of fused and unfused material. Leaving the powder trapped within a part also saves post-processing time, since no powder extraction is required.

Lattice Structures

This approach consists of hollowing a part and replacing the internal solid mass by a lattice structure that provides mechanical integrity via the collective action of many rigid cells. The advantage of this method is that it can retain a higher fraction of the fully dense part's mechanical properties than a hollow part does while it still noticeably reduces the part's mass and cost. This re-design is also a fast process that can be automated with professional software such as Materialise Magics [2] or n-Topology [8]. The main design parameters in these cases are geometry and the distribution of the lattice cells, beam thickness, wall thickness for enclosed lattices and the presence of unfused powder.

- The **geometry** of each cell of the lattice defines the load distribution. Lattice geometries can be isotropic or anisotropic. This choice of geometry allows designers to introduce different local properties on the final part.
- The **point distribution** determines the size of each lattice cell. The higher the cell size given a specific geometry, the fewer cells in the same volume, leading to a higher cost/weight reduction, but also to a greater mechanical trade-off.
- The **thicker the beams**, the better the mechanical properties, but the lower the cost/weight reduction.
- There is no minimum **wall thickness** recommended for enclosed lattices as they are not the main structural agents. Nonetheless, thicker walls provide higher mechanical properties, but lower weight reduction.
- **Unfused powder** can be difficult to remove from a part through drain holes when a part has a lattice structure inside it. Therefore, it is recommended to leave the powder trapped within it or to leave the lattice partially open. A minimum separation of 5 mm between lattice beams is recommended in order to facilitate powder removal.

Topology Optimization

Topology optimization is a Finite-Elements-Method (FEM)-based process that finds the best distribution of material given an optimization goal and a set of constraints. Typical optimization goals are mass reduction and creating specific mechanical properties. This process requires the designer to know the part's function and load distribution in depth, but provides the most optimized method of reducing weight and cost from the original design (**Figure 18**). The time needed to apply this type of re-design is significantly higher than the previous methodologies. Professional software such as nTopology [8] and Solidworks [9] can apply optimization algorithms.



Figure 18: An example of various topology optimization iterations of an industrial part. Deep knowledge of the geometry and performance requirements of the part is required.

A2. Appendix: Part Quality Artifacts

Stair-stepping (Layer Stepping)

All layer-by-layer manufacturing technologies require a discretization of their Z-dimension according to the layer thickness. The visibility of these layers depends mainly on their thicknesses and printing angles. Multi Jet Fusion uses layers of only 80 μm (0.080 mm), which are difficult to see with the naked eye in most situations. However, small angles in the part can cause these layers to be separated in a more noticeable way, as shown in **Figure 19**. Thus, it is recommended to **avoid angles below 20°** between big, flat areas and the XY-plane if these are going to be **facing upwards**. Surfaces **facing downwards** are typically exempt from stepping as long as they are oriented **avoiding angles below 5 – 10°**, as was suggested in **Figure 3**. These values, however, are general indications and they ultimately depend on the application. For optimum results, the best solution is to try several options and choose the one yielding the better look and feel.

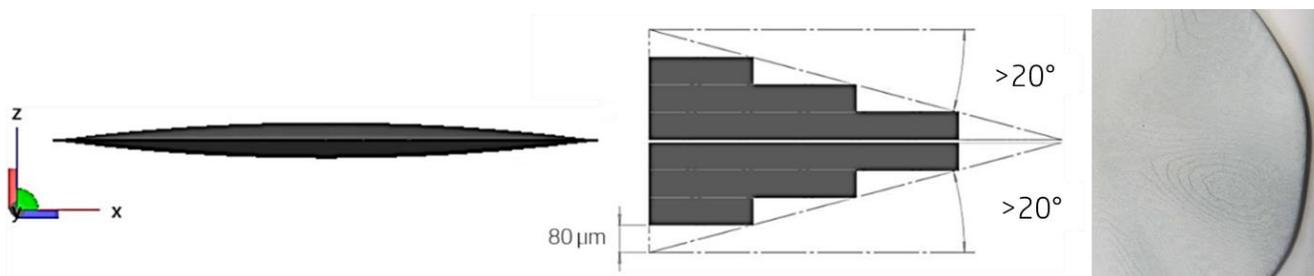


Figure 19: An example of layer stepping and a representation of the rotation threshold values depending on the face's position.

Thermal Bleeding

Thermal bleeding appears when a part receives excessive energy and the surrounding white powder gets melted and attached to the surface of the object (**Figure 20**). To some extent, this effect is intrinsic to the technology and is accounted for with an escalation of the part's volume prior to printing. Therefore, not every situation where white powder is encountered should be classified as thermal bleeding and, instead, only when the dimensional accuracy of the part is affected beyond the capabilities of the system. Moreover, parts insufficiently cleaned by bead-blasting often display white areas that can be mistaken for thermal bleeds. In these cases, scratch the white surface with a hard object (like a piece of metal) and check if the powder is removable. If so, there is no energy excess but a cleaning deficit.

Reducing this effect typically requires lowering the energy delivered to the affected areas, and therefore it is important to understand where and how the part was placed and oriented within the building chamber. Thus, hold the object in the printing position and check where the white areas are located:

- If the **white area is distributed across the whole part and it affects all the dense parts in the print job similarly:**
 - Excessive energy may be being provided by the fusing lamps. Make sure that they are clean and in good condition.
 - Increase separation between large parts.
- If the **white area is distributed across the whole part but only a small number of dense parts in the print job are affected:**
 - The thermal camera may be reading temperatures incorrectly. Make sure that it is clean and in good condition.
 - Check the local packing density of the job in the affected region and re-design the part to homogenize the printed area in the 3 directions, as illustrated in **Figure 6**.

- If the **white area is located only at the faces facing downwards**:
 - Re-orient the part to minimize the bottom surface area, as shown in **Figure 20**.
 - Check the local packing density of the job in the affected region and re-design to homogenize the printed area in the 3 directions, as shown in **Figure 6**.

- If **white or light gray bands appear intermittently along the Z-printing direction**:
 - The presence of the neighboring parts may be affecting the local heat distribution of the part. Make sure that big parts are not too close to each other.
 - Check the local packing density of the job in the affected region and re-design the part to homogenize the printed area in the 3 directions, as pictured in **Figure 6**.

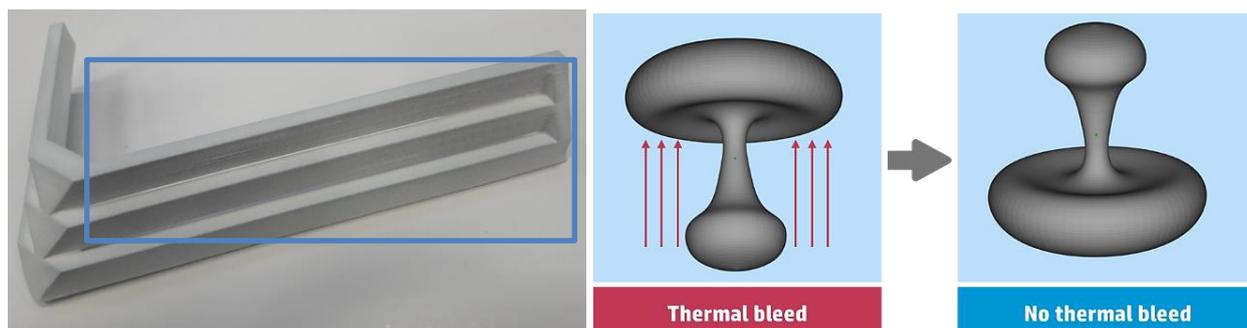


Figure 20: *Left*) Example of thermal bleeding. *Right*) Orientation recommendations to alleviate thermal bleeding on the bottoms of parts.

Elephant Skin

Elephant skin appears when the white powder surrounding a part on the print-bed is cooler than the defined powder temperature. Local deformations can occur due to non-homogeneous shrinkage, as seen in **Figure 21**.

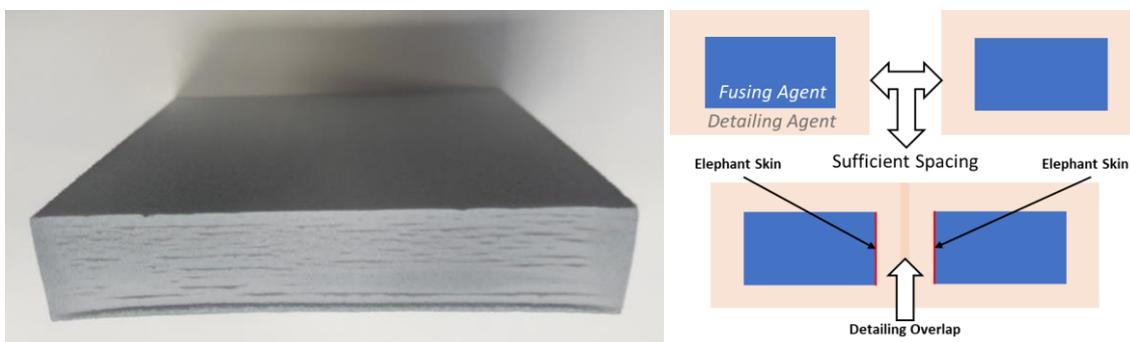


Figure 21: Example of elephant skin

Actions that can be taken to reduce incidences of this artifact are:

- Proper **maintenance of the cover glasses of the various lamps and the thermal camera**.
- This artifact affects denser parts, so consider **reducing their printed volume** following some of the strategies discussed in [Appendix A1](#).
- Make sure that the **separation between big parts is greater than 15 mm**.
- Place potentially problematic **parts as centered as possible**, avoiding the vicinity of the print-bed walls.

Abraded Tops (a.k.a. Fusing uniformity)

Abraded tops (a.k.a. fusing uniformity) appear when there is a big area to fuse at the end of a build. In this situation, the printer adds a considerable amount of detailing agent to prevent thermal bleeding, which causes this irregularity on the surface, the part's color homogeneity and local roughness being altered (**Figure 22**). In white parts, a top surface with this defect could also show a light blueish color. Orienting the part with an angle to minimize its top surface area is the key to reducing the possibility of this defect. Please, keep in mind that angles lower than 20° can induce stepping.

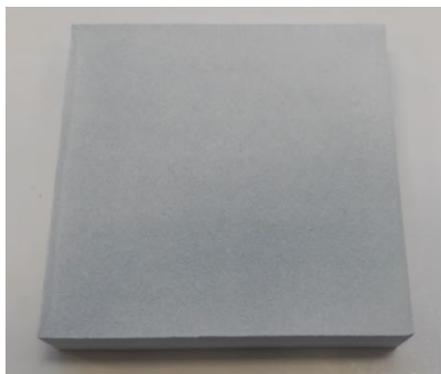


Figure 22: An abraded top of a part printed with a flat orientation.

Surface Capillarity

This effect is intrinsic to powder-bed technologies that rely on melting powder to consolidate objects layer by layer. When an area is fused, it behaves as a fluid and tends to raise up along its borders (as does water inside a glass), as shown in **Figure 23**. Thus, larger areas parallel to the XY-plane are more prone to capillarity, and for them, it is **recommended to rotate the part to mitigate it (Figure 23)**.

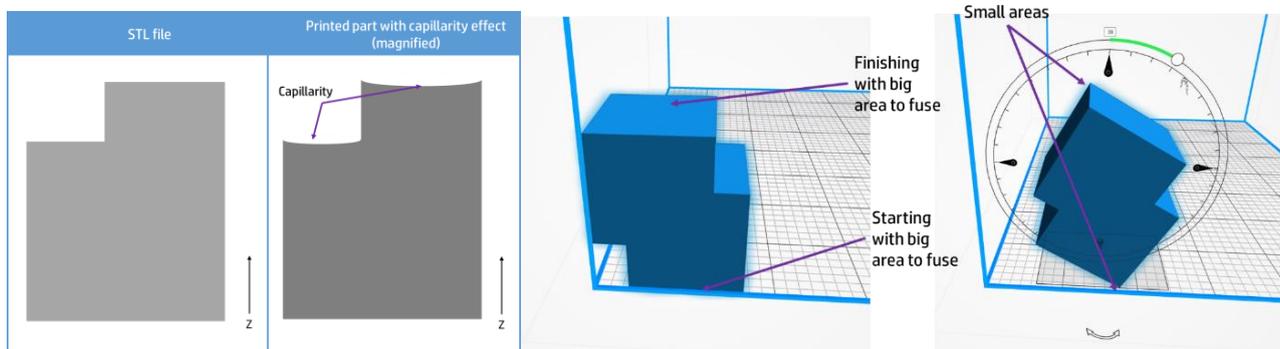


Figure 23: **Left)** A diagram representing the fluidic nature of the capillarity phenomenon. **Right)** Rotation suggestion to reduce capillarity.

Sinks

The external surfaces of a part tend to cool down faster than its inner volumes, especially in denser and bigger objects, causing a thermal gradient. When the core of the part solidifies, it contracts, pulling the already solidified outer shell inwards (**Figure 24**).



Figure 24: A sink on a face of a dense part.

This effect can be minimized by the following actions:

- Consider **reducing the printed volume of the part** by following some of the strategies discussed in [Appendix A1](#).
- **Avoid large flat areas** on the last layer to be printed. It is recommended to rotate the parts (**Figure 23**).
- **Parts prone to displaying sinks or bubbles should be positioned farther from other parts** (approx. >15 mm), especially for objects immediately above them (in the Z-direction). Positioning them in the top quarter of the bucket may help to reduce this effect.

Bubbles

Small pinholes can appear in upwards-facing small features due to the excessive accumulation of heat required to preserve their dimensional accuracy. This, however, is dependent of the geometry of each part and its surroundings. To minimize bubbles, the following actions can be performed:

- Re-orient **small features so that they are facing downwards**.
- Check that the powder used to print is white, yellowing powder can cause an increment in bubbles frequency and severity.

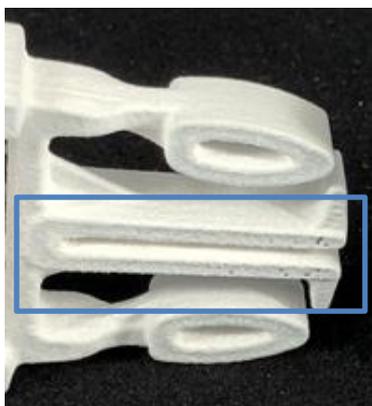


Figure 25: An example of voids caused by bubbles.

Printhead-related Issues

Printheads are in charge of delivering the fusing and detailing agents that control which areas are fused. Thus, deviations from their expected performance can result in part quality variations. This can be minimized by performing active maintenance of the printing elements [1] and by paying attention to early signs of degradation, replacing them before there is ever an issue. The main printhead-related artifacts are summarized below and are shown in **Figure 26**. They are typically easy to diagnose due to their nature of appearing straight along the printing axis.

- **Nozzles being out** results in finer lines and are embossed or debossed compared to the rest of the part depending on if the missing fluid is fusing or detailing agent. Often, the printhead can recover by performing additional maintenance [1]. Alternatively, changing the underperforming elements solves the issue.

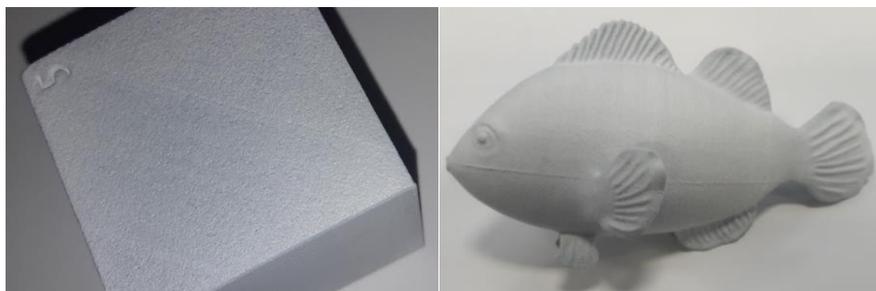


Figure 26: Examples of nozzles being out.



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