Internal draft

Design Optimization Strategies

Transitioning from traditional manufacturing technologies to Multi Jet Fusion

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1. Executive summary

The objective of this white paper is to show several automatic design optimization methods that can be used to help you take full advantage of additive manufacturing when moving the production of parts from traditional manufacturing methods to Multi Jet Fusion (MJF).

The paper provides an analysis of what parts make the most sense to re-design and what re-design strategy is best suited in each case. Two decision trees have been defined to help engineers and designers go through the analysis process in a systematic way.

The three re-design strategies that we've analyzed are: hollowed files, internal lattice structures and topology optimization. The factors considered in each of the strategies are part weight and cost reductions, the required time investment, the software needed to perform the re-design and the required part performance knowledge.

The characteristics of the different re-design strategies can be found in the following picture:

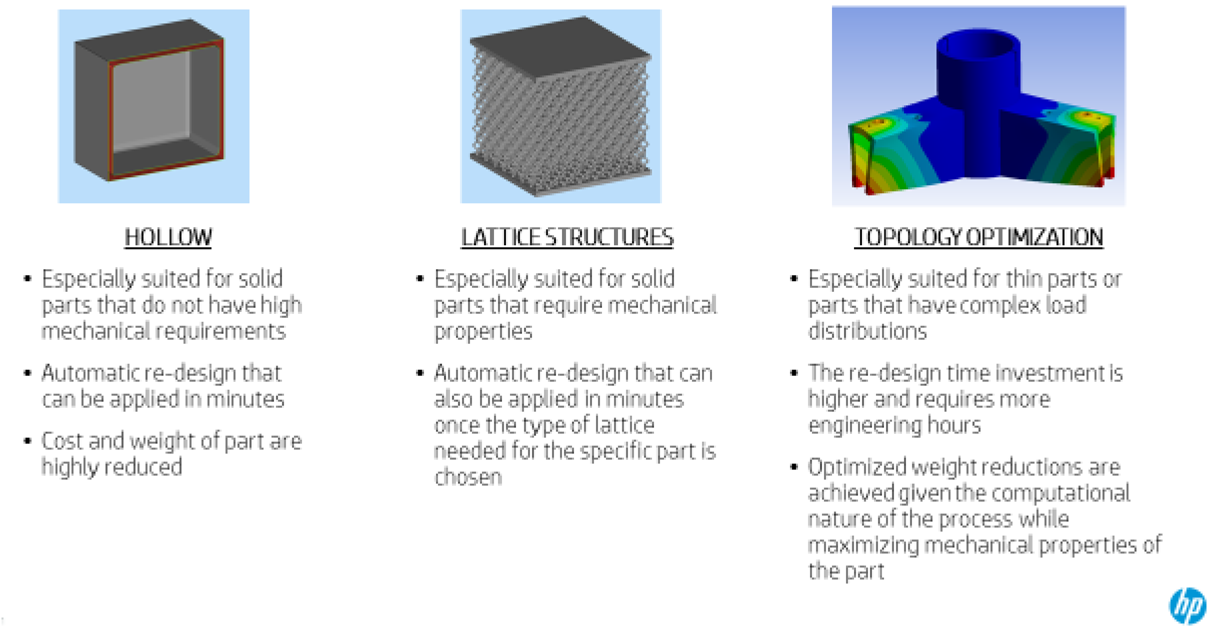


Figure 1: Main characteristics of the three re-design strategies analyzed

2. Introduction

The objective of this paper is to explore the limitations of existing manufacturing methods and show different re-design strategies for MJF that can help to provide added value in terms of cost and performance.

There are three waves of additive manufacturing technology adoption, as seen in Figure 2. Typically, companies start adopting additive manufacturing by direct part replacement. That is, taking an existing design file and printing it without any modifications. It might bring faster time to market and cost reduction in some cases, but it does not fully garner the advantages AM has over traditional manufacturing such as part combination, performance increase and personalization.

Figure 2: Three waves of additive manufacturing technology adoption

In direct part replacement situations, the analysis only considers cost per part comparison and, thus, breakeven curves. Although additive manufacturing might be the most economical solution for prototyping and short-runs, some of the analyzed parts will fall behind when doing this type of cost analysis.

Furthermore, designers always design with the manufacturing method in mind. To bridge the gap for existing designs, this paper is meant to provide a systematic process of adopting MJF's possibilities when changing your part's production from traditional methods to additive manufacturing.

Figure 3 shows how a list of potential MJF candidates can be analyzed and filtered. The re-design strategies proposed in the paper will help increase the number of parts that will pass the feasibility assessment (engineering analysis) and the economical assessment (financial analysis).

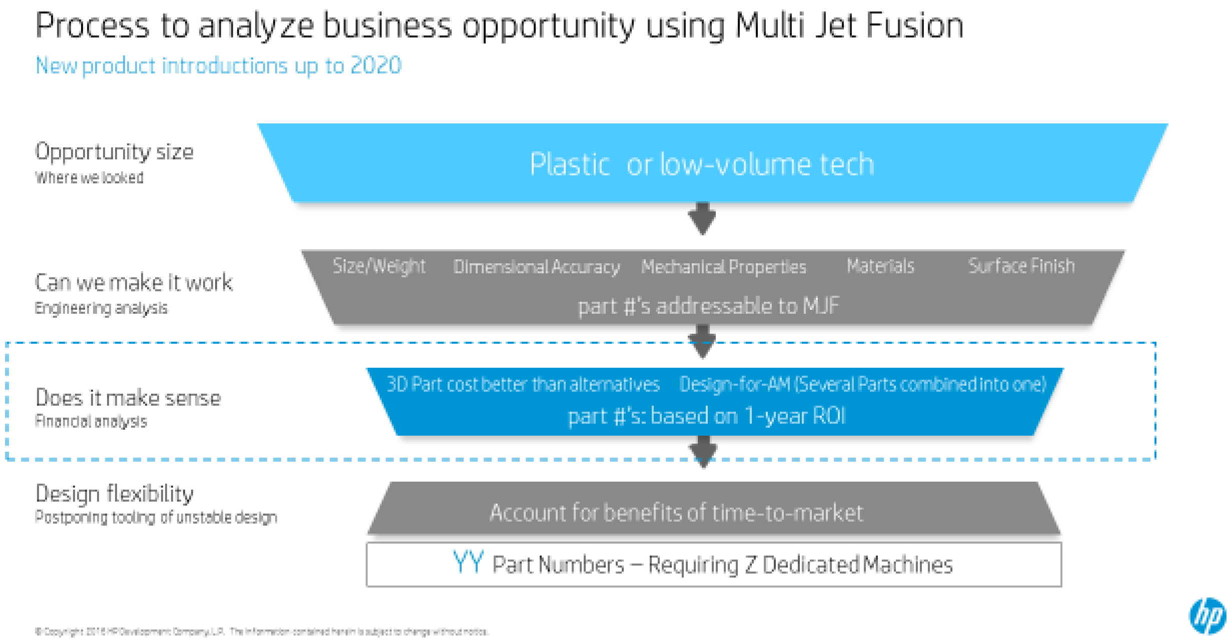


Figure 3: Recommended process for filtering for potential candidates for Multi Jet Fusion

3. Traditional manufacturing methods and potential applications for MJF

3.1. CNC Machining

CNC (computer numerical control) machining is a subtractive manufacturing technology that, starting from a solid block of material, uses different cutting tools to remove material until the desired geometry is achieved.

The advantages of this approach are high dimensional accuracy and material versatility but the technology significantly limits the geometries that can be manufactured.

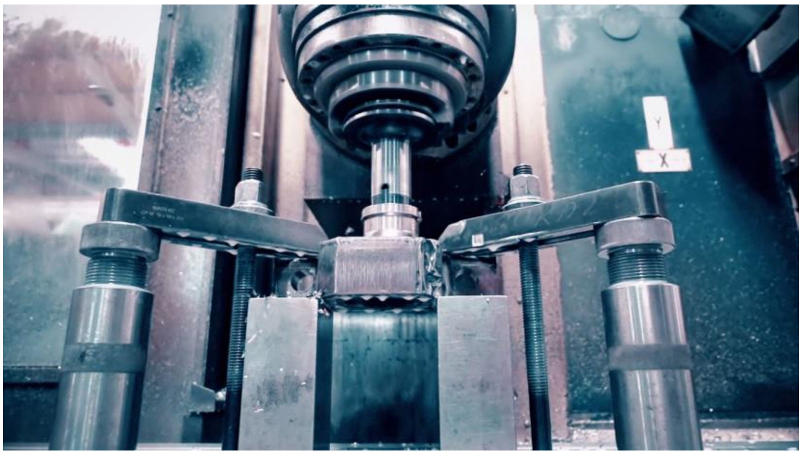


Figure 4: CNC machine in operation

To optimize cost, CNC machining does not rely on volume or material minimization, but rather on the reduction of machining operations. Therefore, an increasing design complexity is linked with a greater cost, which limits the use of this technology in certain applications.

In many cases, this is the best fitted technology to be complemented or substituted by additive manufacturing. Design freedom enables optimized parts that can maintain or improve functionality while reducing weight at no extra cost or even cheaper. For further information on transitioning CNC machined parts to Multi Jet Fusion, see the white paper *"How to complement CNC production with Multi Jet Fusion"* [1].

Typical applications produced by CNC are short-run productions of jigs & fixtures, machinery parts and end-of-arm tooling.

In the case of jigs & fixtures for the production line, reducing the weight can have a significant impact on the day-to-day operations of the factory, as it will improve handling. Design freedom will help optimize the space and bring more ergonomic tools [2] into the line, as well as enable the consolidation of multiple parts into one, reducing assembly operations. Printing the tooling also enables faster changes in the production line, agile manufacturing and inventory reduction. For further examples on these type of parts, see the whitepaper "*MJF manufacturing aids*" [3].

In the case of machinery parts, part combination and design freedom reduces assembly and can increase the performance of the overall subsystem (i.e. preventing leakages or creating internal cooling channels).

Lastly, for grippers, design freedom can bring more optimized end effectors that can better meet their functions. Moreover, reducing the weight of the grippers significantly impacts the performance of the robot by increasing its accuracy [4] and useful life.

The re-design strategies proposed below are especially aimed at reducing the cost per part and weight.

3.2. Injection Molding

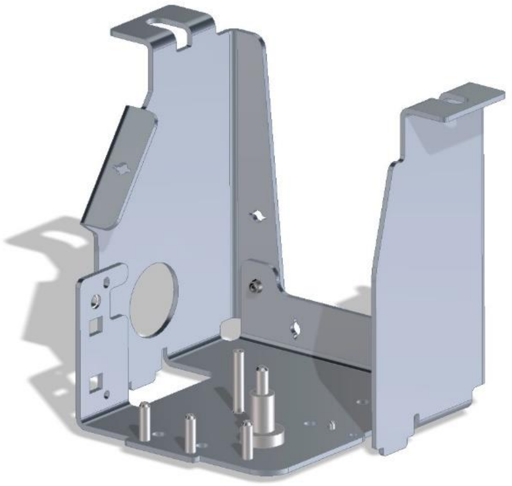
Injection molding is the process of creating parts by injecting plastic material into a mold. Typical applications produced by injection molding are machinery parts, external covers, housings and small plastic parts.

The advantages of this manufacturing method are dimensional accuracy, repeatability and low cost for medium-to-high production volumes. Specific surface finishes can also be achieved on different faces of the same part.

On the other hand, this approach requires a high initial investment to design and produce the mold. Once the mold is created, modifying the design is difficult and very expensive. The fact that the final part needs to be unmolded adds geometry limitations in terms of draft angles and can directly affect the cost of the mold. Moreover, injection-molded parts need to have walls that are consistent in thickness in order to avoid sinks. Complex features can be produced by MJF without affecting speed nor cost, which makes these geometry limitations the main driver behind choosing 3D printing in this area.

3.3. Sheet Metal

Sheet metal fabrication is a manufacturing method that consists of building parts by bending sheets of metal (usually steel or aluminum) until the desired geometry is achieved.



The technology severely limits the geometries that can be produced. These restrictions include walls that must be welded or riveted together, metal inserts to attach parts between them, constant wall thicknesses and impossible bending operations.

Due to the characteristics of this manufacturing method, the automatic re-design strategies proposed in this paper will not apply in most cases and, consequently, it is recommended to re-design the part for 3D printing manually.

Figure 5: Sheet metal part

4. Re-design method overview

The re-design methods that will be discussed are as follows:

1) Original parts
2) Hollowed parts
3) Lattice structures
4) Topology optimization

To characterize them and provide some selection criteria for each method, the following parameters will be tracked when comparing the different re-design methods proposed below.

1. Manufacturing cost

   Cost of the re-designed part after sand blasting and cost reduction versus the original non-redesigned part (in %).

2. Time required for design optimization

   Time required to re-design the part before sending it to print.

3. Part performance knowledge

   Depth of knowledge of the parts' function and the requirements needed to perform the re-design (fixation points, load distributions…).

4. Software required

   Specific additional software that is needed to perform the re-design that is not included in the standard HP offering.

5. Weight reduction

   Weight reduction between the re-designed part and the original part (in %).

In the sections below, the different re-design methods will be explained and summarized with a decision tree aimed at helping engineers decide which method to use in each case.

4.1. Hollowed parts

This method consists of hollowing a part through an automatic process. The advantages of this method are that the re-design is very fast and simple, and that it can significantly reduce the mass of the part; but it can also reduce the mechanical properties to the point that the part does not meet its requirements anymore. Therefore, solid parts that do not have high mechanical requirements are great candidates for this re-design strategy.

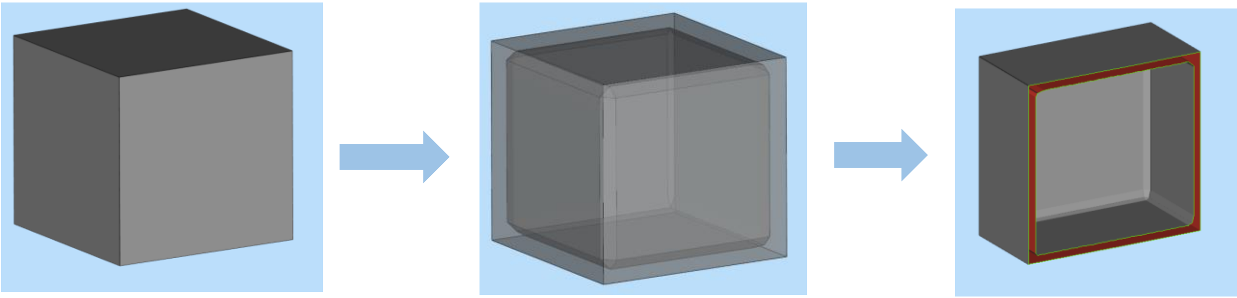


Figure 6: Step-by-step process for hollowing parts

Both CAD (SolidWorks [5], Inventor [6], Catia [7], PTC Creo [8]…) and STL-management software (Materialise Magics [9] or Autodesk Netfabb [10]) can perform this type of re-design automatically.

Given that mechanical properties can be diminished when hollowing parts, depending on the specific mechanical requirements of each part, there are other strategies to minimize this reduction.

For instance, when hollowing a part, the unfused powder can be kept inside. This way, the unfused powder acts as a reinforcement of the part while still reducing the cost and weight of the original solid part, and cleaning time, since the powder inside does not need to be removed. The reason behind the weight reduction is the difference between the fused powder's density and the unfused powder's density, which accounts for roughly half of the density of the fused powder. Furthermore, hollowing parts helps to remove thermal stresses caused by mass accumulation. Although there are no restrictions for printing dense parts, it might not be wise to do so, given the process definition and the thermodynamics involved.

If the part does not have strong mechanical requirements and/or it can be detrimental to the application to spill the unfused powder in case of rupture, then drainage holes can be added. For optimal powder removal, it is recommended to build at least two drainage holes with a minimum diameter of 5 mm in opposite faces of the part, as shown in Figure 7, to enable air flow within the part. Removing the powder from the inside will help you achieve maximum weight reduction but will increase operator cleaning time. In some cases (especially for jigs & fixtures), a wall can be removed, if it is not needed, for easier powder removal.

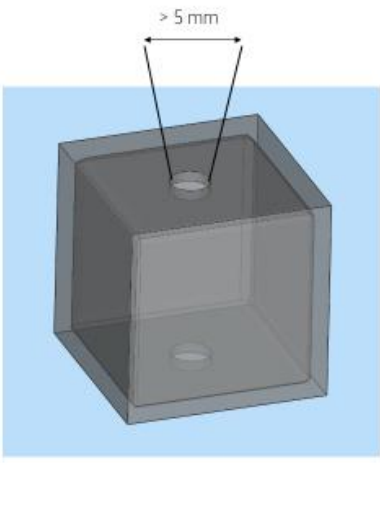


Figure 7: Drainage holes need to be added for powder removal

Regardless of keeping the unfused powder inside the part or not, the thickness of the walls of the hollowing operation is a parameter that needs to be chosen carefully, and the size and functionality of the part must be taken into account. For example, for a handle that will be used by an operator, greater thicknesses can be recommended to improve ergonomics.

To provide a reference measurement for wall thickness when hollowing parts, several cubes were printed, with wall thicknesses ranging from 0.75 mm to 2.5 mm, and with steps of 0.25 mm. The objective was to see which one would fit better in **a general example use case**.

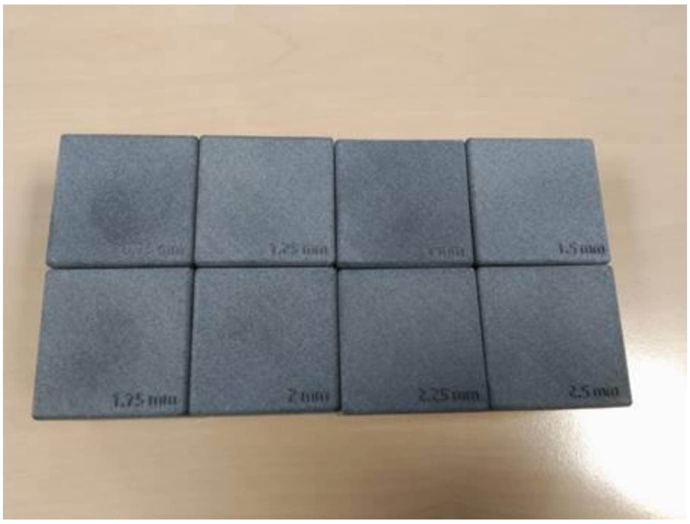


Figure 8: Printed hollowed cubes with different wall thicknesses

Two things were checked for all the cubes:

- **Compression deformation:** Parts that could be clearly deformed with the force applied with one hand were automatically discarded.

- **Handling analysis:** A manual test was performed to check the user experience of the parts. Lower wall thicknesses or cubes without unfused powder inside were found to induce a sensation of feeling weak, even though the parts might have met their requirements, so they were discarded too.

Because of this exercise, in general cases, the minimum **recommended wall thickness is 2 mm**, but for big parts, 2.5 mm will provide better performance. **The optimal value will need to be determined** considering the characteristics of each case. Add maximum thickness before moving onto lattice structures.

Cost reduction, when applying this re-design strategy, stems from the fact that less agent is used given a smaller area to fuse, thus less powder is fused, which can allow for bigger packing densities, and therefore, more parts in a build. For example, when hollowing our cubes, the use of agent was reduced by approximately 80%.

4.2. Parts with internal lattices

This method consists of hollowing the part and replacing the solid mass of the area inside it with a lattice structure. The advantages of this method versus just hollowing the part is that it retains most of the mechanical properties [11] of the original solid part while reducing its mass and, therefore, its cost. Also, this re-design is a fast process that can be automated, but the cost and weight reductions are not as significant as in the previous method.

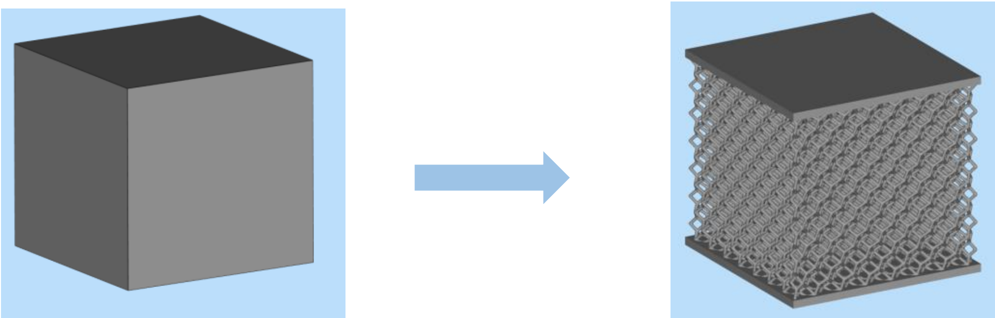


Figure 9: A solid part and one with lattice structures

STL-management software such as Materialise Magics [9], Autodesk Netfabb [12] and n-Topology [13] can let you apply this type of re-design.

Unfused powder can be kept inside of parts but the difficulty of removing it through a drainage hole when having a lattice structure inside is such that is usually not worth it from an economical point of view. Some lattice structures can even become impossible to clean through these holes. Therefore, it is recommended to leave the powder inside, or, in cases where it can't remain inside, remove one of the walls to clean the powder.

There are two parameters by which designers can fine-tune to meet the mechanical requirements of the re-designed part: wall thickness and the type of lattice structure used. The impact of the different wall thicknesses has already been explained in the previous section.

To choose the right type of lattice structure, there are three parameters to consider:

1. **Geometry:** The geometry of each cell of the lattice defines the load distribution. Lattice geometries can be isotropic or anisotropic. This allows the designer to introduce different local properties to the final part, depending on its desired performance.

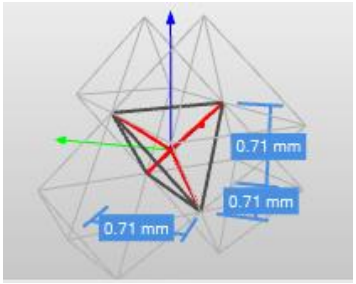
2. **Point distribution or cell size:** Point distribution determines the size of each lattice cell: the bigger the cell size given for a specific geometry, the lower number of cells needed for the same volume, and thus, the higher the weight/cost reductions, but also the higher the reduction in mechanical properties.

3. **Beam thickness:** Defines the thickness of the lattice structure. The thicker the beams, the better the mechanical properties, but the lower the cost/weight reductions.

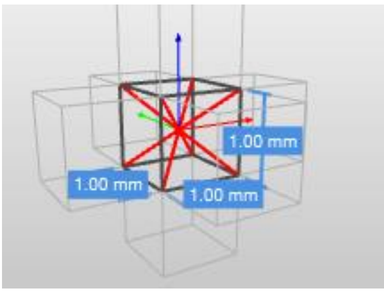
Further studies are being developed to determine the best lattice structures for specific cases but as a general reference, the same analysis as in 4.1 has been performed.

The variables considered in the study were:

1. **Geometry:** Geometries can be isotropic or anisotropic. Figure 11 shows a geometry with a high reduction in volume but with anisotropic behavior. As the intent of this study is to provide an automatic re-design method, only isotropic shapes have been considered. Figure 10 shows the two geometries that have been analyzed. Although these are two of the commonly used in the industry, this is only a tiny subset of all the potential geometries for lattice structures that are available on the market. The first geometry is based on a tetrahedral shape, and the second, on a hexahedron. For flat parts, honeycomb structures are also widely used.



Geometry 1



Geometry 2

Figure 10: Lattice structure geometries analyzed

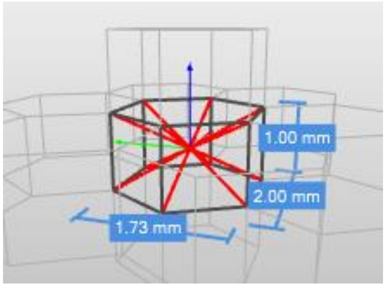


Figure 11: Example of anisotropic geometry

2. **Cell size:** Two cell sizes have been analyzed: 5 mm and 8 mm cells.

3. **Beam thickness:** Three beam thicknesses have been analyzed: 0.8 mm, 1.0 mm and 1.2 mm.

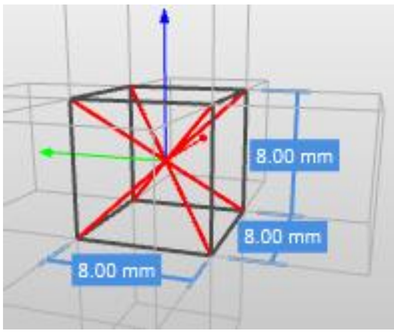
The following tables show the results of the test:

	Geometry 1					
Cell size (mm)	5			8		
Beam thickness (mm)	0.8	1	1.2	0.8	1	1.2
Full volume (cm³)	124.50	124.50	124.50	124.50	124.50	124.50
Lattice volume (cm³)	13.32	46.96	65.42	16.32	19.30	22.85
Volume reduction	89%	62%	47%	87%	84%	82%
Deformation to compression	>0.5 mm	<0.5 mm	<0.5 mm	>1 mm	>0.5 mm	>0.5 mm

	Geometry 2					
Cell size (mm)	5			8		
Beam thickness (mm)	0.8	1	1.2	0.8	1	1.2
Full volume (cm³)	124.50	124.50	124.50	124.50	124.50	124.50
Lattice volume (cm³)	17.88	27.23	38.56	17.548	21.15	25.488
Volume reduction	86%	78%	69%	86%	83%	**80%**
Deformation to compression	>0.5 mm	<0.5 mm	<0.5 mm	>1 mm	>0.5 mm	**<0.5 mm**

Table 1: Study of the different lattice structure geometries

For the parts with internal lattice structures as well, the deformation-to-compression force was applied using a dynamometer, at a force of 200N.



Geometry 3 had a slightly better mechanical performance than Geometry 1. Given the third geometry, the results show that the combination of a higher cell size with a thicker beam provides the best balance between mechanical performance and volume, and therefore the highest cost reduction.

Therefore, given the weight reductions and mechanical performances of the geometries tested, we recommend a **hexahedron-based pyramidal geometry (Geometry 2) with a cell size of 8 mm and a beam thickness of 1.2 mm** as the general lattice structure dimensions that should be applied.

Figure 12: Recommended geometry for general parts

However, each part needs to be studied particularly to determine the type of lattice that will better meet the performance of the part.

A step-by-step guide on how to create a lattice structure using different software can be found in 8.1.

Regarding the cost reduction achieved when applying lattice structures, typically, the use of agent decreases by 60-70%. Thus, **lattice structures are the best recommended re-design for solid parts**, as it is possible to get better mechanical performance, with a very similar cost reduction compared to hollowed parts.

4.3. Parts with topological optimizations

A topological optimization is a FEM (Finite Elements Method)-based process that finds the best distribution of material given an optimization goal and a set of constraints. It works by taking a solid block of material of any shape and removes material from it to minimize or maximize an optimization objective such as mass, displacement, or compliance, while satisfying a set of constraints such as maximum stress or displacement [14].

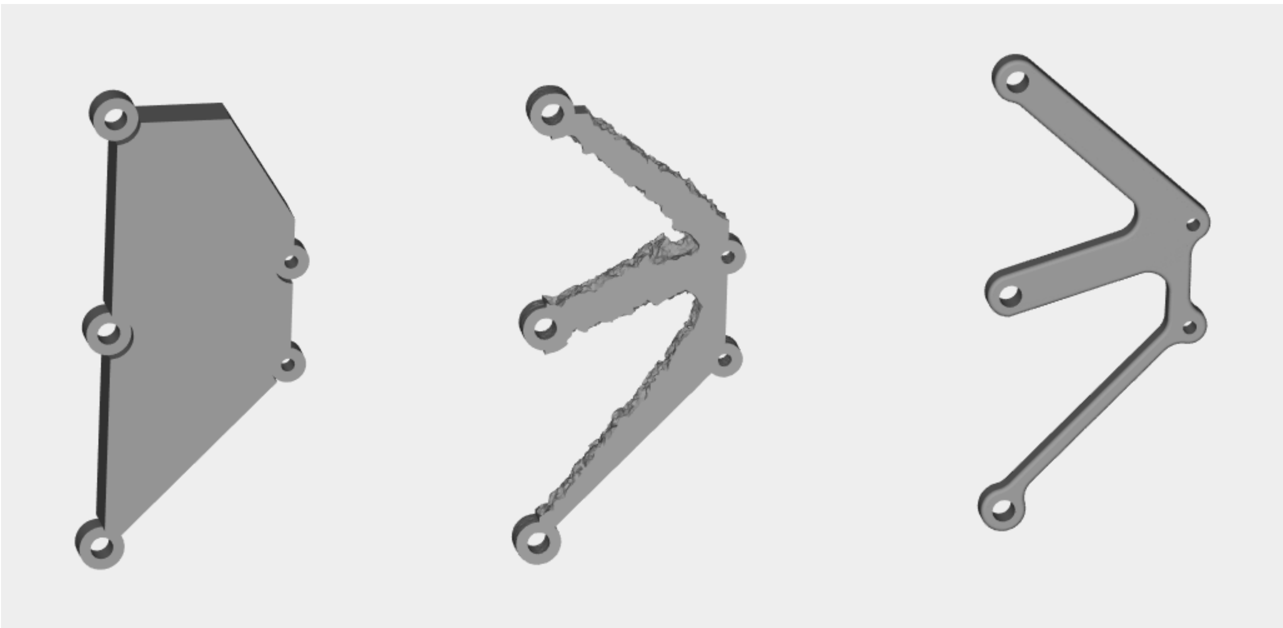


Figure 13: Step-by-step process for an optimization in topology

This process requires the designer to know a part's function and load distributions in depth, but provides the most optimized method of reducing weight, and therefore cost, compared to the original design. The time needed to apply this type of re-design is significantly higher than with the previous methodologies.

To topologically optimize parts, CAD software is required to modify their designs and FEM software is required to perform the topological optimization, which usually comes as a separate module.

The parameters needed to re-design a part using topological optimization are:

1. **Load distribution and part requirements**

2. **A topological optimization objective**, which can either be mass reduction or modifications of mechanical properties; or a specific combination of both [14].

A step-by-step guide on how to apply topological optimizations to a part can also be found in 8.2.

4.4. Decision tree

Starting from a list of potential candidates, the flow chart below will help you decide which parts make the most sense to re-design first. Among them, there will be a design strategy that will be better suited for each specific case, given the balance between cost/weight reductions, performance requirements, production volumes and required time investments.

It is difficult to give an order of magnitude for every variable as they will highly depend on the industry and specific application (i.e. the same production volume can be high for a certain application and low for others, just like with the size of the parts), but the knowledge of the re-design methods and their applicability will help customers to decide the right values to use for each of the parameters in each specific case.

There are many factors that can be considered in the decision of re-designing a specific part or not, but there are three aspects that conglomerate all the potential answers:

1. **Solidness of the part**

   In the case of very dense parts, the potential weight and cost reductions are very relevant when taking advantage of the design freedom of 3D printing and, therefore, these are the most suited parts to which to apply the re-design strategies presented above. For non-dense parts, the first two re-design strategies do not apply and the time invested applying topological optimization strategies needs to be justified by other parameters such as the size of the part or its production volume.

2. **Part Size**

   Reducing the cost and weight by a given percentage will always have a higher absolute impact on big parts, whether that is in terms of cost or performance increase (lightness in weight). In the case of small parts, the impact of the change needs to be evaluated in terms of production volume to justify the time invested in the re-design.

3. **Production Volume**

   High production volumes can make a re-design with lower cost/weight reductions have a significant impact and, therefore, re-designs need to be evaluated in these cases indeed.

The decision tree shown in Figure 13 can be used to evaluate the list of parts that are best suited for re-design first using any of the design strategies explained above. In the following chapter, a step-by-step, guided example of a series of jigs & fixtures for an internal manufacturing line are evaluated.

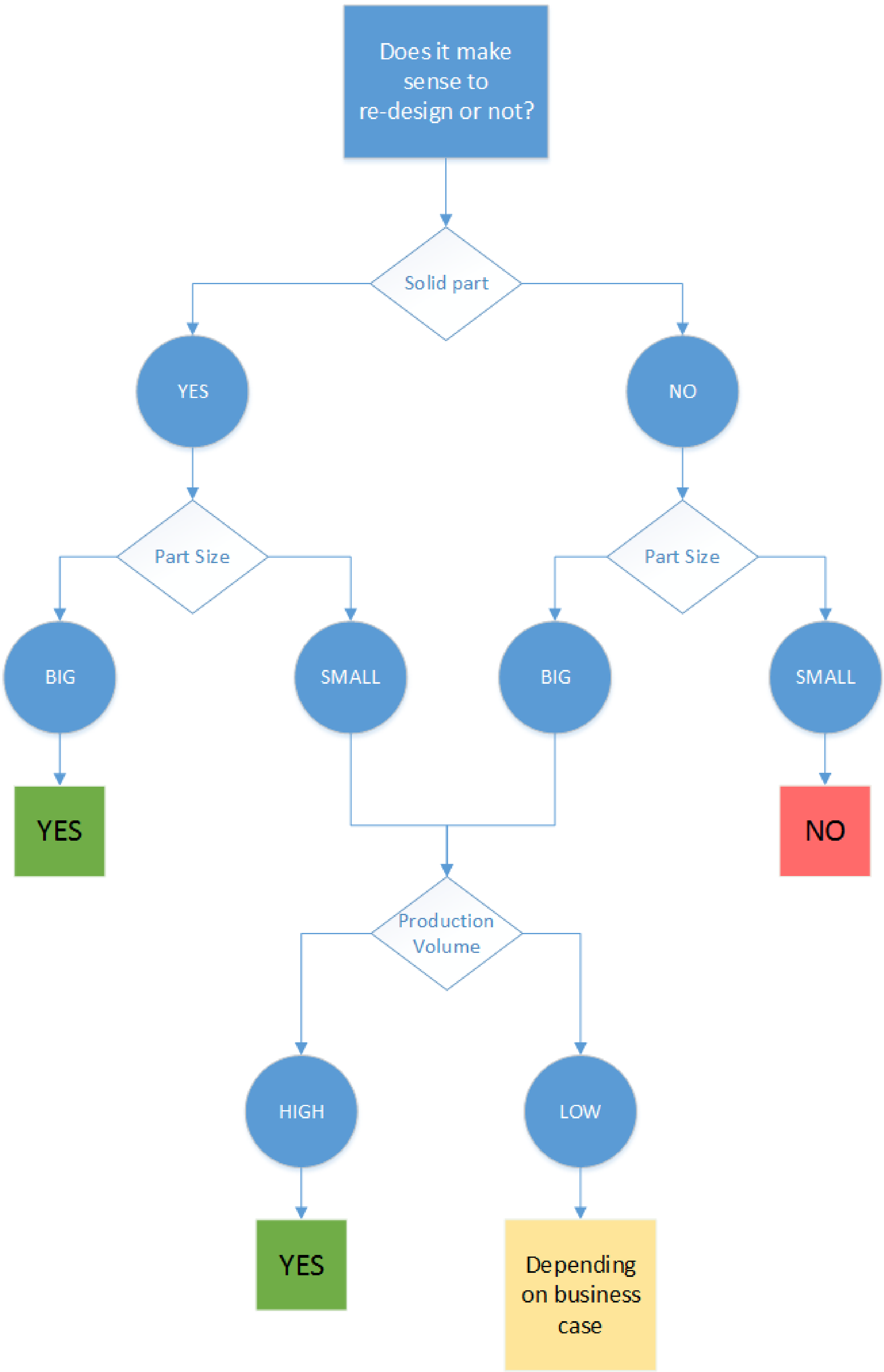


Figure 14: Decision tree for deciding whether to re-design a part or not

For parts that are worth re-designing, there are four aspects that will help you to decide on the best strategy:

1. Mechanical properties

   Hollowing strategies will most likely not be suitable when parts need to resist mechanical stresses. Therefore, it is important to understand the need (or lack thereof) for those requirements from the beginning.

2. Performance complexity

   Performance complexity refers to the complexity of the loads applied to a part, and thus, it only applies for parts that do need mechanical properties in the first place. In cases where load distribution is simple, it does not always make sense to apply topological optimization strategies because a manual re-design or an automatic lattice structure could be even easier and faster to apply and may result in the same levels of cost/weight reduction. However, each specific case needs to be analyzed. Optimizing topology is recommended when the complexity of a part is such that it is not trivial for the designer to find the best re-design of the part.

3. Solidness of the part

   Sometimes the re-design method that should be used will be determined by the solidness of the part. In the case of very dense parts, applying a lattice structure to or hollowing them will bring about the best cost/weight reductions, but it will not make sense to apply lattice structures or hollow parts when they are not dense. For them, a manual re-design or a topological optimization are the best suited re-design strategy.

4. Production volumes

   The time invested in the parts' re-design needs to be justified when analyzing the business case. Therefore, it is important to take this parameter into account as well when deciding the re-design strategy to use.

The following decision tree will help you to decide which re-design strategy is best suited for each specific type of part.

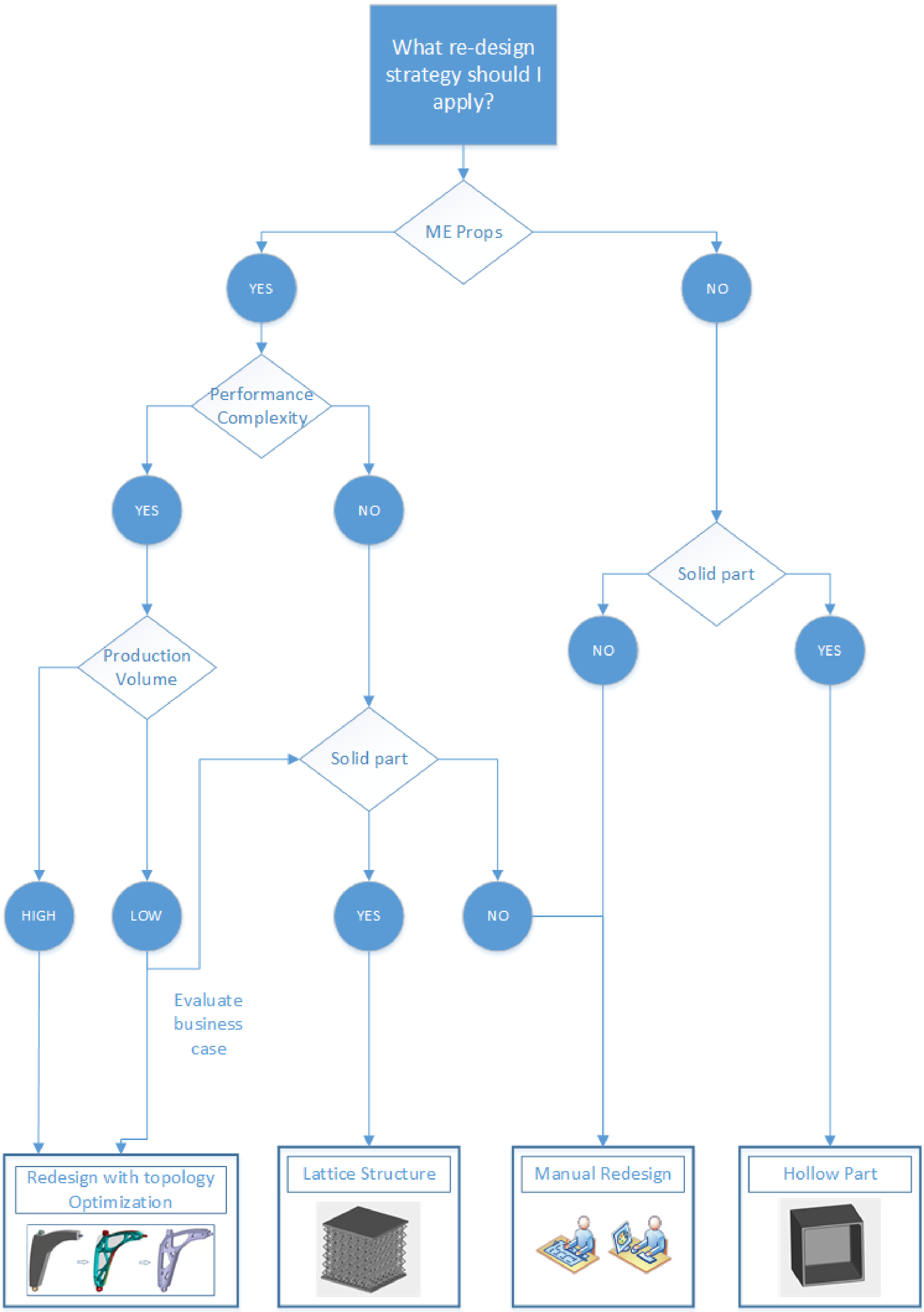


Figure 15: Decision tree for deciding on the best suited re-design strategy for each type of part

4.5. Qualitative comparison

The following table and chart qualitatively compare the three re-design strategies based on the criteria described at the beginning of the chapter.

CRITERIA / RE-DESIGN STRATEGY	Hollow	Internal Lattice Structure	Topological Optimizations
Manufacturing cost reduction	High	High	Very High
Time required for design optimization	Minutes	Minutes	Hours
Part performance knowledge	Basic	Basic	High
SW required	CAD or STL-management	CAD or STL-management	CAD + FEM
Weight reduction	High-Very High (depending on keeping the unfused powder inside or not)	Medium-High	Very High

Table 2: Summary of the different re-design methods

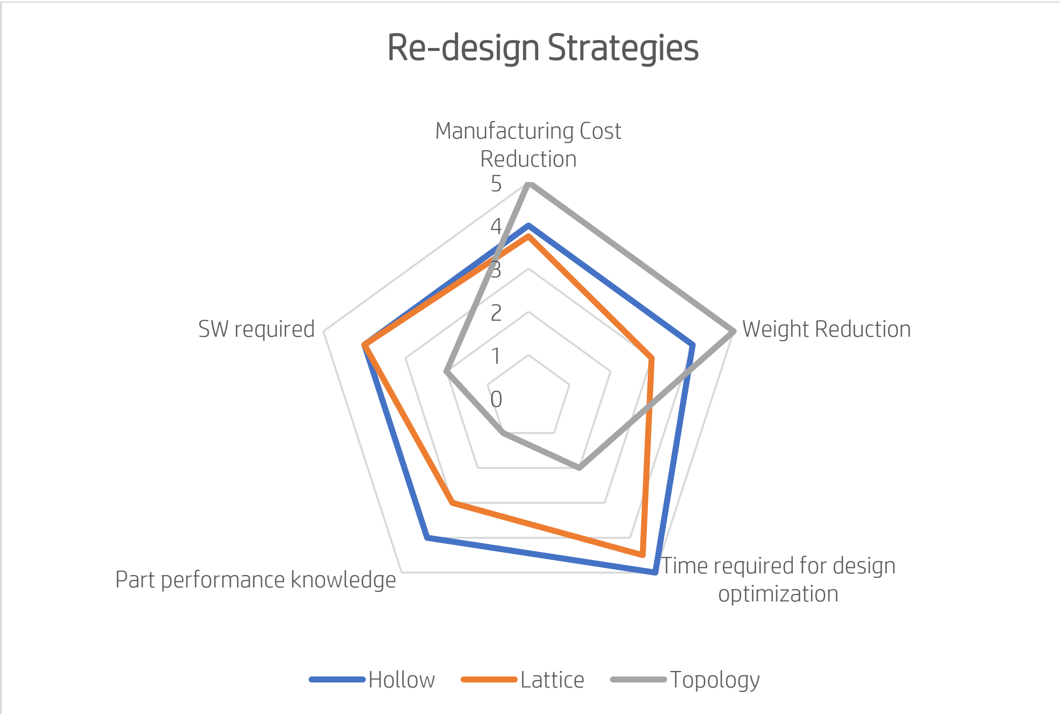


Figure 16: Radar chart comparing the different attributes of each re-design strategy

4.6. Automatic Product Parametric Design

Parametric design is the process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response

[15] [16]. The term *parametric* originates from mathematics (parametric equations) and refers to the use of certain parameters or variables that can be edited to manipulate or alter the result of an equation or system [17]. Software like SolidWorks, Catia, or Inventor can be used for that purpose.

Automatic product parametric design refers to the ability to automatically apply a given re-design method to different parts, given some variable parameters. This strategy is very well suited in cases where, for instance, a lattice structure has been determined and needs to be applied to a set of different parts with different geometries.

An example of this strategy being used can be seen in Figure 17, where a predefined lattice structure is applied automatically to customized insoles coming with varying personalized shapes.

Figure 17: Personalized insoles with automatically-applied lattice structures

Software that can be used for this strategy is, for instance, Grasshopper 3D [18], or Trinckle [19].

5. Case study results

This chapter is geared towards at using the decision trees and the different re-design methods explained above for real cases. Its intent is to show you the applicability of these decision trees and the results achieved with each re-design strategy in terms of cost/weight reduction and performance.

5.1. HP 3D Supplies production line parts

The intent of this example is to show, first, how the decision trees explained above can be used to classify parts worth optimizing or not and which design strategy to use for them, and secondly, the outcome of the applied re-designs.

Use Case

Application	Jigs & fixtures for the HP 3D Supplies production line
Current manufacturing method	Plastic CNC machining
Main reason to move to MJF	Cost, Low volume production

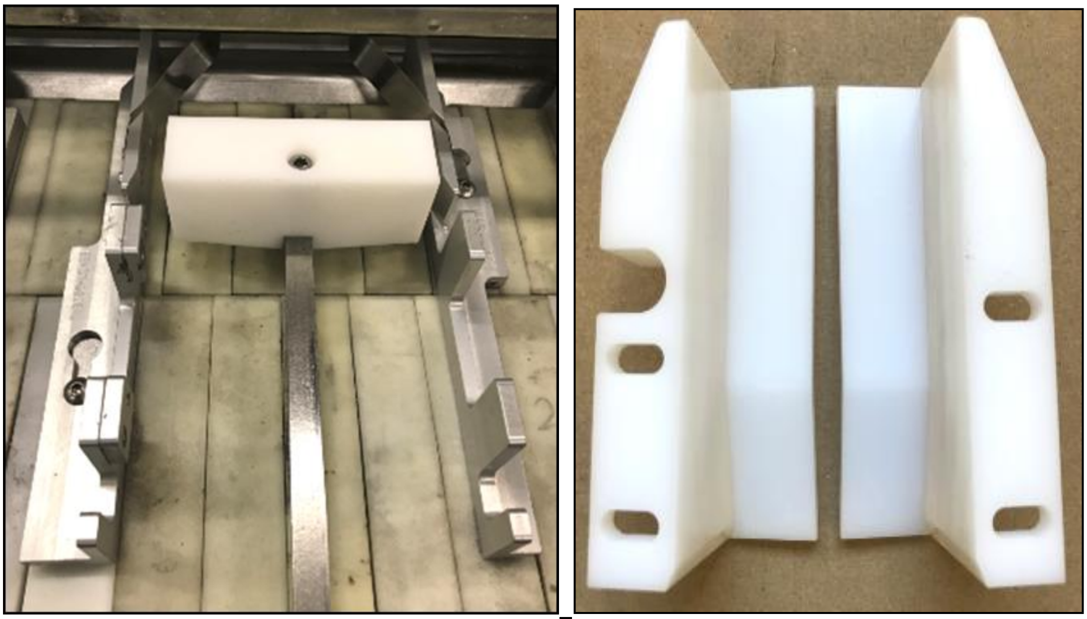
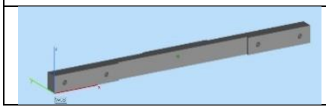
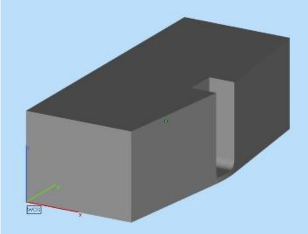
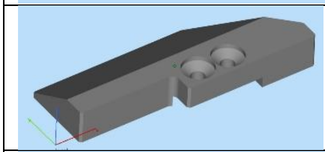
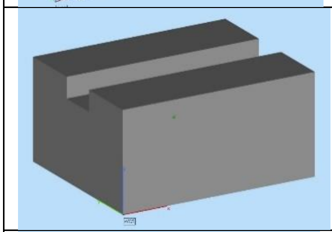
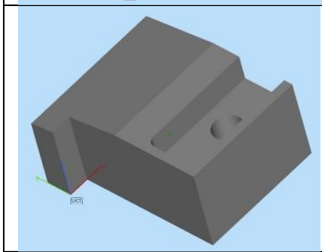
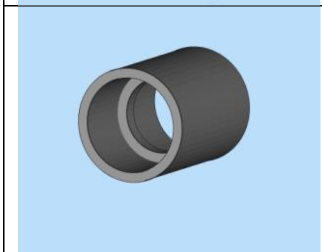
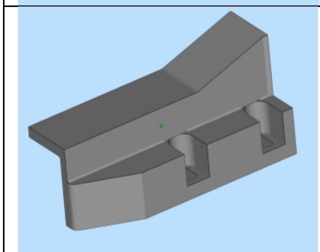
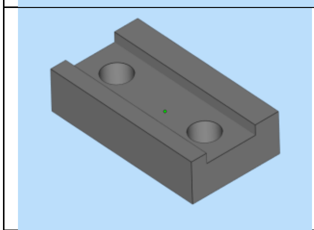


Figure 18: Plastic CNC machined parts in the HP 3D Supplies production line

Filtering for candidates

Part	Solid Part	Part Size	Production Volume	RE-DESIGN?
	Yes	Big	Very Low	YES

	Yes	Medium	Very Low	YES (positive business case)
	Yes	Medium	Very Low	YES (positive business case)
	Yes	Small	Very Low	YES (positive business case)
	Yes	Small	Very Low	YES (positive business case)
	No	Small	Very Low	NO
	No	Small	Very Low	NO
	Yes	Very Small	Very Low	NO (negative business case)

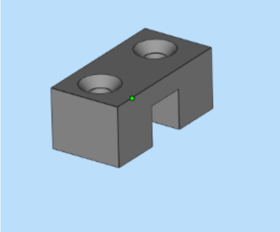
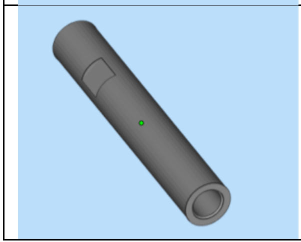
	Yes	Very Small	Very Low	NO (negative business case)
	No	Small	Very Low	NO

Table 3: HP 3D Supplies candidate filtering

As can be seen from the analysis, only 5 parts were considered worth optimizing. The others were discarded, mainly because they had very simple designs (like shafts) or were very small parts for which it was not worth investing the time needed to re-design.

The following table shows the thinking process for defining the best-suited re-design strategy.

<u>Re-design strategy</u>

All the parts that were chosen to be re-designed share the same characteristics as per the recommended re-design strategy.

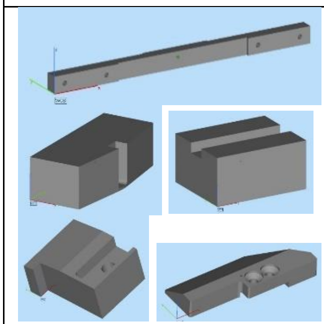
Part/s	ME Props	Performance Complexity	Solid Part	Production Volume	RECOMMENDED RE-DESIGN STRATEGY
	No	No	Yes	Very Low	**Hollowing**

Table 4: HP 3D Supplies re-design strategies

The recommended re-design strategy for the parts above is to hollow them. Depending on the usage of the part and the special conditions of the environment where it will be used, an internal lattice structure could also be used to make them stronger. Given that the required time investment for both re-design strategies is very similar and the cost reductions too, a study will be done using both options to further investigate their performance. In a coming update to this whitepaper, the mechanical performance of both versions of the parts in the production line will be revealed.

<u>Results</u>

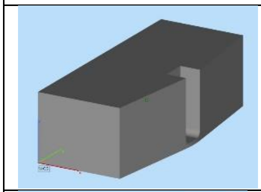
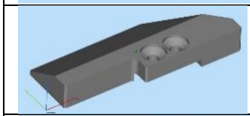
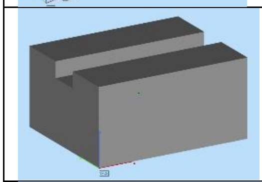
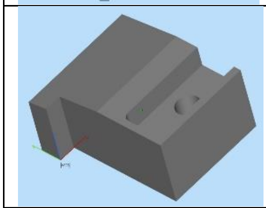
Part	Re-design Strategy	% Cost Reduction	% Weight Reduction
	Hollowing	52%	54%
	Using lattices	45%	45%
	Hollowing	68%	71%
	Using lattices	62%	61%
	Hollowing	30%	48%
	Using lattices	40%	40%
	Hollowing	63%	64%
	Using lattices	55%	56%
	Hollowing	42%	42%
	Using lattices	34%	34%

Table 5: HP 3D Supplies cost/weight reductions vs. original solid MJF part

*Disclaimer: All costs were calculated at 500 builds/year, a 5-year machine amortization, and with an average use of agent. This could vary depending on the print mode used.

5.2. An HP Processing Station part: The lance positioner

The intent of the following case study is to show an example of a part that is suited for re-design using topological optimization.

<u>Use Case</u>

Application	HP 3D Processing Station upgrade – Lance positioner
Current manufacturing method	Injection molding
Main reason to move to MJF	Performance, part combination

Re-design Strategy

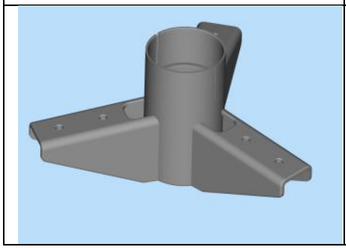
Part	Solid Part	Part Size	Production Volume	RE-DESIGN?
	No	Big	Medium-High	YES

Table 6: HP Processing Station lance positioner re-design feasibility

Apart from the increased performance of being able to combine multiple parts into one, the fact that it's a big part means that a re-design to reduce cost and weight has a significant impact on the bottom line.

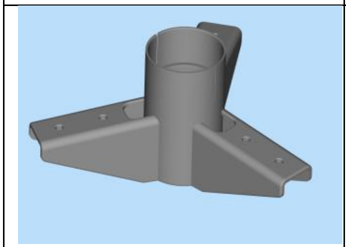
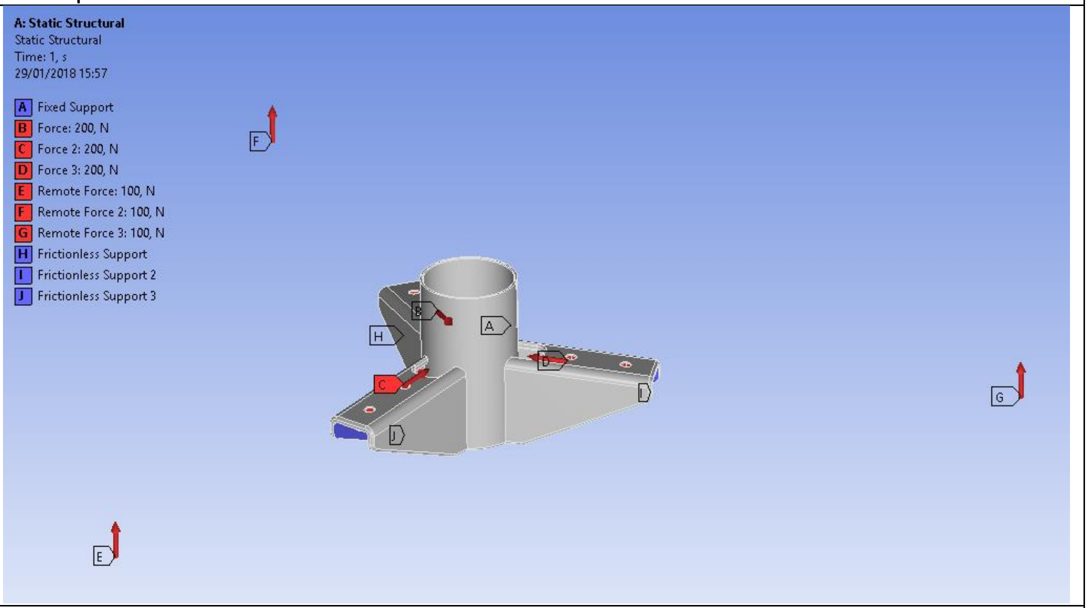
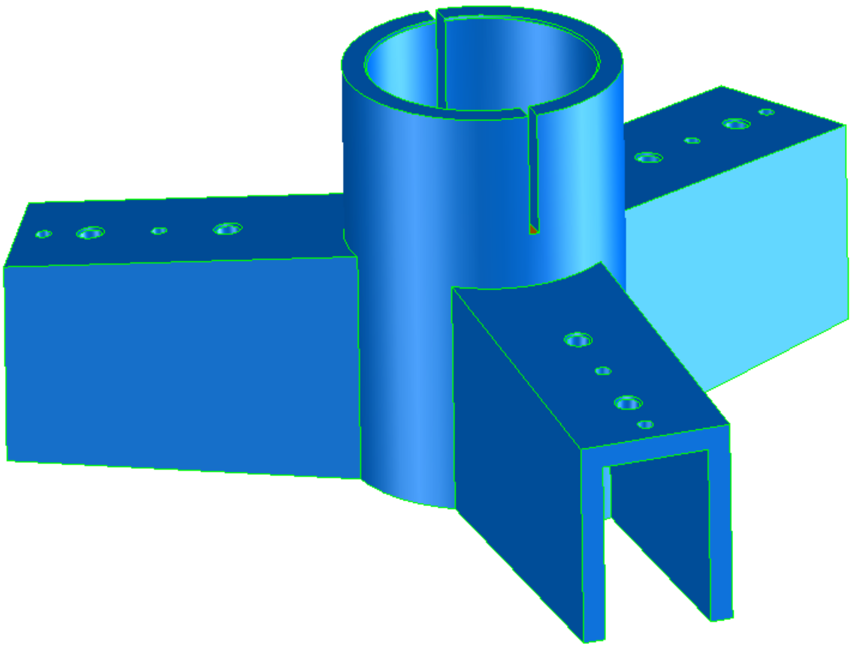
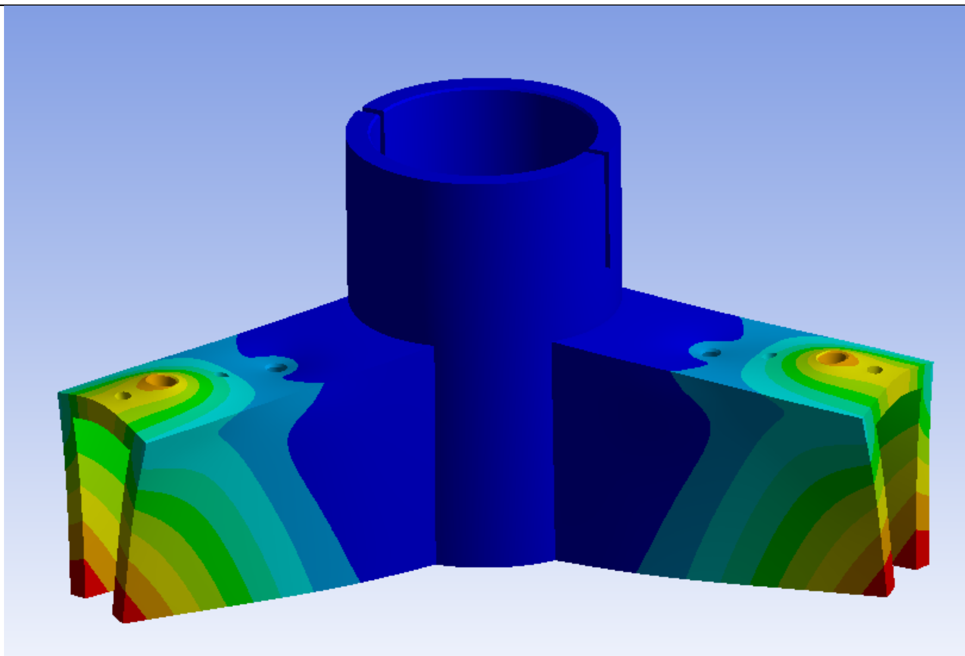
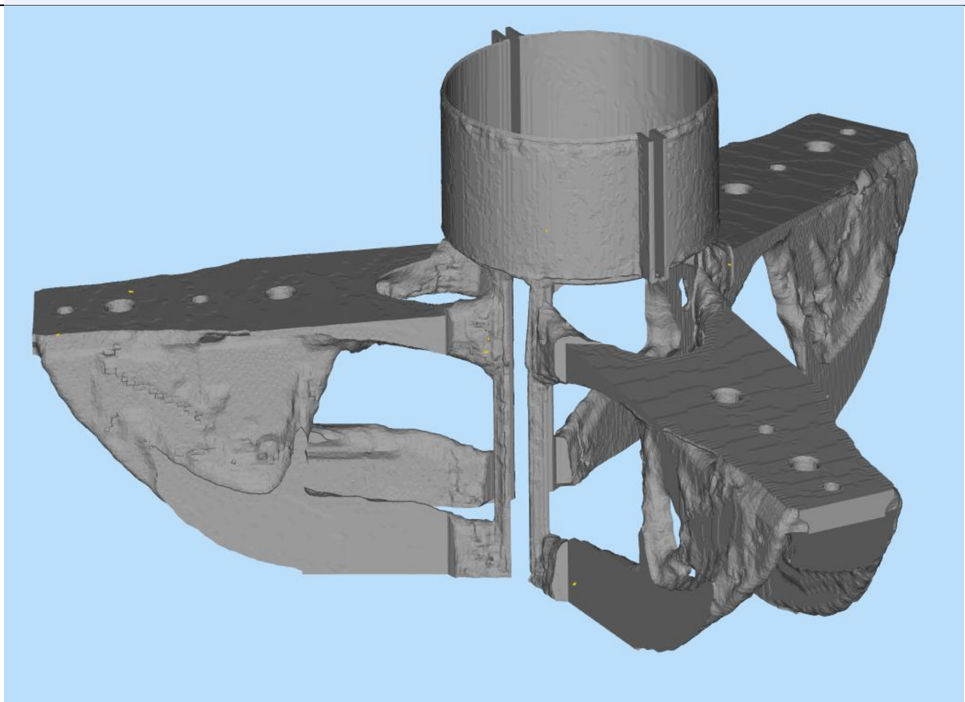
Part	ME Props	Performance Complexity	Solid Part	Production Volume	RECOMMENDED RE-DESIGN STRATEGY
	Yes	Yes	No	Medium-High	Topology Optimization

Table 7: Re-design strategy for the HP Processing Station lance positioner

Having thin walls makes this a poor candidate for applying any of the other re-design strategies. Besides that, the complex load distribution converts this part into the typical example where computer-based simulations help the designer create the most optimized design.

Re-design Process

Step	Description
1. Understand the performance of the part	
2. Create the design space volume	

3. FEM study of the design space	
4. Apply topological optimization	

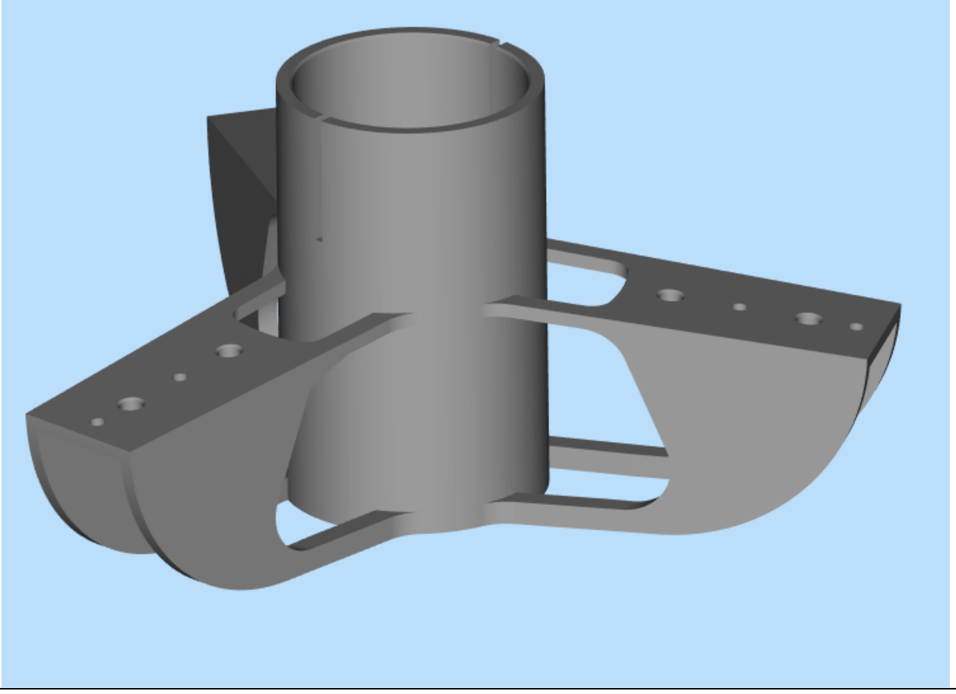
5. Finish the re-design	

Table 8: Step-by-step process of an optimization in topology

Instead of using software to smoothen the surfaces, the option of manual re-design following the topological optimization results was chosen in this specific case. The reason for that is that there were some features that were not represented in the FEM analysis that had to be included in the final design, such as the surfaces to handle the part with or wanting to add some structural features to make the part stiffer, visually.

Results

The FEM analysis of the re-designed part showed not only a cost and weight reduction, but also an even more significant increase in the mechanical performance of the part, as shown in the table below.

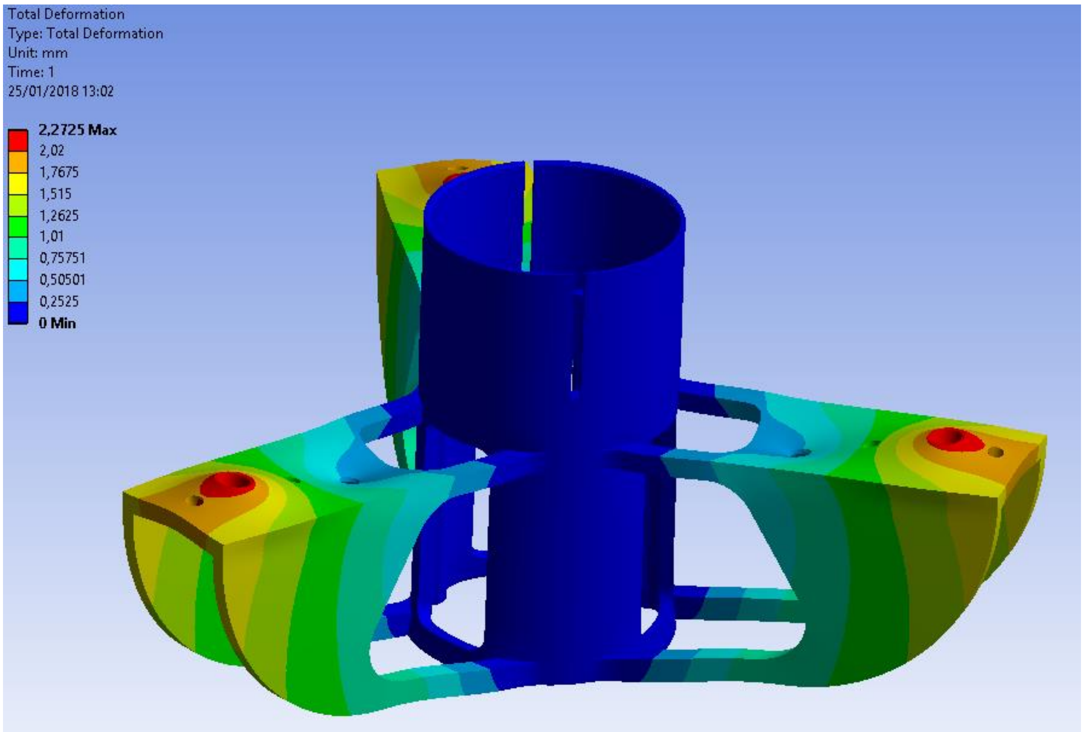


Figure 19: FEM analysis of the re-designed part

	Current part (IM)	Original part (MJF)	Optimized Part (MJF)	Re-design Reduction
Weight (gr)	-	103.07	93.6	9.19%
Max deformation (mm)	-	2.783	2.2725	18.34%
Max stress (Mpa)	-	185.18	118.63	35.94%
Cost ($)	23.00	25.64	24.18	5.69%
Cost of the mold ($)	40,000	-	-	-

Table 9: Results of the analysis of the optimized part

*Disclaimer: all costs were calculated at 500 builds/year, a 5-year machine amortization, and an average use of agent. This could vary depending on the print mode used.

The initial breakeven point between the IM part and the MJF one was 15,150 parts. Besides offering an 18% lower deformation and supporting 36% higher stress, the optimized part brings a more than doubled breakeven point of up to 33,900 parts. This is an example of how applying a re-design, that in this case took 10h of engineering time, can make a business case for a part and even increase its performance.

5.3. Sag Tubi's bending and control process

- Sag Tubi is an Italian tube bending company which bends and deforms tubes by performing many varied processes.
- Among the uses of these tubes are hydraulic systems for automotive applications such as intake, water, oil, cooling, brake, clutch and fuel lines, and structural parts such as body frames in a wide range of diameters from 4mm to 150mm.

- Their facility can produce 250,000 products per month and up to 2,000 different parts per month.

BACKGROUND

- Sag Tubi checks the bent tubes by using fixtures manufactured by CNC machining. The materials that are utilized are steel and aluminum.
- Some of the fixtures have been replaced by parts printed with Multi Jet Fusion, as they bring advantages to their processes which were not previously available.

REQUIREMENTS

The requirements for this precise application are:

- Product demand changes every week so rapid fabrication of control gauges for prototype construction is important.
- Rapid production of precise gauges in plastic reduces prototype lead time.

Why MJF?

- Prototypes can be constructed faster using printed gauges, without having to wait for the preparation of the long-term series production gauges.
- The geometric complexity is no problem. The possibility of full design freedom permits the construction of precision gauges for even the most complex of tube routings.
- Replica bent tubes can be reproduced with all their components assembled, just like the finished piece.

5.4. Gripper System

As a part of the German government's initiative to support industrial development, a program was set up by the government in Baden-Württemberg together with engineering and technical schools and industry leaders. The "Lernfabrik 4.0" ("Learning Factory") is an automated production line, based on real equipment provided by Festo Didactic [15], which will be used to educate and train students on the challenges and opportunities coming in the era of Industry 4.0.

Figure 20: Learning Factory at the Philipp-Matthäus-Hahn-Schule Gewerbliches Schulzentrum Balingen school *[16]*

The part analyzed below is part of this assembly line in the Philipp-Matthäus-Hahn-Schule Gewerbliches Schulzentrum Balingen School facilities. The student Simon Wäschle manually re-designed this part for 3D printing by combining multiple parts into one and by taking advantage of the material reduction possibilities. The function of the part is to act as an end effector in this educational production line.

The intent of this example is to show a case where a different re-design strategy from the ones seen above would be the best suited.

<u>Use Case</u>

Application	Gripper system assembly for an automated production line
Current manufacturing method	CNC machining (aluminum)
Main reason to move to MJF	Performance, part combination

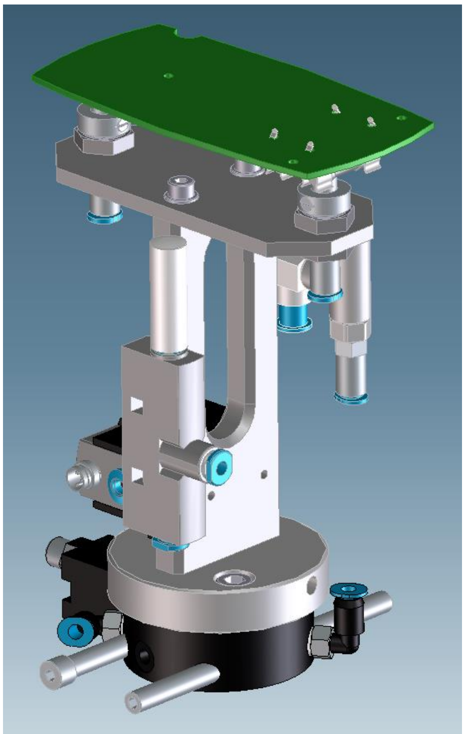


Figure 21: Original design for CNC machining

Re-design Strategy

Part	Solid Part	Part Size	Production Volume	RE-DESIGN?
	No	Big	Low	Depending on the business case

Table 10: Re-design feasibility for the gripper system assembly

For thin parts like this one, where the original design was based on thin (~5 mm) aluminum plates, the only re-design strategies that make sense are optimized topologies and manual re-design. The reason behind re-designing this part was to reduce the complexity of assembly and to combine all the structural parts into one. Therefore, it made sense to take advantage of doing that and thus re-design it for MJF.

Part	ME Props	Performance Complexity	Solid Part	Production Volume	RECOMMENDED RE-DESIGN STRATEGY

	No	No	No	Low	Manual re-design

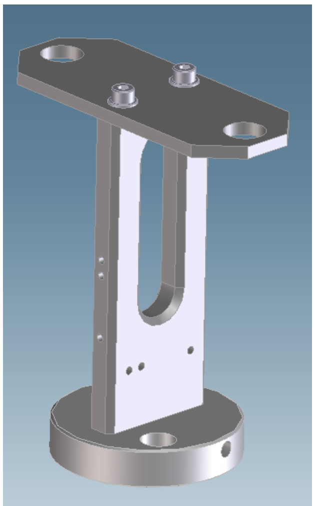
Table 11: Re-design strategy for gripper system assembly

As the part does not have strict mechanical requirements and only should support its own weight (plus a few grams), the recommended re-design strategy would be to manually re-design it for Multi Jet Fusion.

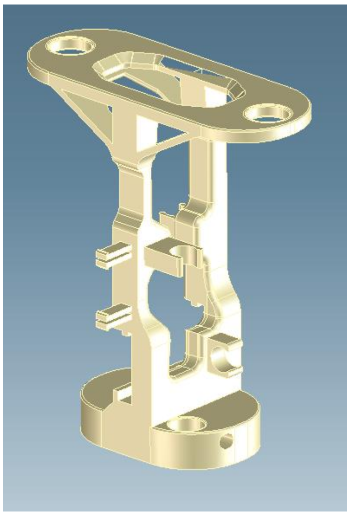
<u>Results</u>

Version 1: Part combination of 3 machined parts and 4 screws into 1 part.

Version 2: Manual optimization of the design to reduce material consumption and add features to optimize the assembly process.



Part combination



Manual re-design optimization by Simon Wäschle

Figure 22: Optimized design for Multi Jet Fusion

Printed part photo

5.5. FitStation

The objective of this example is to show how parametric design can be used to automatically apply a predefined lattice structure into a series of unique parts and modify their designs to adapt to certain parameters.

FitStation is an end to end footwear solution powered by HP. FitStation captures 3D scans of your foot, pressure measurements and gait analyses, identifies your unique path of motion and builds your Kinetic Profile. It then uses that data to create individualized products designed specifically for you [20].

Parametric design is used to modify the design of the insole given the input of various parameters coming from the 10 zones of the foot that are analyzed. Figure 24 and **Error! Reference source not found.** show an example of how predefined geometries (bottom ribs) are applied automatically given specific data parameters.

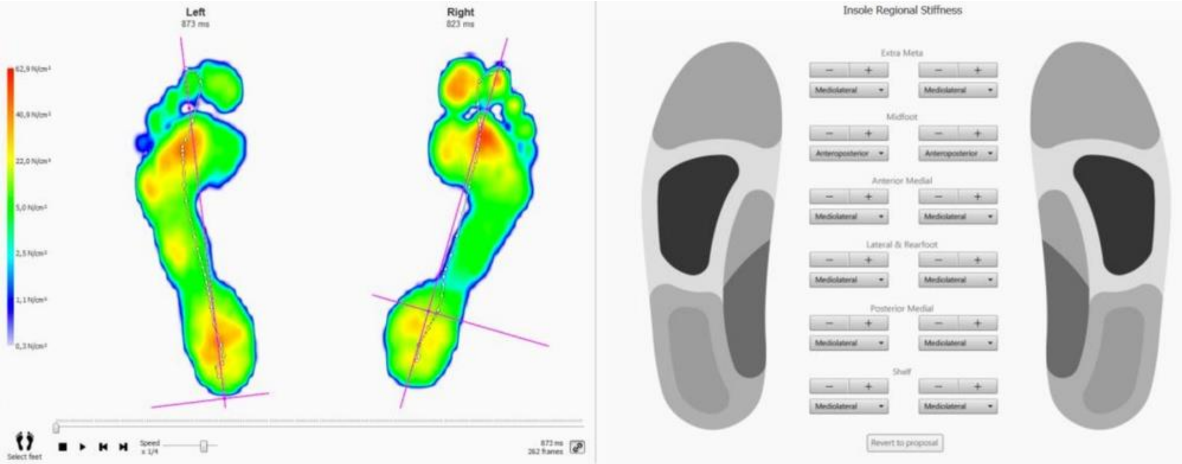


Figure 23: Pressure analysis and analyzed zones

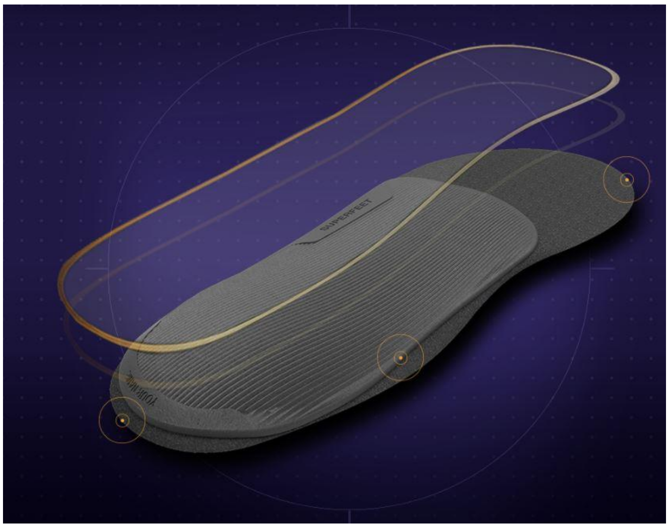


Figure 24: ME3D insole with personalized rib design

6. Conclusions

One of the main advantages of additive manufacturing is design freedom. By embracing it, designers will no longer have to think about tooling or machining constraints. However, as it has been explained here, parts would need to be re-designed with this freedom in mind to achieve the benefits in terms of cost, weight reduction and performance. This paper has discussed three different automatic re-design strategies that can be used to add value to parts designed for Multi Jet Fusion, and has helped to explain how to filter for potential candidates for MJF.

The main results of the investigation can be summarized in the following points:

- The **re-design decision trees** presented in this whitepaper will help your teams filter through the candidates to be 3D-printed and assess the recommended re-design strategy for each part.
- **Big, solid parts** are great candidates for which to apply re-design strategies.
- Considering the low time investment required to apply the re-design, hollowing parts or creating internal lattice structures results in **high weight/cost reductions vs. invested re-design time**. However, these strategies can only be applied to dense parts.
- **Lattice structures** are applied especially when dense parts require mechanical performance but have a very similar cost reduction as hollow parts, which makes them a **very recommended re-design strategy to maintain sufficient mechanical properties and obtain high cost reductions**.
- Topological optimization methods provide the most **optimized cost/weight reductions while maximizing the mechanical performance of a part**, but require a significantly higher investment of time.
- For thin parts, topology optimization is the only re-design strategy that can be used and the time investment needs to be justified by the production volume (business case) or by the performance increase that can be obtained.
- **Wall thicknesses lower than 2 to 2.5 mm** are not recommended when hollowing parts. The recommended wall thickness will depend on the specific function and size of each part.
- Out of the three lattice geometries analyzed in this paper, to achieve the best balance between cost/weight reduction and mechanical performance, the recommended geometry is the **hexahedron-based pyramid (Geometry 3) with a cell size of 8 mm and a beam thickness of 1.2 mm.**
- Although there are no printing limitations for the parameters analyzed (i.e. dense parts), it is wise to re-design the parts to **achieve the best part quality**. The throughput when printing massive parts can be **limited by the packing density limit**. Thus, these re-design strategies will also help maximize the productivity of your printer.
- **Automatic product parametric design** can help to automate a re-design and adapt the resulting outcome to a series of input parameters.

The following chart provides a high-level summary of the balance between cost/weight reduction and mechanical performance for the analyzed re-design strategies.

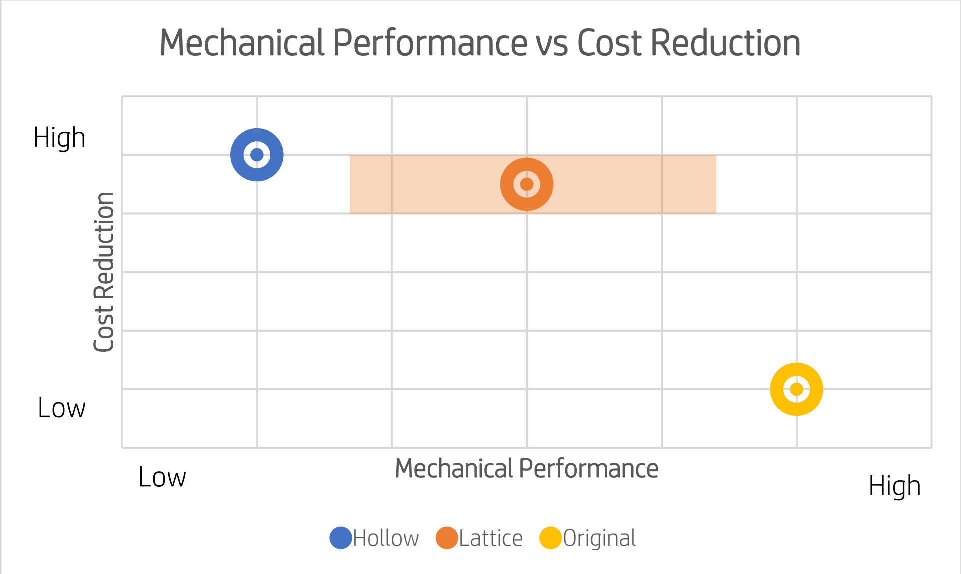


Figure 25: Mechanical performance vs. cost reduction balance for each re-design strategy

Topology optimization is a special case that needs to be studied for each part because the cost reduction and the mechanical performance will depend on the characteristics of the part and the objective of the topological optimization.

7. References

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8. Appendix 1

8.1. Lattice structures: A step-by-step guide

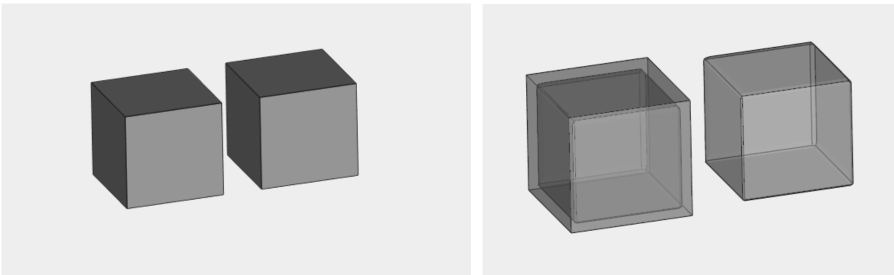
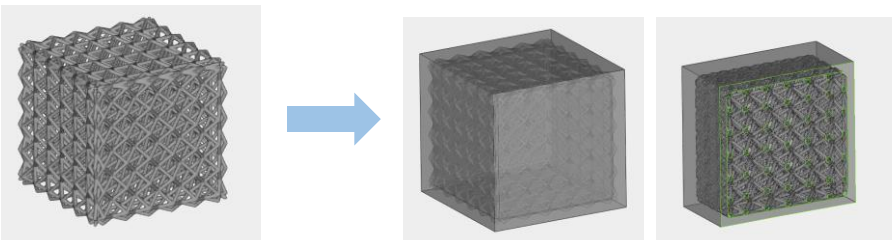
Step	Description
1. Define outer shell	There is software capable of performing this operation automatically by choosing the outer shell thickness, the detail size and its direction. Alternatively: - Create a duplicate of the part [17] - Hollow the part twice with different wall thicknesses such as 2.5 mm and 2.00 mm - Keep the outside shell for the 2.5 mm wall part - Keep the core for the 2.00mm wall part. This is the part that will be converted into lattices. - The difference between lattices will ensure a good intersection between the lattice structure and the outside shell. 
2. Choose the structure and create the lattice	There is software available that can apply pre-defined structures to the volumes, along with cell size, and sometimes, beam thickness. In case the software cannot do it automatically, convert the core into a lattice structure and merge both parts (the outside shell and the lattice structure). The most important thing is to know the characteristics desired of the final part to be able to choose the right lattice structure. 
3. (Optional) Add drainage holes	In case the powder needs to be removed from the inside of a part, the user can add drainage holes for that purpose.

Table 12: Step-by-step lattice structure process

8.2. Topological optimization: A step-by-step guide

Step	Description
1. Understand the performance of the part	Load distribution, operation, requirements, support points, etc.
2. Create the design space volume	Topological optimization works by removing material until a part reaches the minimum volume necessary for fulfilling a given objective. Therefore, to take full advantage of the process, it is necessary to create a solid that contains all the required features of the part (interfaces with other elements, mainly) and that fully occupies the volume available.
3. FEM study of the design space	A mechanical analysis is performed to make the topological optimization. All the part's loads must be included in the study. There is software that allows you to separate these loads into different performance scenarios.
4. Apply topological optimization	The process is automatic but needs to have a specific topological objective, set by the designer/engineer. The objective can either be reducing mass, keeping mechanical properties or a combination of both. Software allows users to decide the level of reduction in volume, once the optimization has been done. Note: There is software where steps 3 & 4 are performed together.
5. Finish the re-design	The result of the topological optimization is a non-elegant part that must be refined. Depending on the software used, there are two options: a. Smoothen the resulting part: Using smoothening tools that allow you to refine the final geometry until it becomes an exportable part. b. Manual re-designs: Manually re-design an original part using the results of our topological optimization study as your design guidelines.

Table 13: Step-by-step topology optimization process