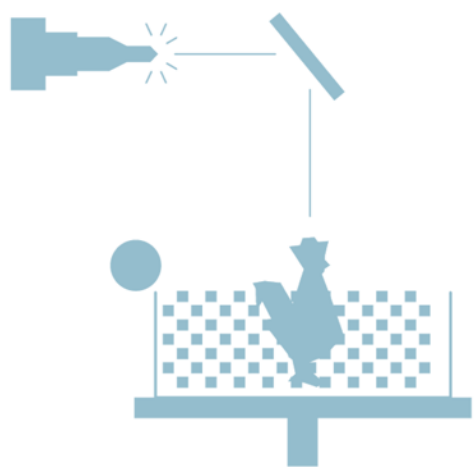


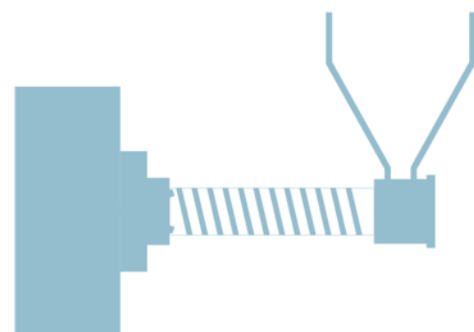
A SCULPTEO GUIDE

TO COST EFFICIENCY THROUGH SHORT SERIES MANUFACTURING



3D PRINTING

VS



INJECTION MOLDING

HOW SCULPTEO'S BATCH CONTROL 3D PRINTING COMPARES TO INJECTION MOLDS

INTRODUCTION

“Ordering multiple objects directly on our website turns 3D printing into a real manufacturing solution. By making it cost-effective for people to order higher volumes, Sculpteo is taking 3D printing beyond prototypes and on-demand manufacturing and into mass-production.”

- *Clément Moreau, Cofounder & CEO of Sculpteo*

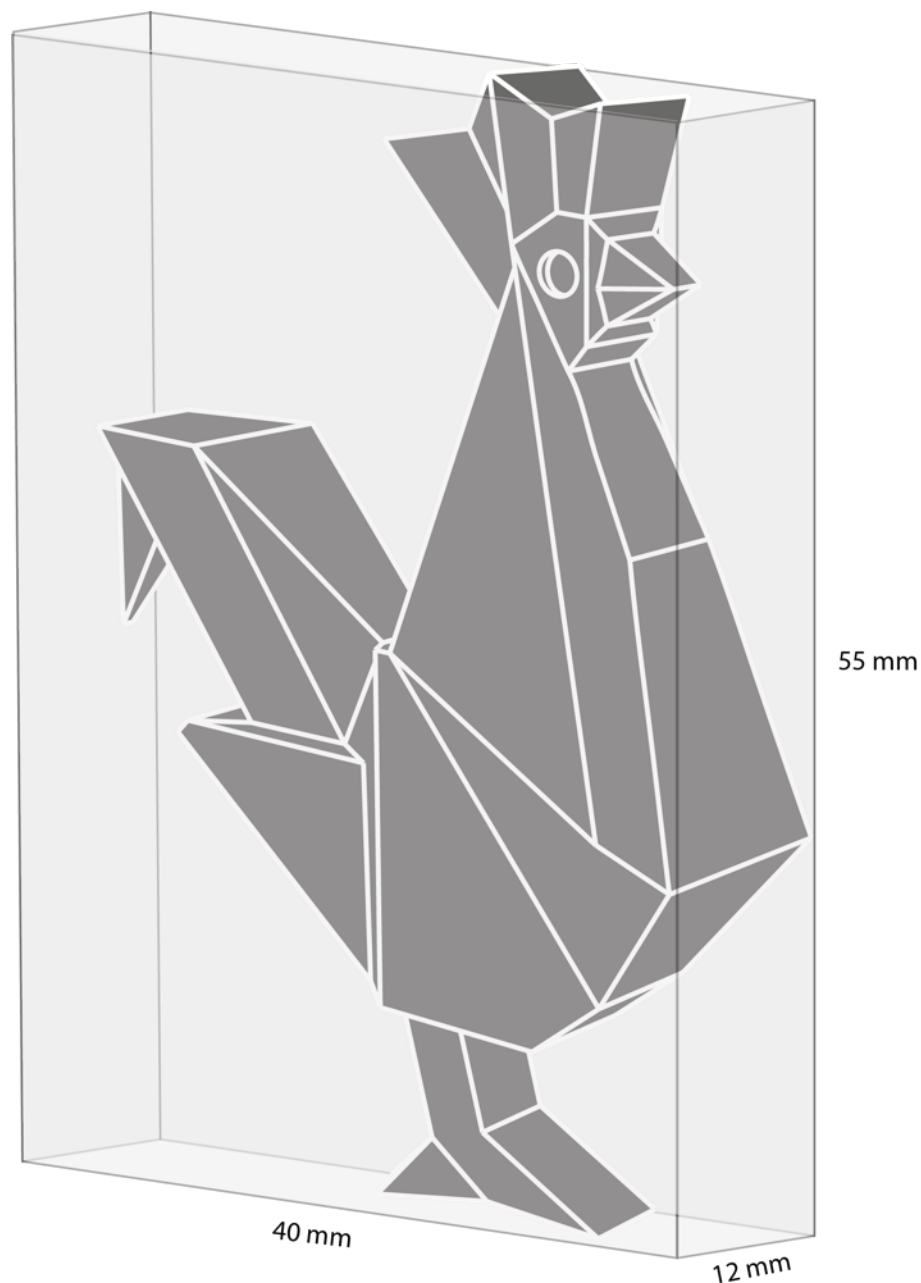
In the spirit of Mr. Moreau, the subsequent study was conducted to demonstrate the competitive nature of 3D printing as a manufacturing alternative to injection molding for small volume manufacturing runs. Cost data was collected from a series of injection molding vendors for parts of varying complexity and size. This data was then compared to the 3D printing production cost using the “Batch Control” feature for Selective Laser Sintering (SLS) offered by Sculpteo. In the context of this data, this report aims to answer the following question: “Compared to injection molding, when is 3D printing a cost-effective manufacturing method?”

The first step in answering this question is to address the material properties of parts manufactured via SLS compared to those of injection molded parts. A demonstration of the tensile strength of SLS parts compared to injection molded parts is presented in CHAPTER 1. CHAPTER 2 defines the cost-efficacy study by comparing cost estimation data for injection molding and 3D printing of five unique parts. CHAPTER 3 determines the influence that the size of an object has on the price of a 3D printed part versus that of an injection molded part. The final study is presented in CHAPTER 4, where the influence of an object’s complexity on the price of the part is examined for both 3D printing and injection molding.

Based on these studies, a convenient infographic summarizes the data into an easy reference tool for helping to decide if 3D printing is the best option for your small volume manufacturing requirements.

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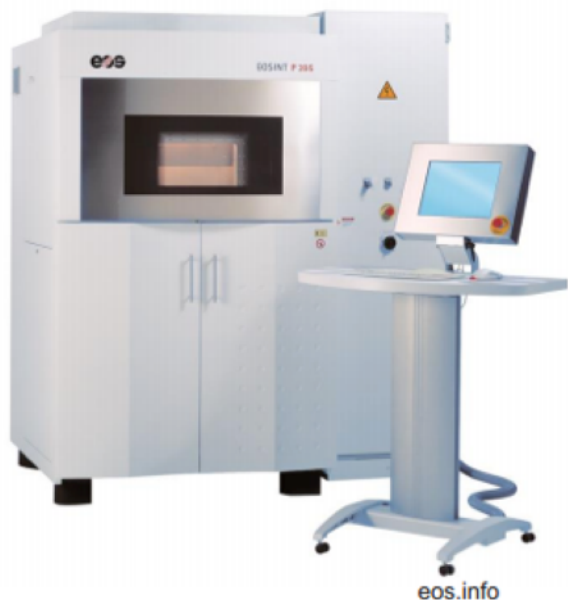
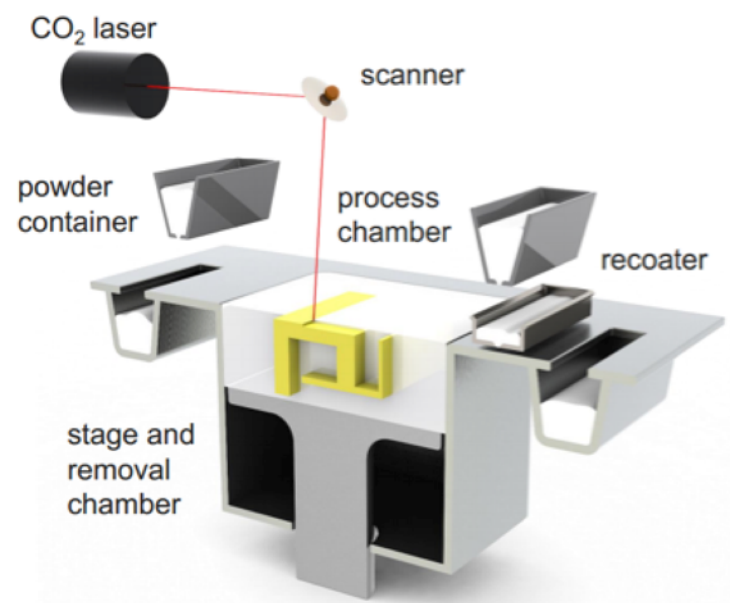
1 SELECTIVE LASER SINTERING – MATERIAL CONSIDERATIONS

Parts manufactured via 3D printing are often considered to perform poorly as compared to their injection molded counterpart. Therefore, before 3D printing can be confirmed as a viable method for manufacturing, it must be confirmed that the mechanical properties of 3D printed parts compare favorably to parts produced through injection molding. In the following investigation, the tensile strength of parts produced by the 3D printing (or Additive Manufacturing) method called Selective Laser Sintering is examined.

SELECTIVE LASER SINTERING (SLS)

SLS is an Additive Manufacturing method that uses a powder bed fusion process to build 3D parts. Below is a diagram of the process.

Powdered polymer build material, typically nylon, is transferred from containers holding fresh powder onto the build stage in the process chamber with a recoater tool. A laser then selectively scans the thin layer of powder, sintering together powder particles in the shape of the cross-section of the first layer of the 3D part. The build platform then descends one layer depth and the recoater transfers more fresh powder from the hopper to the surface of the first layer. Just like the first layer, the second cross-section of the 3D model is scanned and sintered. The laser scanning process simultaneously generates the current layer and adjoins it to the previous layer, making a solid part. There is no need to generate support material in polymer powder bed processes as the packing of the un-sintered powder supports the structure as its being built. This also means that separate parts can be stacked on one another in the build chamber, which can increase system throughput. The particular SLS system of focus for this study is the EOSINT P395 (image shown below).

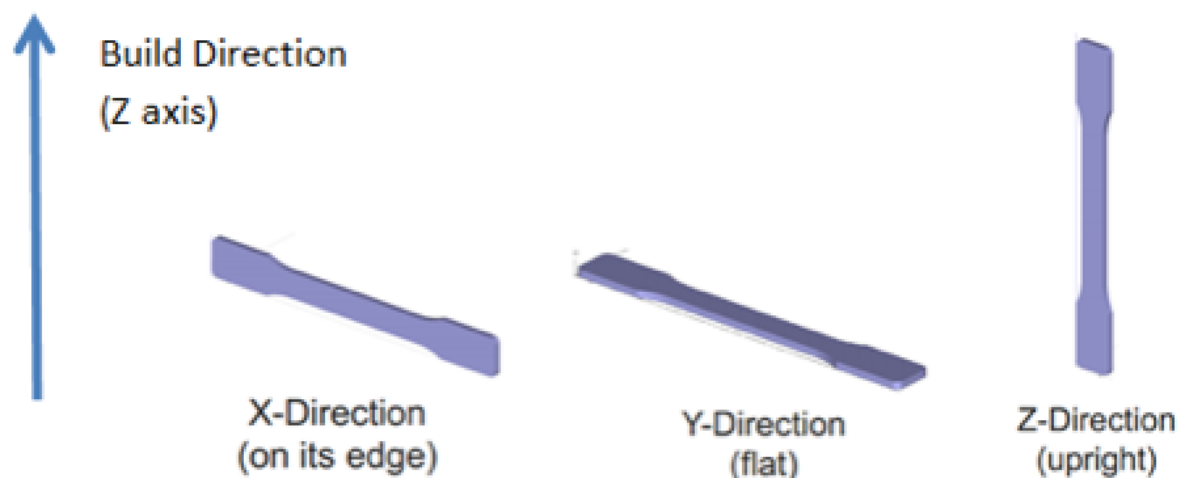


The EOS system can manufacture many different types of polyamide, including one polymer called PA12 (part of the PA 2000 series), a type of nylon. The EOS website lists PA12 series materials with tensile strengths that range from 48 to 54 MPa. However, due to the layer stacking manner in which parts are manufactured via SLS, part homogeneity and isotropy is a significant concern. To address this, the impact of part orientation of SLS parts on tensile strength was investigated.

BUILD ORIENTATION

When conducting tensile strength tests, the test specimens are manufactured according to ASTM standard geometry and fixed by their ends to a tensile testing rig. The test rig pulls the specimens lengthwise, increasing the load while measuring the strain (deformation) of the part until fracture. The three images below demonstrate the three directions that the test specimens were oriented for printing.

The build direction arrow indicates the direction in which layers of build material were stacked during the build process. For reference, the “Y-direction” specimen has the fewest layers, whereas the “Z-direction” specimen has the most layers.



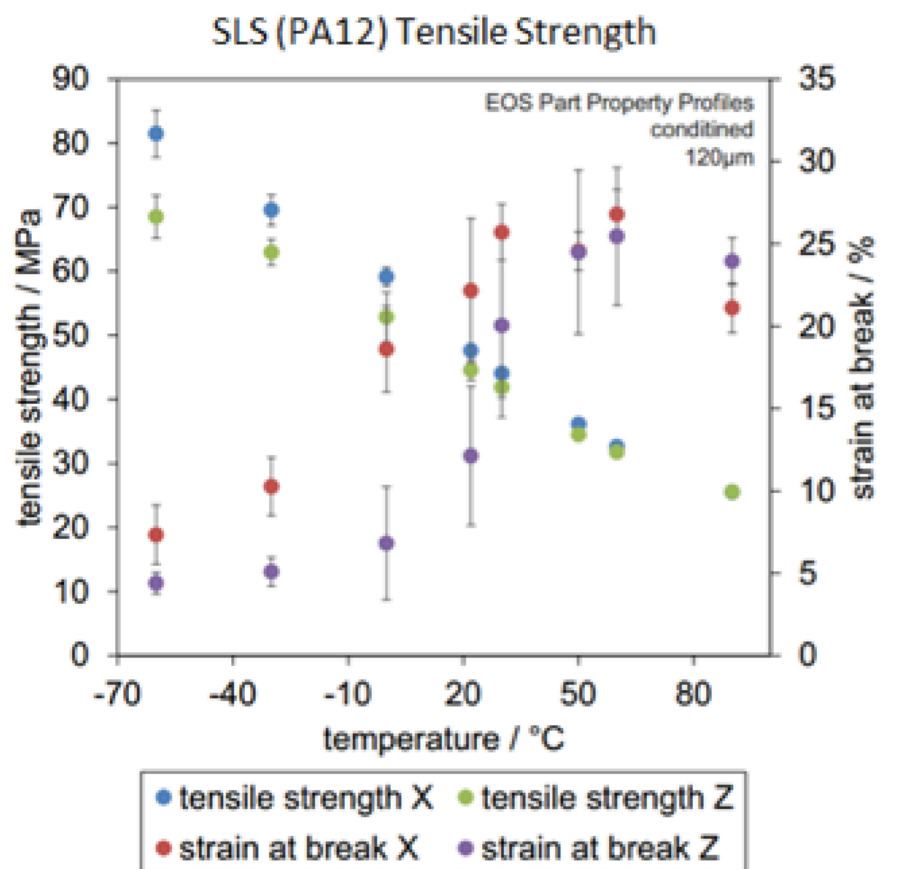
WHY TENSILE STRENGTH TESTS

Tensile behavior is a common test for materials destined for mechanical applications. As such is the case, tensile tests can be conducted for a better understanding of tensile strength and elongation at break. Tensile strength gives an indication on material load-bearing capability, it is the maximum stress that the material can withstand without permanent deformation. Strain at break is a complementary data referring to the ability of the material to accommodate deformation before it collapses, it is the deformation at which the material breaks. Both sets of information are important, a material with high strength can have a low elongation at break, resulting in a hard yet brittle material (like ceramic).

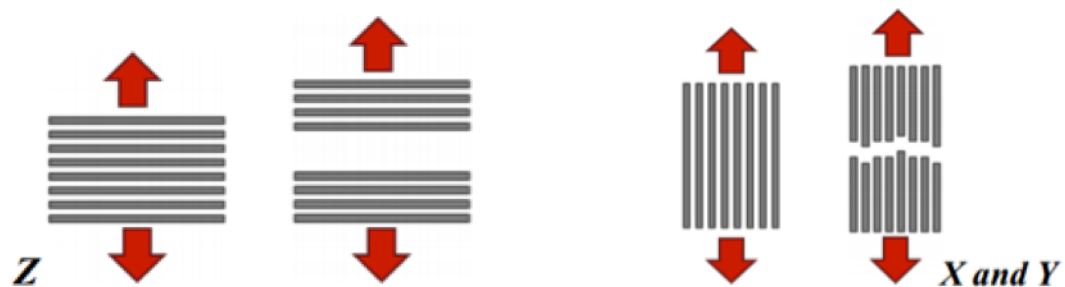
TENSILE STRENGTH OF FDM VS. SLS PARTS

Print orientation has a considerable impact on the strength of the part. The following chart shows the tensile strength of PA12 SLS parts printed with the EOSINT P395 in the X and Z-directions. The green dots show the tensile strength of printed parts oriented in the Z-direction (upright), whereas the blue dots show the tensile strength of printed parts oriented in the X-direction (on its edge).

The chart to the right shows that both the Tensile Strength and Strain at Break in the X-direction (blue and red dots, respectively) are only slightly greater than (if not equal to) the Z-direction (green and purple dots, respectively) of the SLS PA12 parts at all temperatures. The largest difference in tensile strength between the two orientations was 10MPa, occurring at -60°C.



This orientation dependent performance is an artifact of the layer-stacking manufacturing method. When pulling a tensile test specimen in the same direction that the cross-sectional layers were stacked (the build direction), the samples exhibit lower strength. However, if pulled along the path of the laser (X- or Y-directions), the material exhibits strength greater before fracture. This can be understood by looking at the break behavior of the specimens, shown in the images below.



The left image shows the break behavior for specimens built in the Z-direction, where separation occurs at the interface between two stacked layers. The right image shows that pulling an SLS part along the laser path (X- and Y-directions) requires fracture of many individual sintered layers. As a result, SLS parts exhibit some anisotropic behavior as fracture at the layer interface occurs at a lower load than fractures along the laser path. In other words, the mechanical properties of an SLS part can be directionally dependent. However, the chart above shows that the tensile stress and strain properties of SLS parts differ by a small margin, and could be considered isotropic at room temperature.

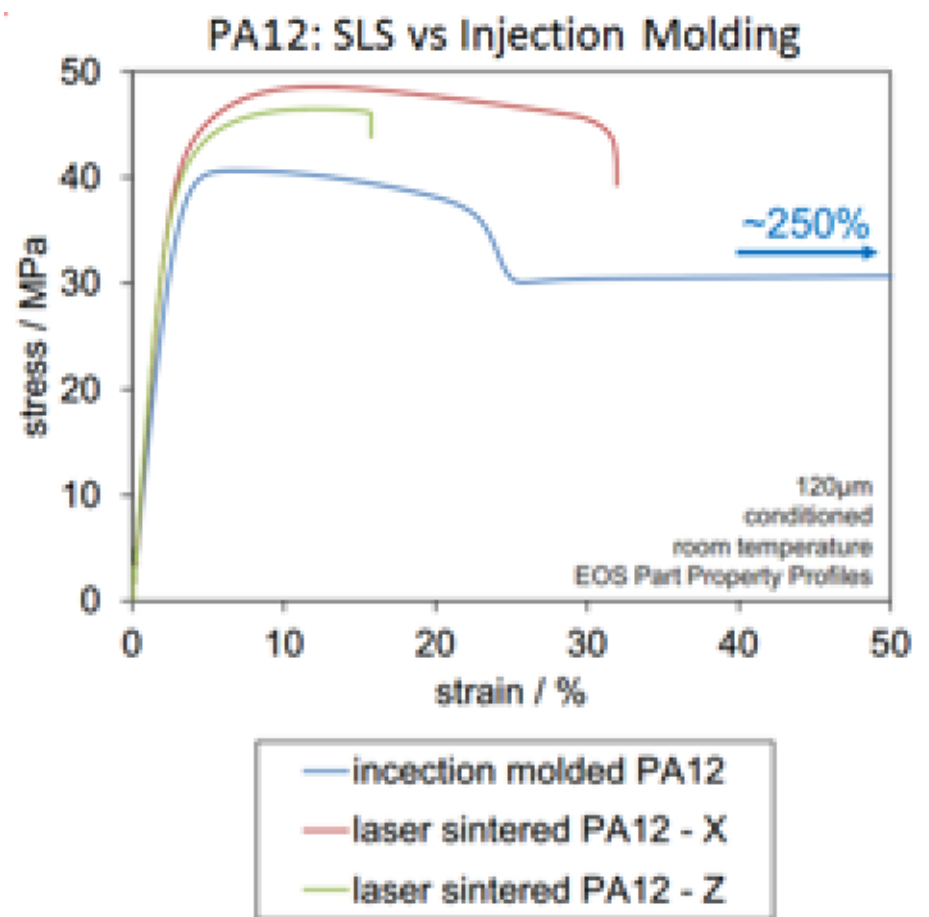
TENSILE STRENGTH OF INJECTION-MOLDED VS. AM PARTS

To understand the comparative performance of AM parts to traditional injection molded specimens, the researchers at DMRC generated standard stress-strain curves. A stress-strain curve shows the relationship between the deformation (strain) of a material exhibited as a result of tensile loading (stress).

The chart shown below compares the tensile properties of PA12 fabricated via SLS versus injection molded parts. The data representing the sample printed in the X-direction is shown in red, the sample printed in the Z-direction is shown in green, and the injection molded sample is in blue.

Both the SLS print orientations demonstrated higher stress than the injection molded part. Furthermore, the stress-strain curves show that the AM manufactured parts can exhibit similar strength to the injection molded parts, but exhibit much lower strain break. The lower strain can most likely be attributed to the internal

structure of the parts. Compared to AM processes, injection molding typically has lower porosity and greater homogeneity, leaving fewer imperfections in the structure of the material to encourage crack propagation.



SLS CONSIDERATIONS

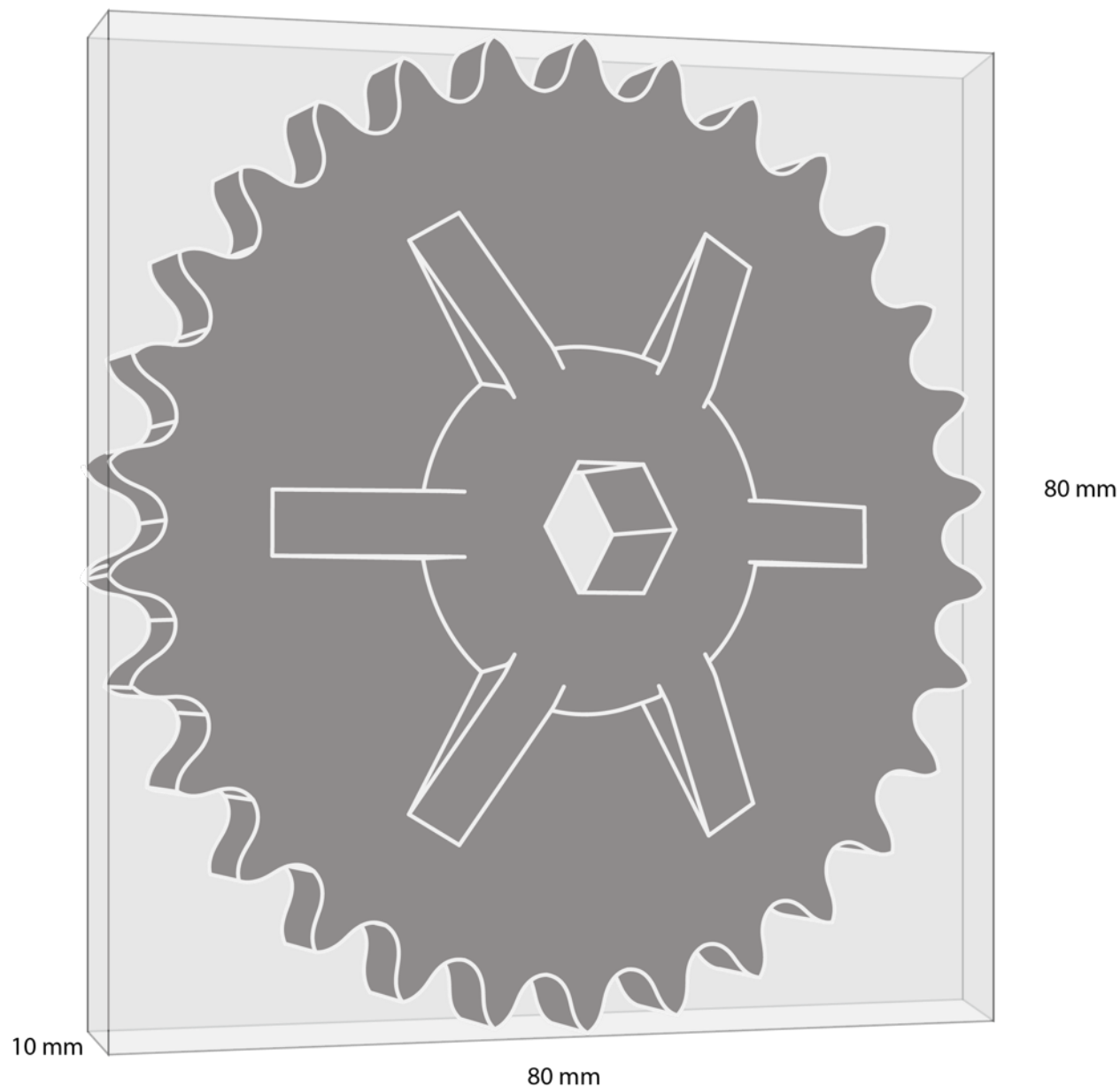
After reviewing the data generated by the researchers at DMRC, there are several trends that stand out. These trends can be translated into three considerations to keep in mind when designing a part for additive manufacturing of polymers:

- SLS printed parts demonstrate only a small amount of anisotropy.
- SLS test specimens have a slightly higher tensile strength when printed in the X- or Y- direction than the Z-direction.
- SLS parts can exhibit similar tensile strength to injection molded parts, but fracture at much lower strains.

Visit the EOS materials database to learn about other SLS powders.

Research Credit: Matthias Fischer and Stefan Josupeit from DMRC (Direct Manufacturing Research Center)

“Material Properties of Additive Manufactured Polymer Parts”, Inside 3D Printing Conference and Expo, Berlin, March 11, 2014”



2

CASE STUDIES – FIVE REPRESENTATIVE PARTS

In the first of three studies, estimated manufacturing cost data was collected for five unique and representative models of products that are commonly manufactured via injection molding. These five objects – a cockerel, a go-pro Handle, a remote control case, a car handle, and a sprocket – are listed in the chart below with their bounding box dimensions:

The purpose behind these case studies is to understand the cost effective point of Sculpteo batch control 3D printing when compared to rapid injection molding for industry representative parts.

| | Cockerel | Go Pro Handle | Remote Control Case | Car Handle | Sprocket |
|-------------------------|--------------------------|--------------------------|---------------------------|---------------------------|--------------------------|
| Bounding Box Dimensions | 55mm x 12mm x 40mm | 40mm x 55mm x 51mm | 226mm x 62mm x 19mm | 150mm x 58mm x 25mm | 80mm x 80mm x 10mm |

METHODOLOGY

To determine the estimated 3D printing production cost for each of the five parts, a 3D model was uploaded to the Sculpteo website. Algorithms check the part for 3D printability, focusing on design errors that may cause 3D prints to fail. Specifically, Sculpteo conducts a “Solidity Check” which confirms that all features on the part are above the minimum feature size threshold of approximately 1 mm. Next, utilizing the “Batch Control” feature for Selective Laser Sintering, Sculpteo calculates a cost per unit as well as a total batch cost. Batch control is automatically enabled once an order of 20 or more parts is selected, and helps to optimize unit price by generating a dedicated production run. Greater control over the production run is enabled, including orientation, layer thickness, and finish quality to optimize part cost to best suit the individual application. The options selected for the five part case studies were white plastic (Nylon PA12) raw finish (sand blasted) with a standard layer thickness (100 micrometers).

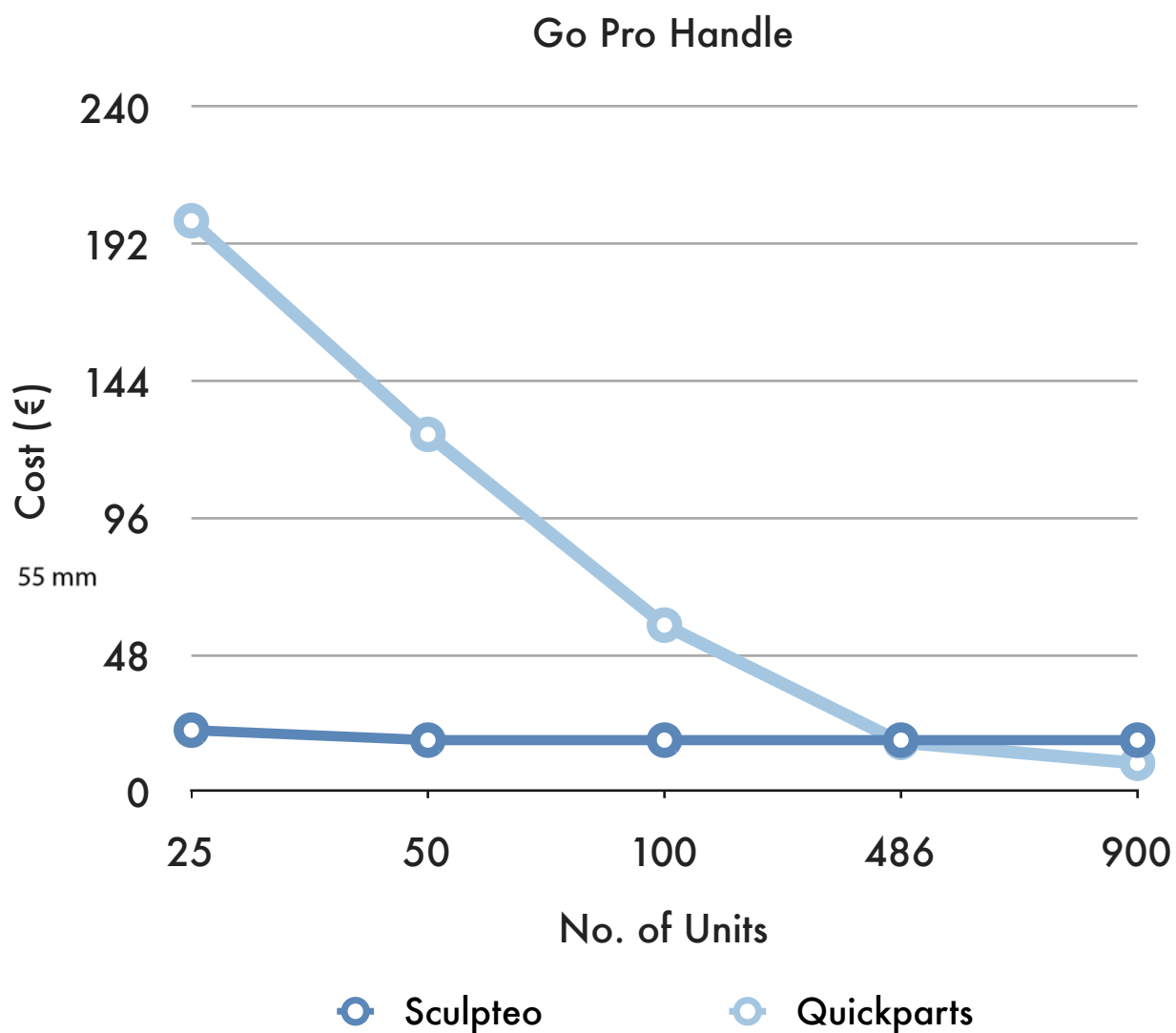
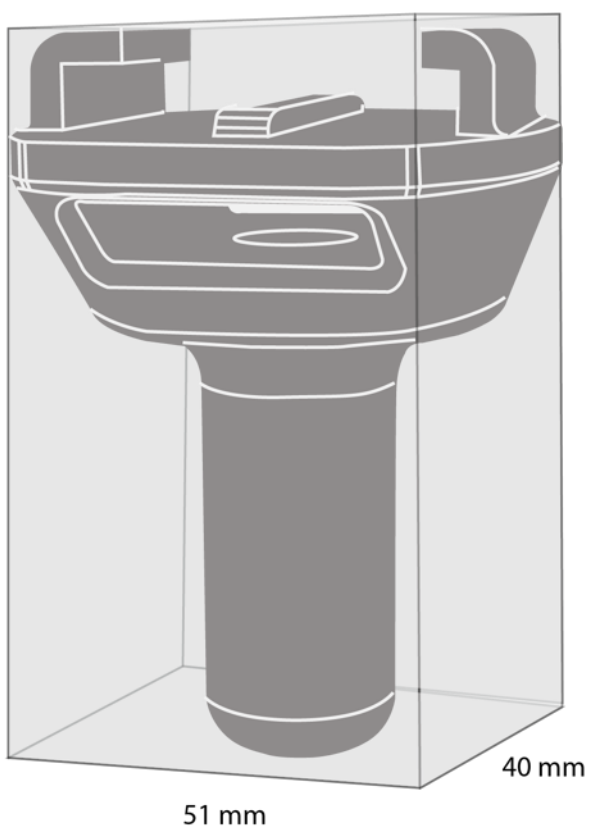
The injection molding production costs were estimated by requesting quotes from companies that offer rapid injection molding services. The companies analyze the 3D model for manufacturability, looking at design elements such as part orientation and parting line, draft, thickness, warp analysis, and more. Once the part is production ready, quotes were generated for manufacture via the “rapid injection molding” method. This method is used for prototypes and short series manufacturing, typically limited to 10,000 units. However, this process does not enable the manufacture of parts with a hollow interior. For parts containing a hollow interior, a secondary manufacturing method called “gas assisted injection molding” was utilized.

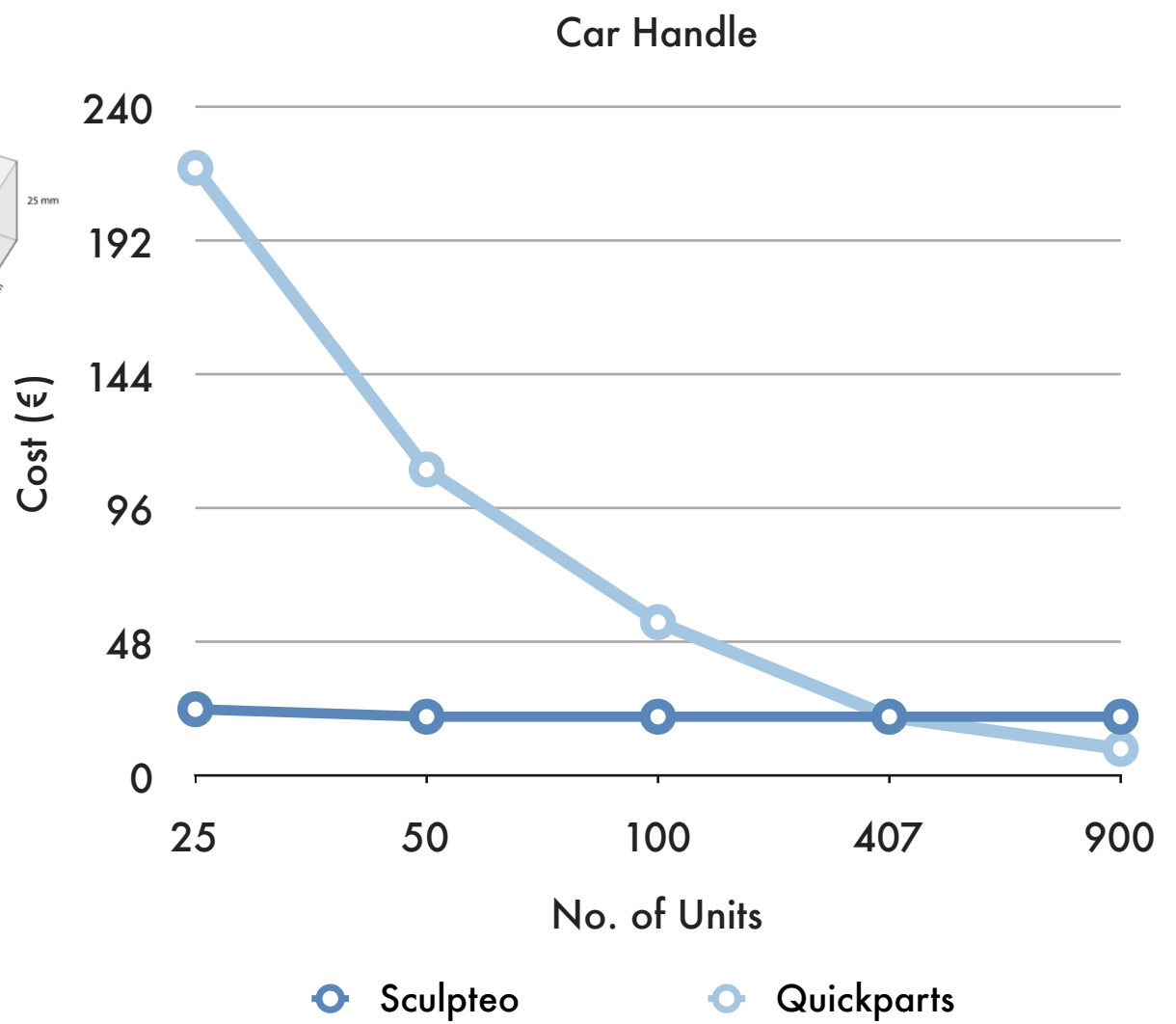
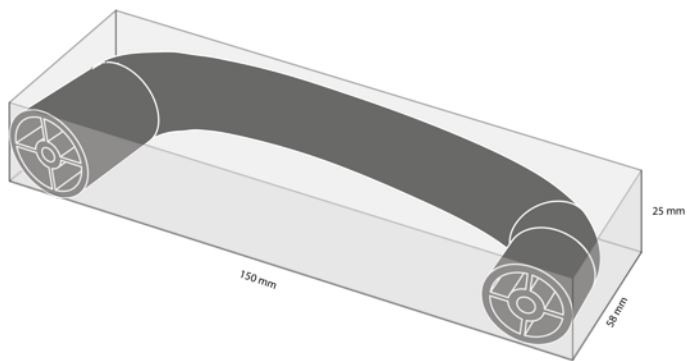
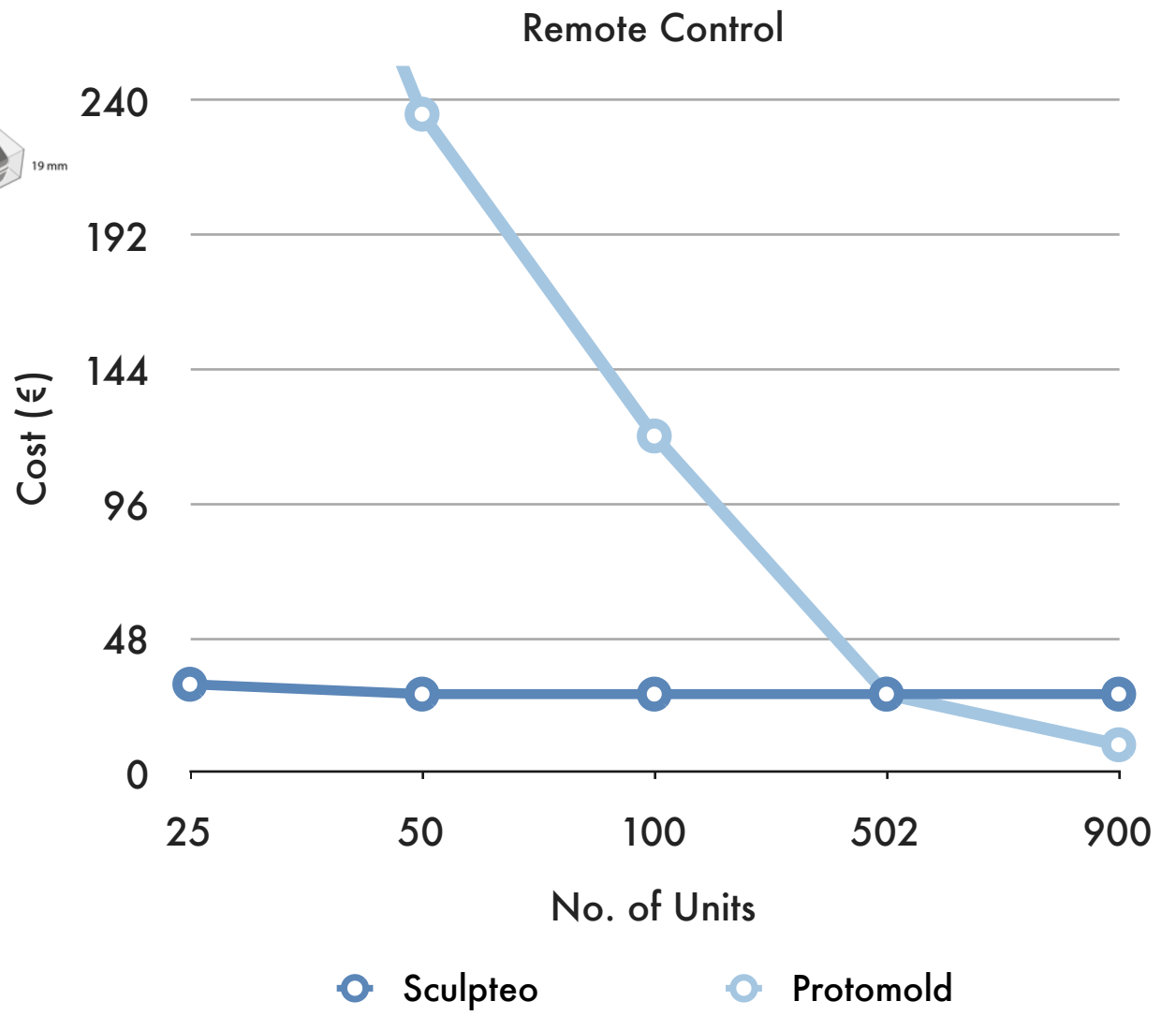
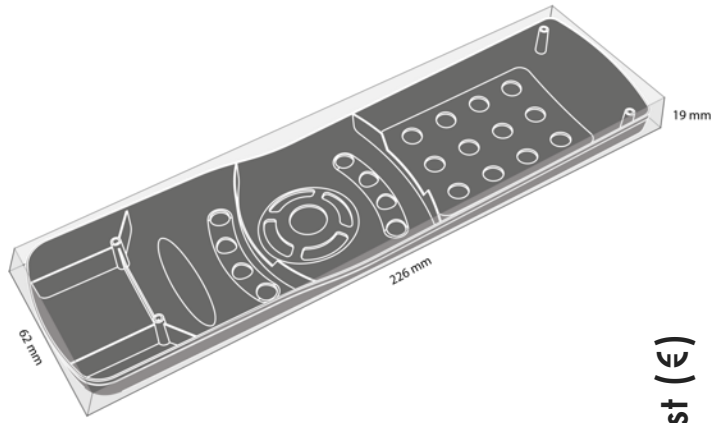
The table below summarizes which companies were used to generate the production cost data, as well as the part material, and the method of injection molding.

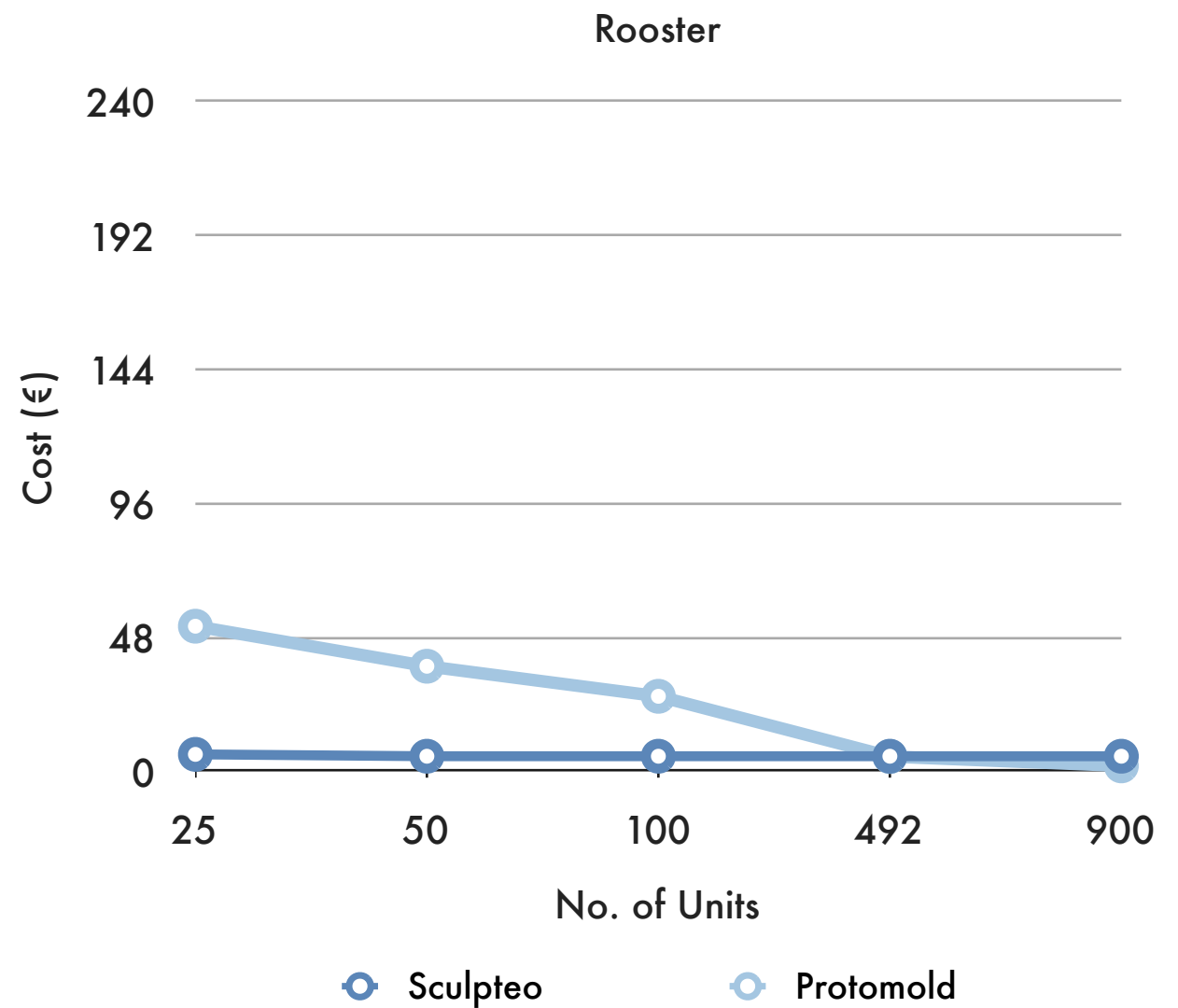
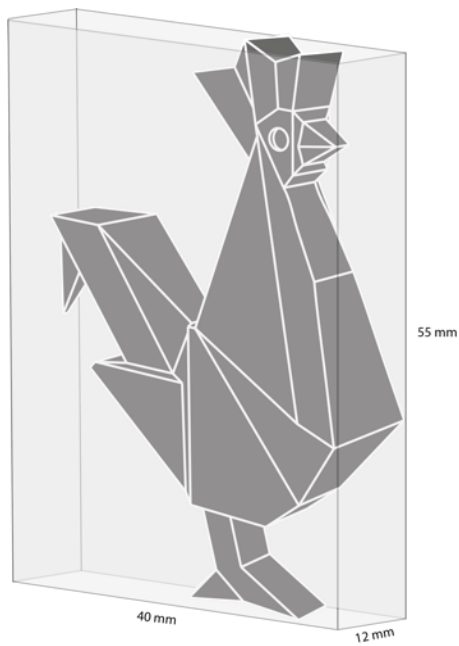
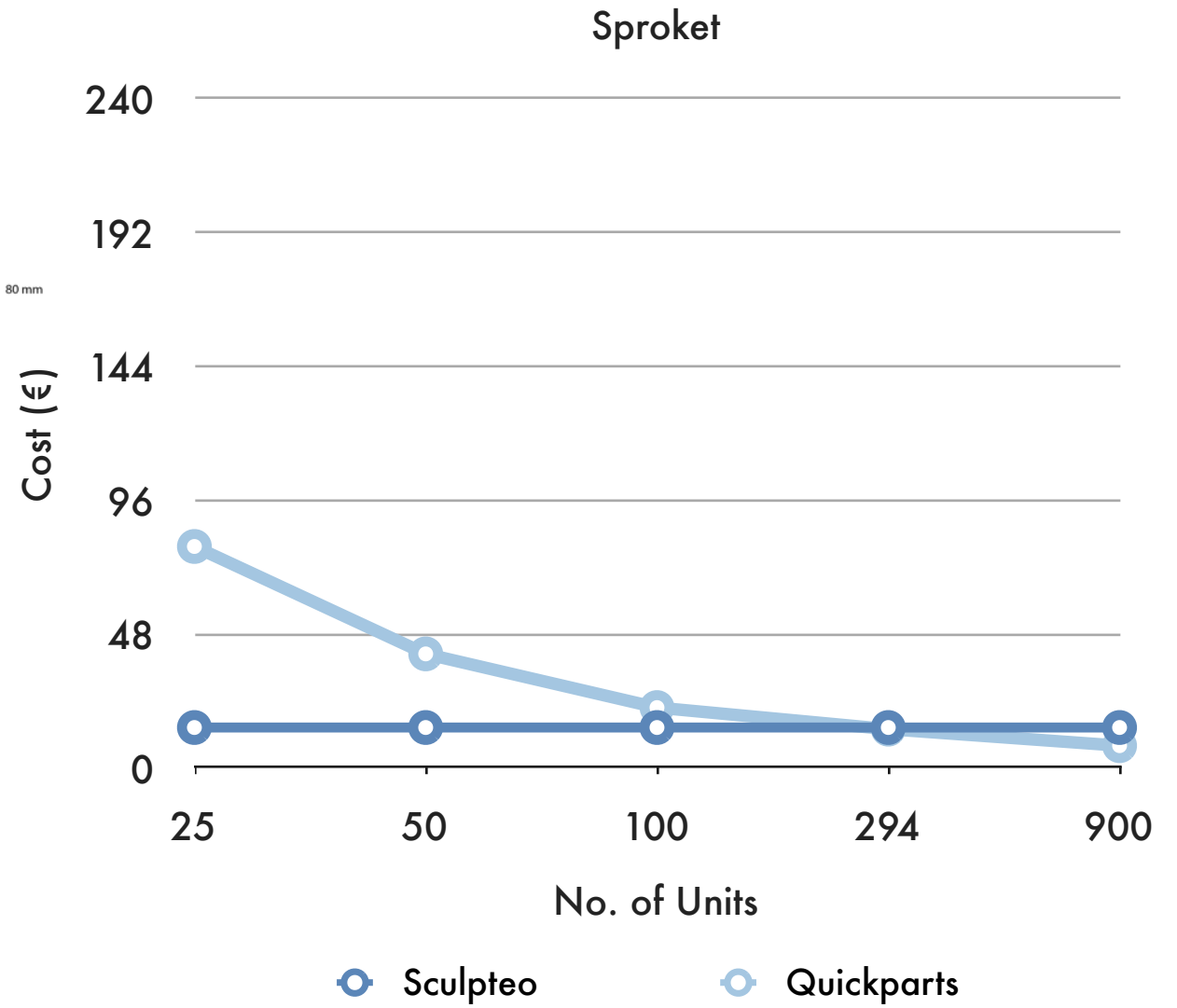
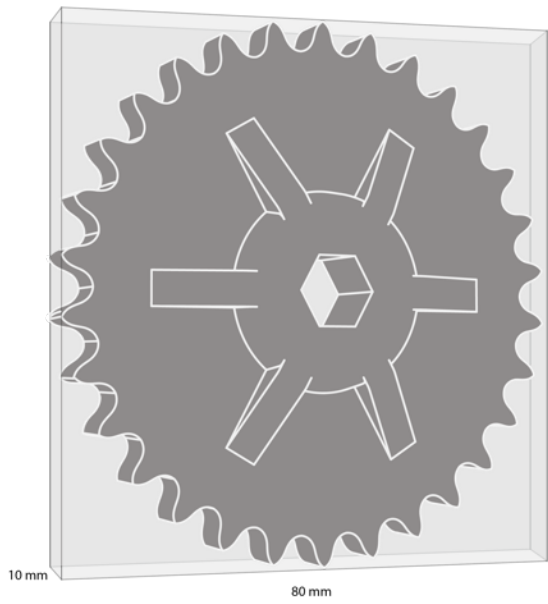
| | Quoted By | Material | IM Method |
|---------------------|------------------|---------------------|------------------|
| Cockerel | Protomold | Prolypropylene (PP) | Rapid |
| Go-Pro Handle | Quickpart | Prolypropylene (PP) | Rapid |
| Remote Control Case | Quickpart | ABS | Rapid |
| Car Handle | Sinomould | Prolypropylene (PP) | Gas Assisted |
| Sproket | Protomold | Nylon 6 | Rapid |

RESULTS AND ANALYSIS

The results for the collected data are summarized in the charts below. Each chart depicts the cost of the injection molded part per unit versus the cost of the 3D printed part per unit. The injection molding datasets includes startup costs such as the cost of tooling. The intersection of the two lines defines the number of manufactured units where 3D printing and injection molding per unit cost overlaps; in other words, the intersection represents the upper limit of the number of 3D printed units where 3D printing remains viable as a manufacturing method.



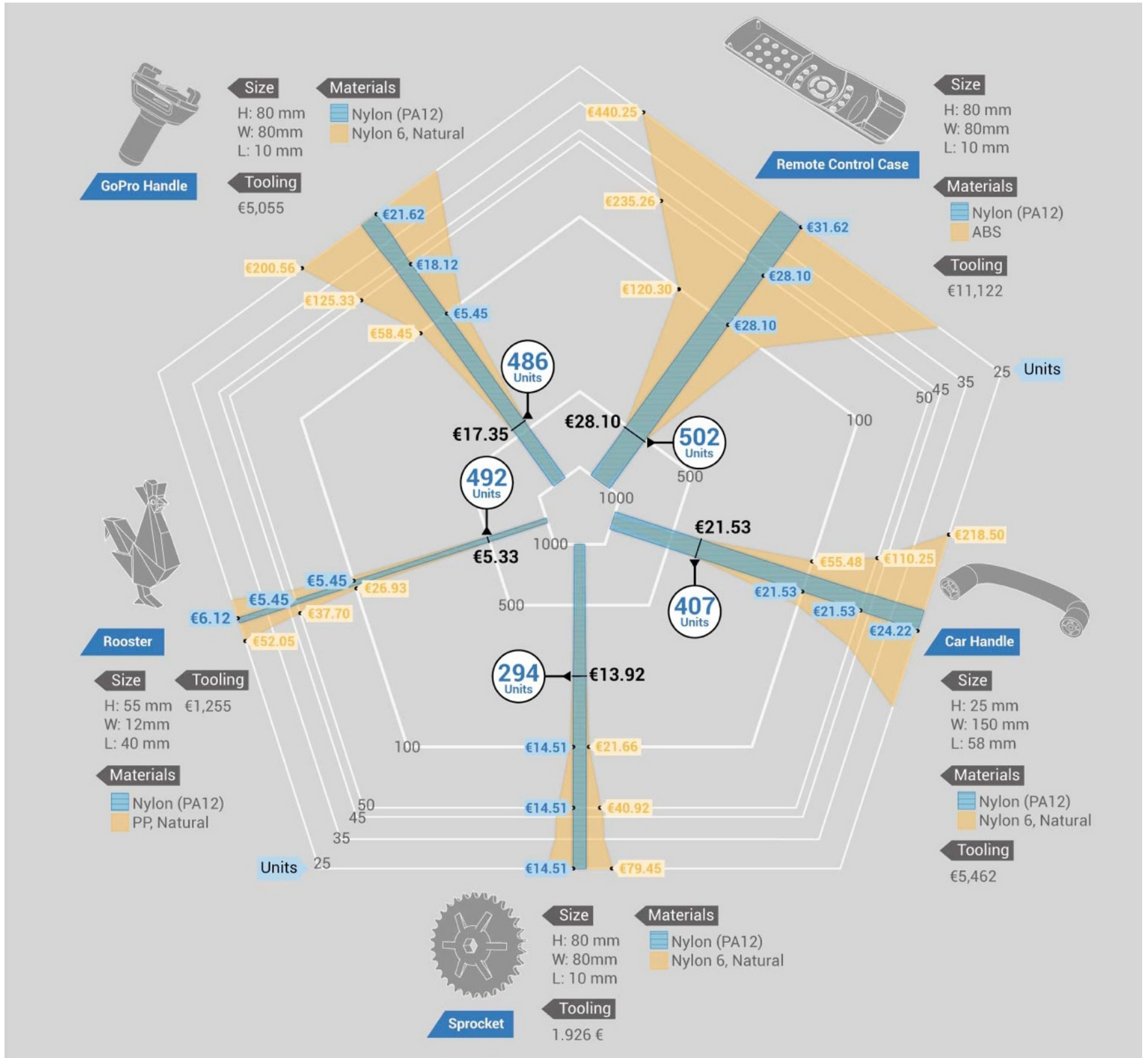




The data from the above charts is summarized in the table below:

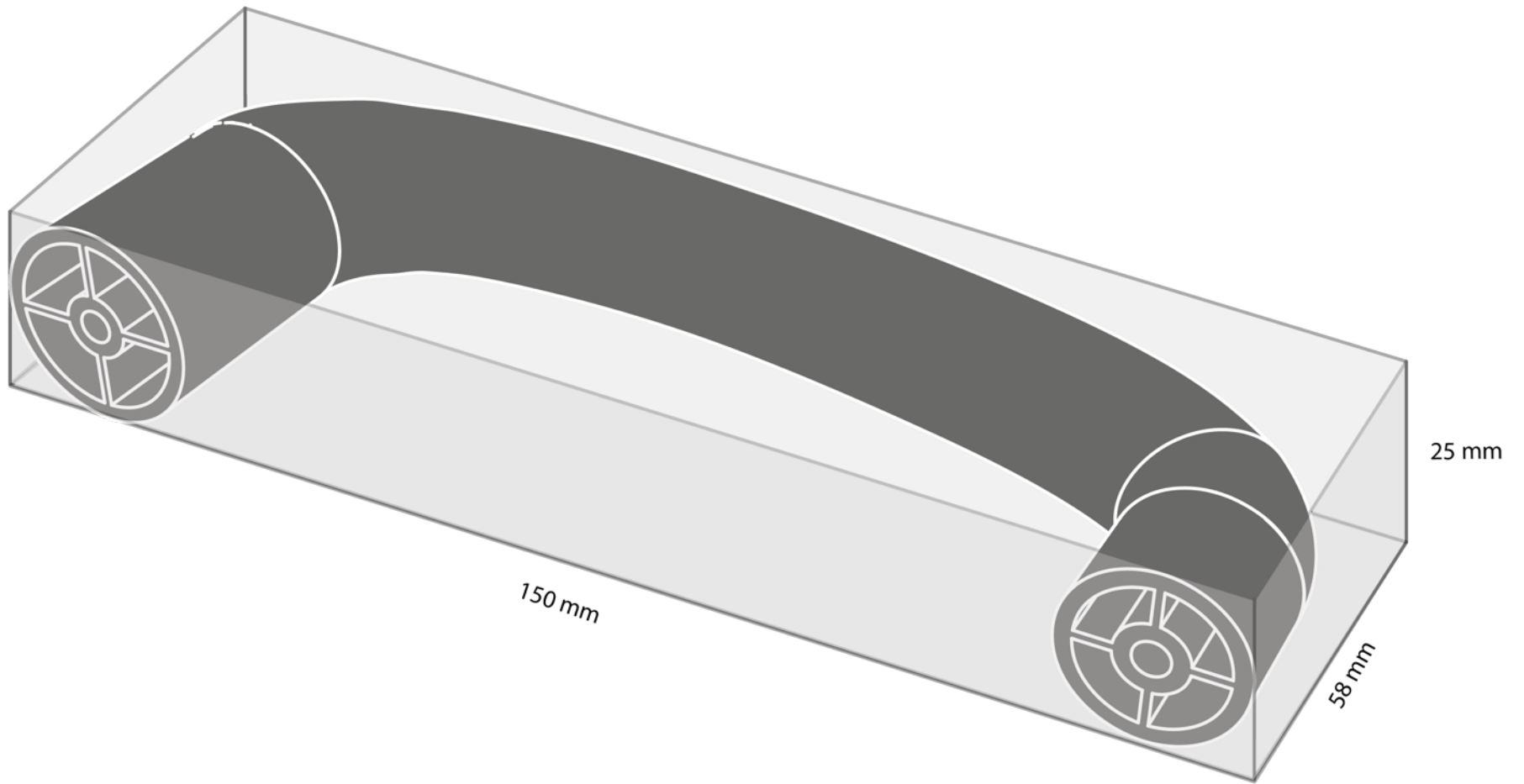
| | Number of Units | Unit Cost (€) | Bounding Box Size |
|---------------------|-----------------|---------------|--------------------|
| Cockerel | 492 | 5.33 | 55mm x 12mm 40mm |
| Go-Pro Handle | 486 | 17.35 | 40mm x 55mm x 51mm |
| Remote Control Case | 502 | 28.10 | 226mm x 62mm 19mm |
| Car Handle | 407 | 21.53 | 150mm x 58mm 25mm |
| Sprocket | 294 | 13.92 | 80mm x 80mm x 10mm |

The infographic on the following page represents offers an intuitive understanding of the information in the table and graphs of the previous pages. Each of the five case studies are represented: the blue areas of the infographic represent the cost per unit of the 3D printed part, characterized by the constant price per part; the yellow areas of the image demonstrate the cost per unit of the injection molded parts. This data contains the cost of tooling as well, identifiable by the extremely high start-up costs. Following these bar charts towards the middle of the pentagon, the value at which the yellow and blue areas meet represents the last unit where 3D printing is economically viable as a manufacturing method. As no special tooling is required in to 3D print parts, there is no high start-up cost, and the cost per part remains constant once batch control is enabled.



CONCLUSION

The data collected demonstrates that 3D printing can provide the economical means to manufacture batches of approximately 500 units cheaper than rapid injection molding methods. The injection molded parts and 3D printed parts being compared are not of the same material, though their material properties are comparable. Additionally, the parts that are 3D printed have a different surface finish than those that have been injection molded. Should the surface finish and material properties of the 3D printed part serve the needs of the desired application, then 3D printing remains an economical manufacturing method for upwards of 500 unit production runs (dependent on unit size).



3

INFLUENCE OF OBJECT SIZE ON PRICE

In the second study, the influence associated with increasing part size in both 3D printing and injection molding manufacturing methods is analyzed. To accomplish this, quotes for both 3D printing and injection molding were generated for a generic, hollow, five-sided box of increasing size.

METHODOLOGY

Similar to the five case studies presented above, the 3D printing quotes were generated by Sculpteo utilizing the “Batch Control” feature for Selective Laser Sintering. For the rapid injection molding, the prices for the parts were calculated using CustomPartNet, a leading free online resource for cost estimation of manufactured parts. Utilizing their extensive part gallery, a box was selected to generate baseline manufacturing cost estimates for injection molding. The selected settings for both manufacturing processes are specified in the table below.

Using the CustomPartNet estimation tool, manufacturing cost estimations were generated for part volumes starting at 10 units, then at intervals of 50 from 50 units to 1000 units (10, 50, 100, 150, etc...). This data was then plotted to compare total cost to number of units manufactured. Similarly, using the batch control feature by Sculpteo set standard layer thickness (100 micrometers), the same data was collected.

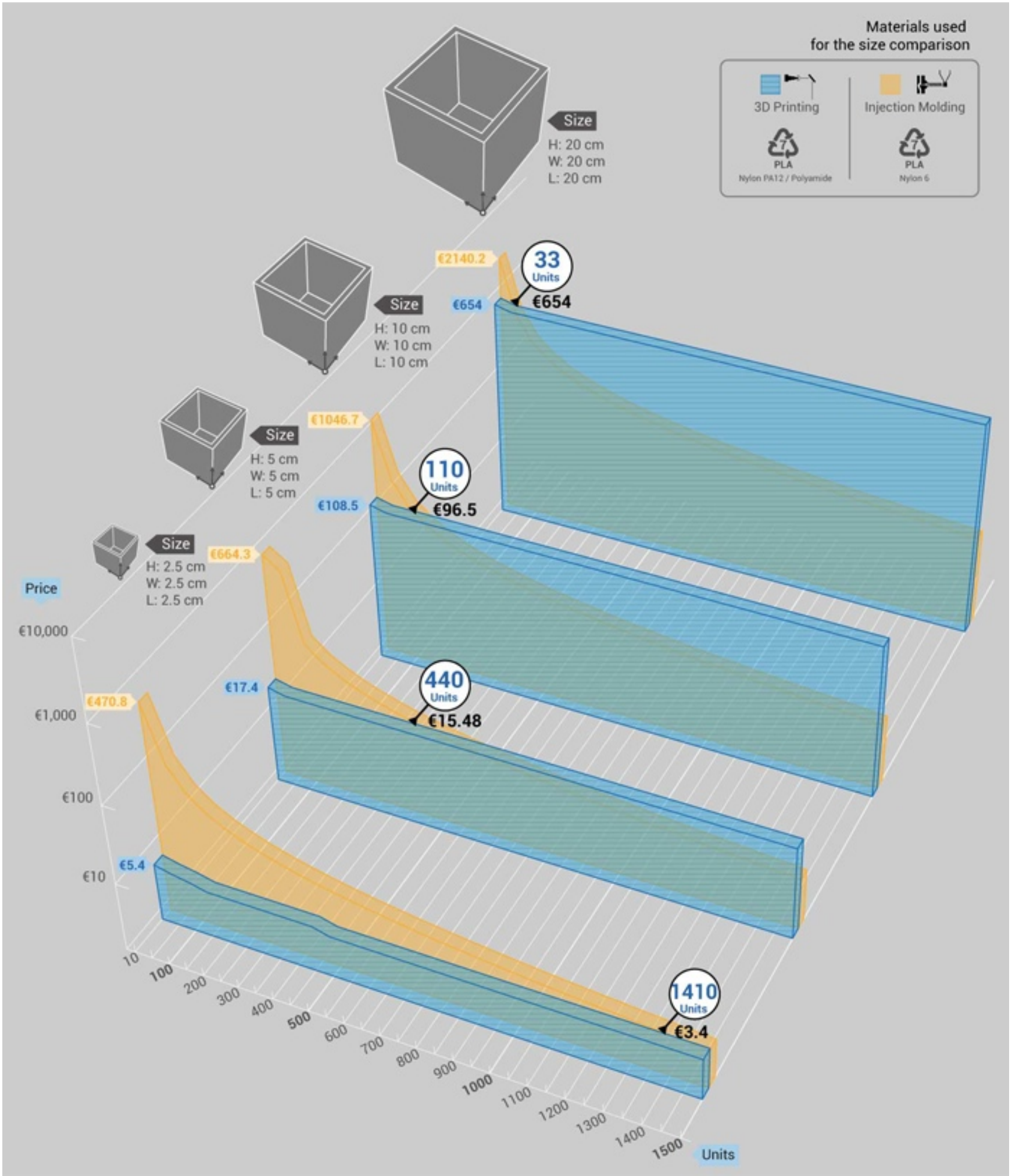
| | 3D Printing | Rapid Injection Molding |
|-------------------|--------------------|--------------------------------|
| Material | Nylon (PA12) | Nylon 6 |
| Wall Thickness | 1mm | 1mm |
| Tolerance | 1.15mm | “Moderate Precision” at 0.25mm |
| Surface Roughness | Raw (Sand Blasted) | “Not Critical” |

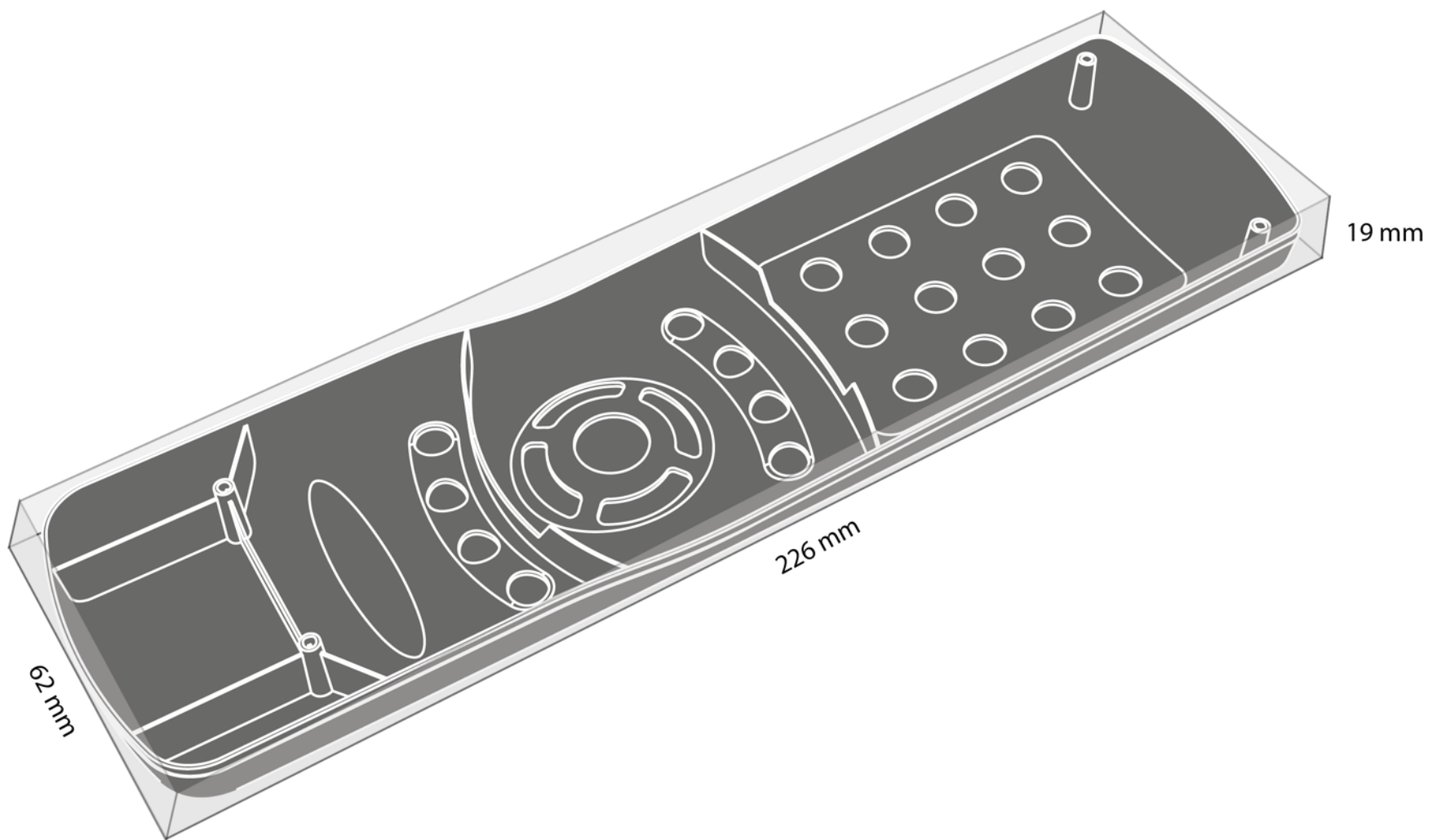
RESULTS & ANALYSIS

The table below presents the upper economical unit manufacturing limit of 3D printing when compared to the cost of rapid injection molding of generic hollow boxes of increasing size.

| | No. of Units | Unit Cost (€) |
|---------------------------------|--------------|---------------|
| 2.5 x 2.5 x 2.5 cm ³ | 1410 | 3.4 |
| 5 x 5 x 5 cm ³ | 440 | 15.48 |
| 10 x 10 x 10 cm ³ | 110 | 96.5 |
| 20 x 20 x 20 cm ³ | 33 | 654 |

The data demonstrates that 3D printing becomes less cost effective as object size increases. The high cost of the largest box is a strong representation of the cost calculation algorithms for SLS. Material quantity and machine manufacturing time per unit are critical elements in the SLS process. Increasing the Z-dimension (height of the part in the build volume of the SLS machine) means the part takes the longer to manufacture and more material is used in the production process (both the real quantity and the manufacturing quantity). Furthermore, as an object grows in size, fewer can fit within a single build volume, meaning that a greater number of production runs will be required. Rapid Injection Molding is not restricted by any of these considerations. This means that 3D printing does not retain its economic viability for large parts unless the production runs are very small.





4

INFLUENCE OF OBJECT COMPLEXITY ON PRICE

In the third and final portion of this study, influence associated with increasing part complexity is analyzed again with the 3D printing and injection molding manufacturing methods. To do this, estimations of production costs for both 3D printing and rapid injection molding were generated for a generic 5cm³ box, a box with an external flange, a box with an internal flange, and a box with two holes.

METHODOLOGY

Similar to the two previously presented studies, the 3D printing quotes were again generated through Sculpteo utilizing the batch control feature for Selective Laser Sintering. For rapid injection molding, the prices for the parts were again calculated using CustomPartNet and the extensive part gallery. The selected settings for both manufacturing processes are specified in the table below.

Repeating the data collection process described in CHAPTER 4, manufacturing cost estimations were generated for part volumes starting at 10 units, then at intervals of 50 from 50 units to 1000 units (10, 50, 100, 150, etc.) This data was then plotted on a chart comparing total cost to number of units manufactured. The same data was collected using batch control with the layer thickness set to the standard 100 micrometers.

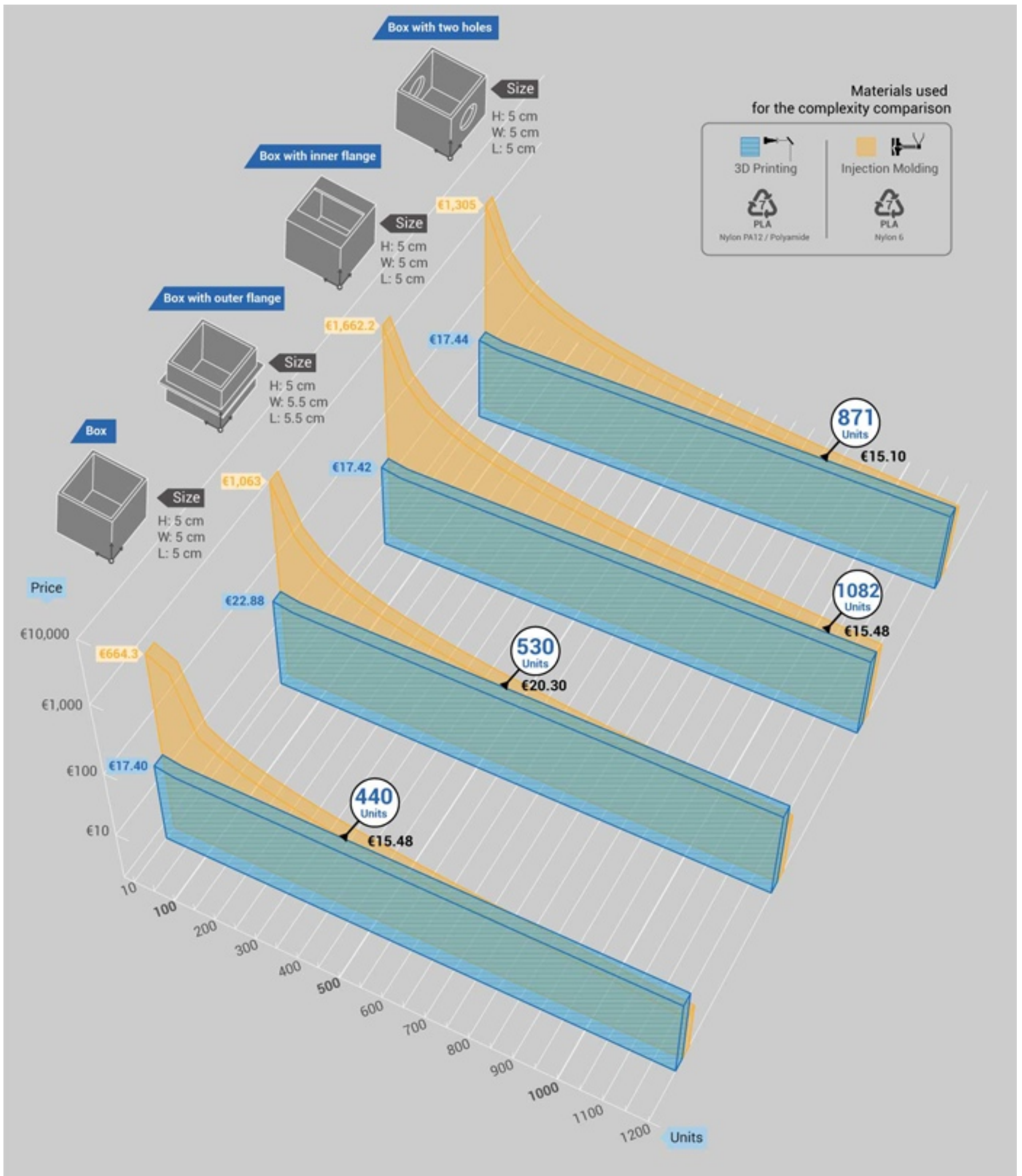
| | 3D Printing | Rapid Injection Molding |
|-------------------|--------------------|--------------------------------|
| Material | Nylon (PA12) | Nylon 6 |
| Wall Thickness | 1mm | 1mm |
| Tolerance | 1.15mm | “Moderate Precision” at 0.25mm |
| Surface Roughness | Raw (Sand Blasted) | “Not Critical” |

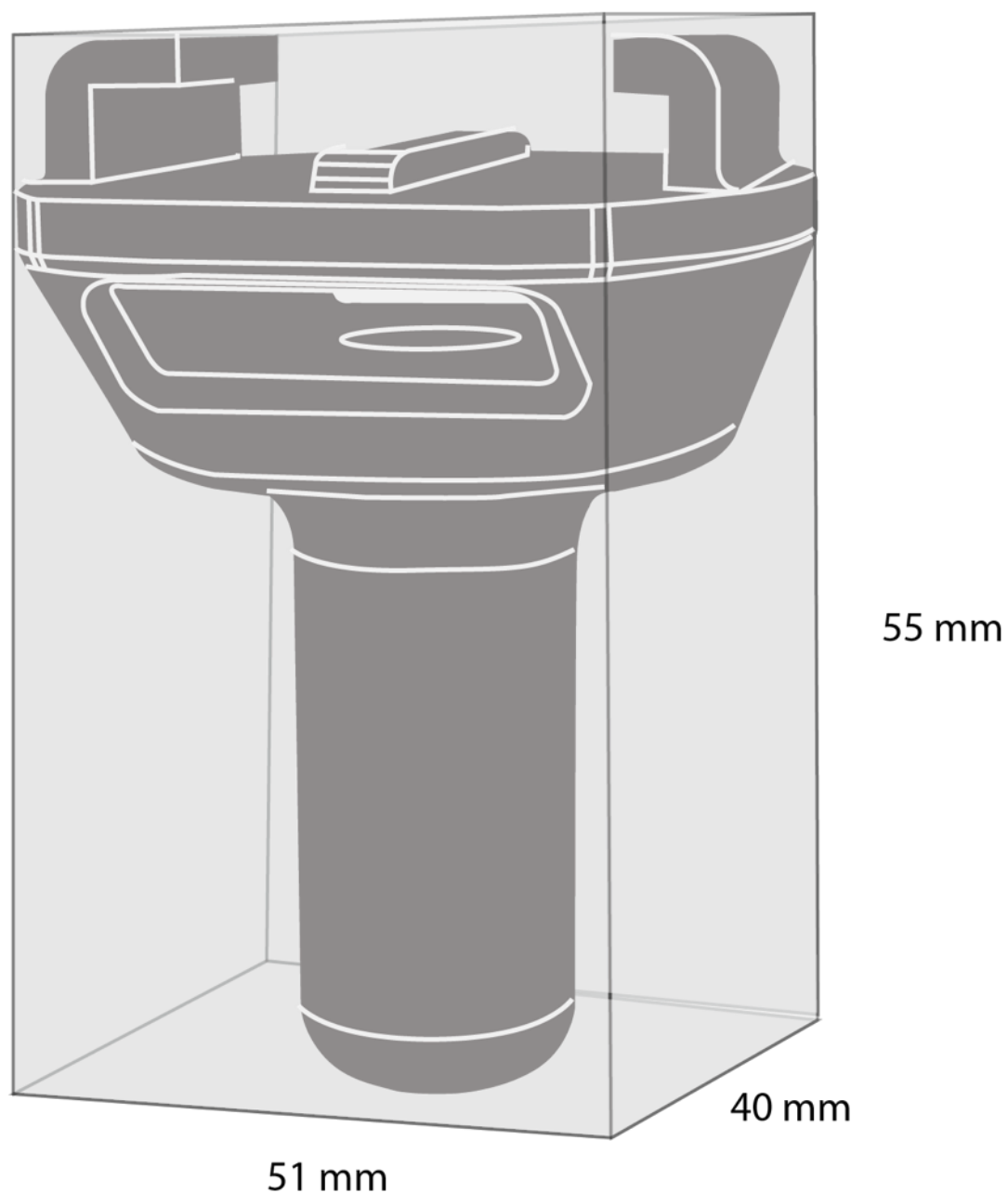
RESULTS & ANALYSIS

The table below presents the upper economical unit manufacturing limit of 3D printing when compared to the cost of rapid injection molding of generic hollow boxes of increasing complexity.

| | No. of Units | Unit Cost (€) |
|-----------------------|--------------|---------------|
| Box | 440 | 15.48 |
| Box with flange | 530 | 20.30 |
| Box with inner flange | 1082 | 15.48 |
| Box with two holes | 871 | 15.10 |

The data shows that as a part becomes more complex, the more cost effective it is to utilize 3D printing as a manufacturing method. This is correlated to the increasing complexity of the tooling for rapid injection molding. However, as is often said about 3D printing, complexity is free. Provided that the build area and material volume usage remains largely unchanged, introducing complexity to a part will not dramatically change the unit cost, and in some cases may even reduce it. The external flange added to the box for the part named “Box with flange” increases the XY area of the part, demonstrating that increasing the build area increases the cost of the 3D printed part. Regardless, this study demonstrates that 3D printing, and particularly Sculpteo’s Batch Control feature for SLS additive manufacturing, has significant advantage for low volume manufacturing of parts with complex features. Following this trend, the more complex a part is, the more economical it will be to manufacture via 3D printing.





5

SUMMARY OF STUDY AND CONCLUSIONS

At the beginning of this study the question, “Compared to injection molding, when is 3D printing a cost-effective manufacturing method?” was posed. Comparing Sculpteo’s Batch Control tool with various rapid injection-mold manufacturers, the study sheds light onto the cost effectiveness of using 3D printing as a production method.

Two separate studies were conducted. One study determined the influence that complexity and size play on the cost of an object, while the other used five representative examples to determine the quantity of objects which would be more cost effective to 3D print as opposed to injection molding.

For each of the 3D printed parts, the price was generated using the Sculpteo Batch Control feature with 100 micrometer layer resolution, the sandblasted (“raw”) finish, and Nylon PA 12 selected as the

material. The injection molds were quoted by a variety of companies including Protomold, Sinomold, Quickpart and CustomPartNet.

The two studies concerning the influence of size and complexity on manufacturing cost resulted in significant trends. With regards to size: the smaller the object, greater the cost efficiency of a 3D print. This is a result of the current size standards for industrial-scale printers across the industry.

Similarly, with regards to complexity: the greater the complexity of an object, greater the cost efficiency of a 3D print. Complexity of an object does not affect 3D printing prices, whereas an object with flanges, holes, or other complexities will be more expensive through an injection mold.

The other portion of the study focused on five representative parts meant to determine the exact quantity of objects that would be more cost effective to manufacture via 3D printing as opposed to injection molding. The exact numbers varied dependent on the complexity and size of the objects with a range of 294 to 502 objects.

Given these results, the question of when 3D printing is most cost effective can be answered as follows: 3D printing is a cost effective manufacturing method for mid-quantity series of high complexity objects.

This information could benefit every stage of product development, though in particular the design stage. Industrial or product designers need no longer be limited by the complexity of an object destined for manufacturing, instead size has become the primary determinate. Within a bounding box (likely determined by the product's eventual quantity) an object is able to be infinitely complex without greatly affecting the price.

In conclusion, 3D printing is an economically viable solution for manufacturing and current technologies have lifted the financial burden of complex objects. Designers and product developers can now consider 3D printing smaller, more complex series of objects as a viable solution to their manufacturing needs.

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