Additive manufacturing

Technological design (not only) for additive manufacturing

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Additive manufacturing

Classification AM according the standard ISO/ASTM 52900:

1. material extrusion:
2. material jetting:
3. binder jetting:
4. sheet lamination:
5. vat photo-polymerization:
6. powder bed fusion:
7. directed energy deposition

SLA
DLP
PolyJet
SLS
SLM (DMLS)
EBM
3DP
MJF
LOM
TIJ
APF
FLM (FDM, FFF)

Technological design

The technological design is basically a design that allows production with the least possible labour, respectively production costs.

The cost of products manufacturing is not only affected by the choice of technology. The concept of the component design and the whole assembly has a significant influence. The technological design is of great importance from an economic point of view. It is largely due to production productivity and competitiveness.

Principles of technological design

- Simple shapes respecting production technology.
- Simple kinematic schemes.
- Reasonable demands on production accuracy.
- Clearly defined quality requirements.
- Defect prevention.
- Choosing the right material.
- Use of standardized parts and work-pieces.
- Utilization of production possibilities of the company.
- Minimizing production preparation.
- Minimization of production (overhead) costs.
- Use of mechanization and automation.
- Depending on the production needs, a suitable choice of dimensioning method.
- Take into account installation, assembly and disassembly.

Main requirements for design - material selection

- Use of metallurgical work-pieces (for machining technology).
- Limitation of the number of types and dimensions of semi-finished products used.
- Choose materials with regard to the optimal usability of their properties.
- Use of optimal production technology.
- Optimize the amount of waste during production.

Main requirements for design - part shape and size selection

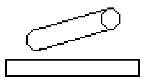
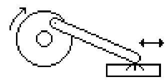
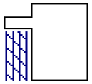
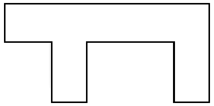
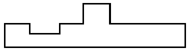
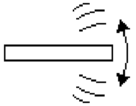
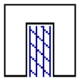
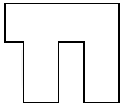
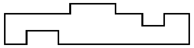
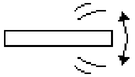
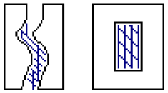
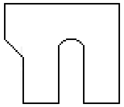
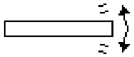
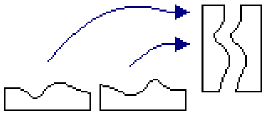
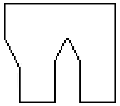
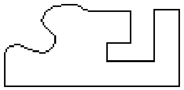
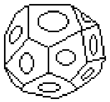
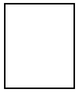
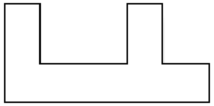
- Dimensioning of components based on calculations.
- Do not require an unnecessarily high degree of accuracy and surface quality.
- Eliminate interrelations of GD&T.
- Choice of the simplest shapes possible.
- Choice of shapes with regard to the use of universal tools, jigs and gauges.
- Use of purchased elements and semi-finished products.

Main requirements for design – assembly, maintenance and disassembly

- Reduction of assembly work.
- Create subassemblies so that they can be assembled separately.
- Design parts with regard to the use of assembly and disassembly aids.
- Finding a solution with minimal maintenance requirements.
- Design parts so that fast-wearing parts can be easily replaced.
- Minimize the need to use special fixtures etc.

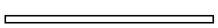
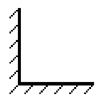
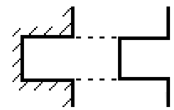
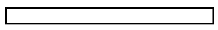
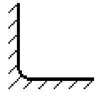
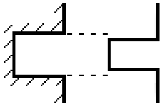
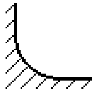
Design for Additive Manufacturing

Instructions: Mark one for each category for the part you plan to print.

Complexity	Functionality	Material Removal	Unsupported Features	Sum Across Rows	Totals
Simple parts are inefficient for AM	AM parts are light and medium duty	Support structures ruin surface finish	Unsupported features will droop		
** The part is the same shape as common stock materials, or is completely 2D 	* Mating surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles 	The part is smaller than or the same size as the required support structure 	There are long, unsupported features 	x5 =	
* The part is mostly 2D and can be made in a mill or lathe without repositioning it in the clamp 	* Mating surfaces move significantly, experience large forces, or must endure 100-1000 cycles 	There are small gaps that will require support structures 	There are short, unsupported features 	x4 =	
The part can be made in a mill or lathe, but only after repositioning it in the clamp at least once 	Mating surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles 	Internal cavities, channels, or holes do not have openings for removing materials 	Overhang features have a slopped support 	x3 =	
The part curvature is complex (splines or arcs) for machining operation such as a mill or lathe 	Mating surfaces will move minimally, experience low forces, or are intended to endure 2-10 cycles 	Material can be easily removed from internal cavities, channels, or holes 	Overhanging features have a minimum of 45deg support 	x2 =	
There are interior features or surface curvature is too complex to be machined 	Surfaces are purely non-functional or experience virtually no cycles 	There are no internal cavities, channels, or holes 	Part is oriented so there are no overhanging features 	x1 =	

Design for Additive Manufacturing

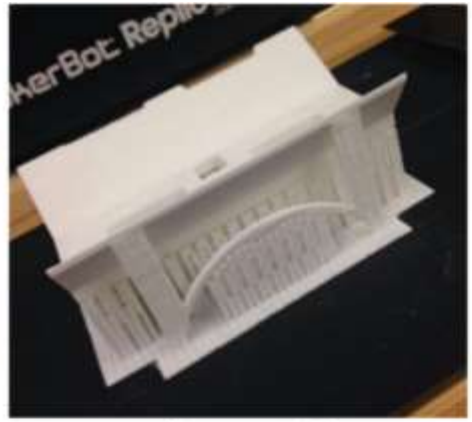
Instructions: Mark one for each category for the part you plan to print.

Thin Features	Stress Concentration	Tolerances	Geometric Exactness	Sum Across Rows	Totals
Thin features will almost always break	Interior corners must transition gradually	Mating parts should not be the same size	Large, flat areas tend to warp		
Some walls are less than 1.5mm thick 	Interior corners have no chamfer, fillet, or rib 	Hole or length dimensions are nominal 	The part has large, flat surfaces or has a form that is important to be exact 	x5 =	
Walls are between 1.5mm and 3mm thick 	Interior corners have chamfers, fillets, and/or ribs 	Hole or length tolerances are adjusted for shrinkage or fit 	The part has medium-sized, flat surfaces, or forms that are should be close to exact 	x3 =	
Walls are more than 3mm thick 	Interior corners have generous chamfers, fillets, and/or ribs 	Hole and length tolerances are considered or are not important 	The part has small or no flat surfaces, or forms that need to be exact 	x1 =	
Starred Ratings		**Total score:**			
***** Consider a different manufacturing process ****** Strongly consider a different manufacturing process		33 – 40 Needs redesign 24 – 32 Consider redesign 16 – 23 Moderate likelihood of success 8 – 15 Higher likelihood of success		Overall Total	

A quick method for reducing the number of printing and prototyping failures, by Joran W. Booth, 2015

Design for Additive Manufacturing – examples and scores

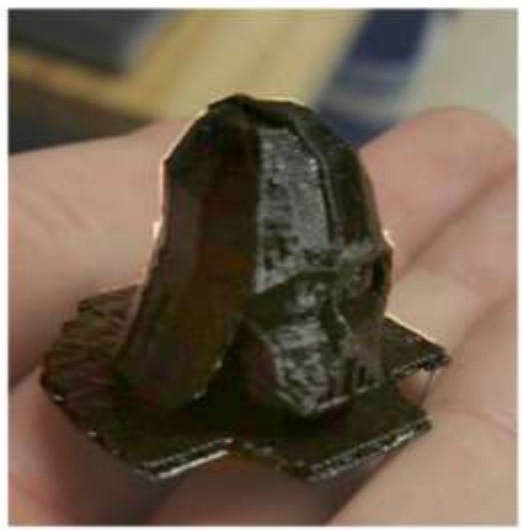
Score = 24



Score = 22

Score = 19

Score = 16



Score = 15

Score = 11

Source: BOOTH, Joran W., Jeffrey ALPEROVICH, Pratik CHAWLA, Jiayan MA, Tahira N. REID a Karthik RAMANI. The Design for Additive Manufacturing Worksheet. *Journal of Mechanical Design* [online]. 2017, **139**(10)

Principles and procedures in the design of production using additive technologies

1. The part has thin details or walls that are less than 0.8 mm for standard resolution or 0.4 - 0.5 mm for high resolution machines.

Because the AM principle is a "layer-by-layer" construction, something smaller or thinner often can't even be built.

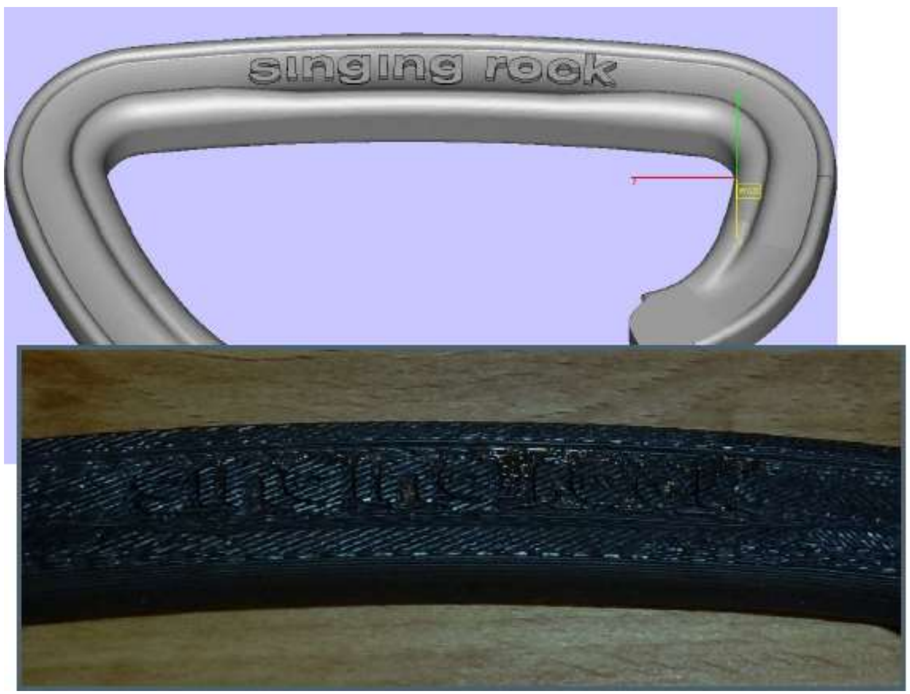
Great attention should be paid to raised or recessed logos and small text areas, "sharp" features that taper to zero thickness, and zigzag sections of any design where thickness can vary.

Principles and procedures in the design of production using additive technologies

The part has thin details or walls that are less than 0.8 mm for standard resolution or 0.4 - 0.5 mm for high resolution machines.

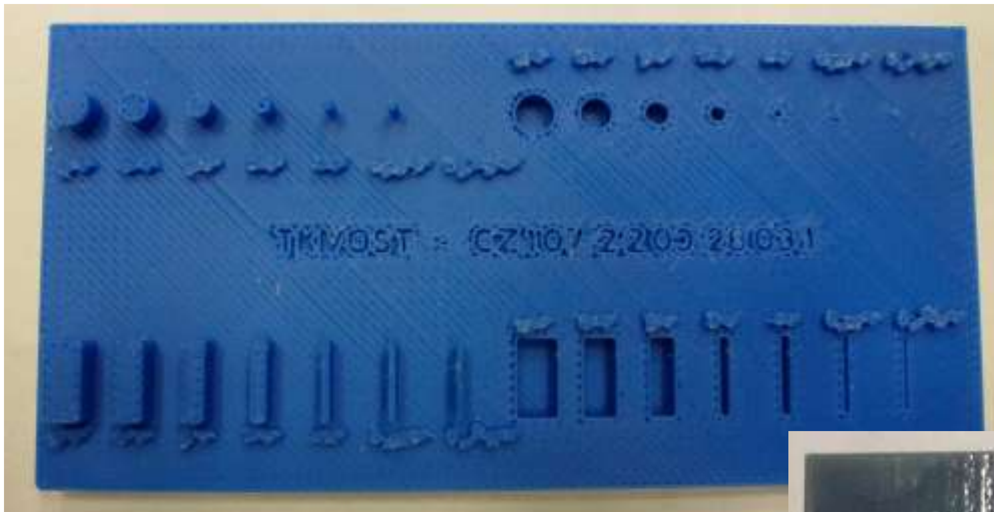
Principles and procedures in the design of production using additive technologies

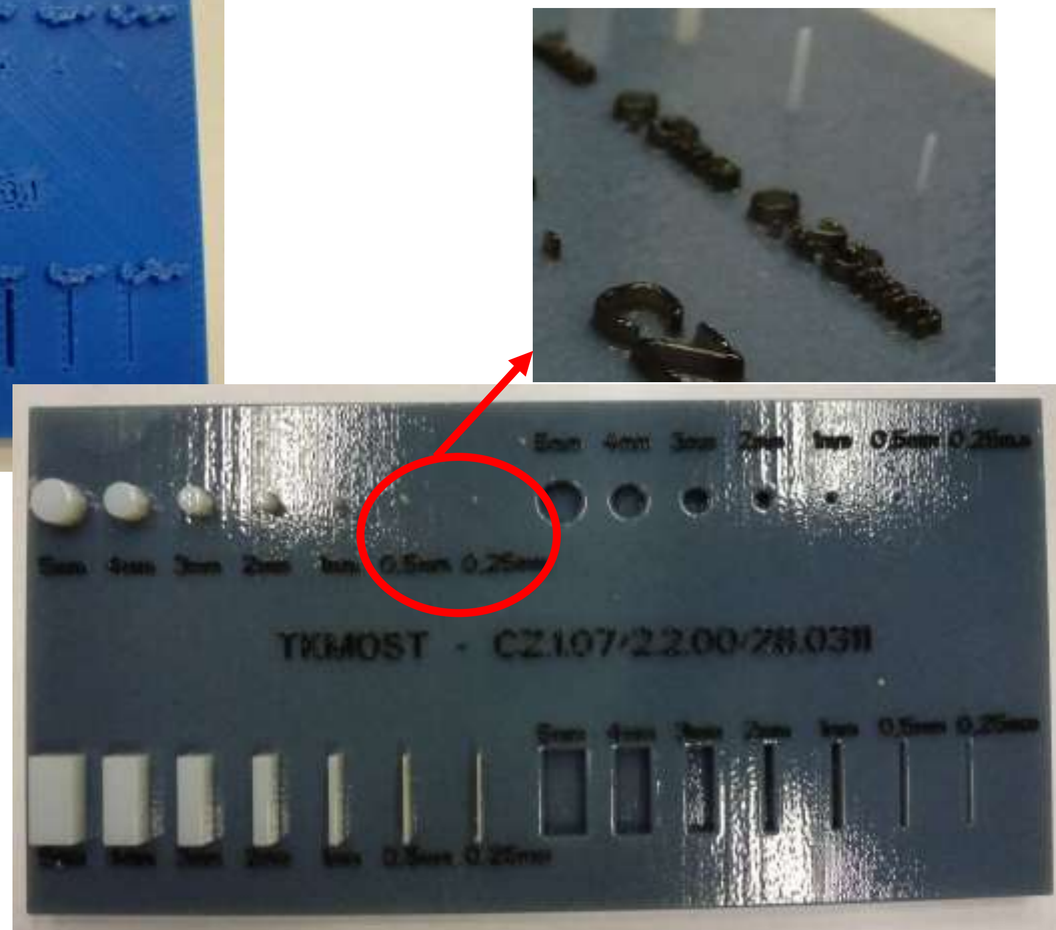
The part has thin details or walls that are less than 0.8 mm for standard resolution or 0.4 - 0.5 mm for high resolution machines.



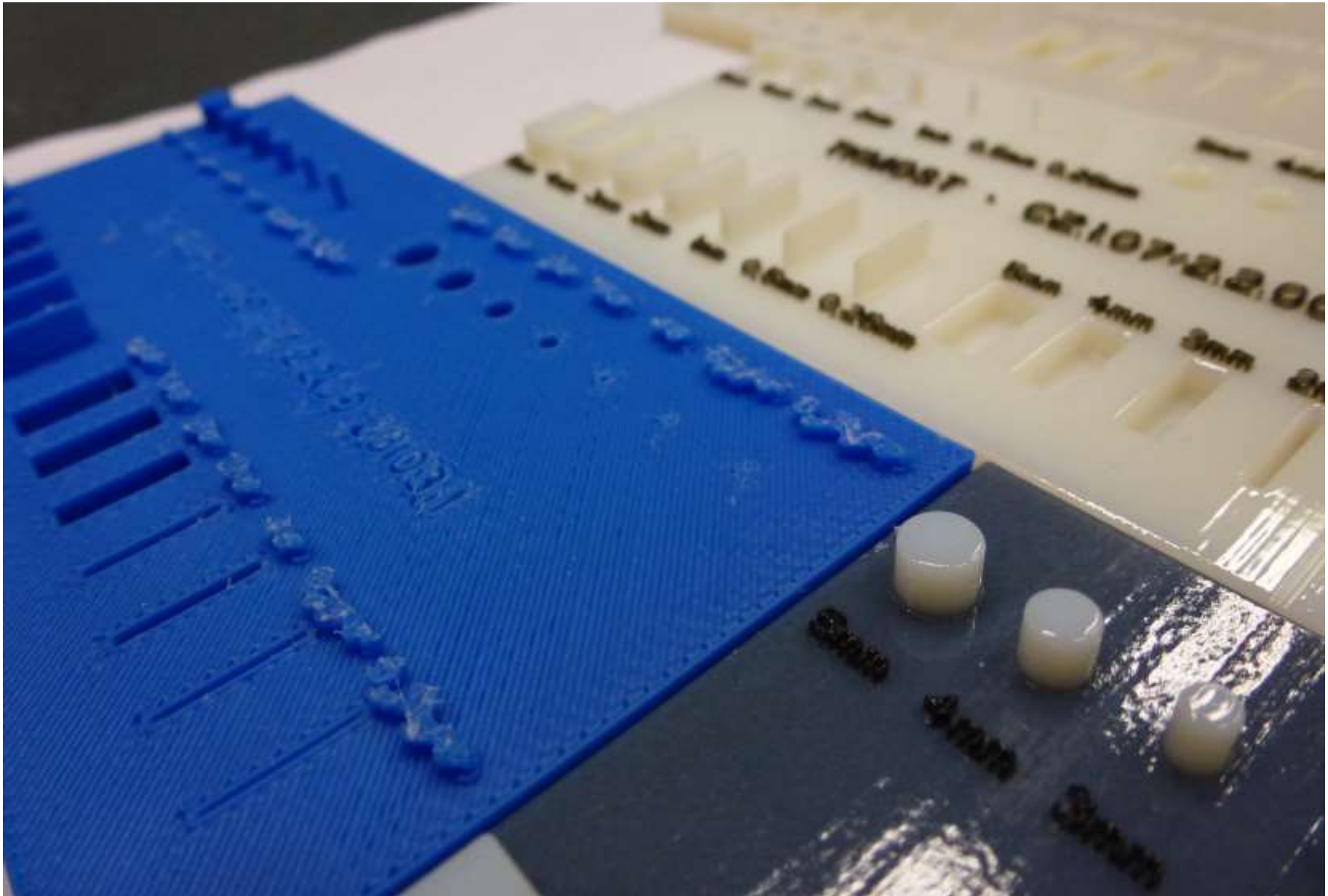
Principles and procedures in the design of production using additive technologies

Comparison of AM details of different technologies - left FDM, right Polyjet based on similar input data.





Principles and procedures in the design of production using additive technologies



Principles and procedures in the design of production using additive technologies

2. The native CAD model is converted to .STL format with very low resolution, which results in rough, large flat areas on the model surface.

If the resolution of the .STL file is too low, the model will be rough, instead of smooth surfaces and curves.

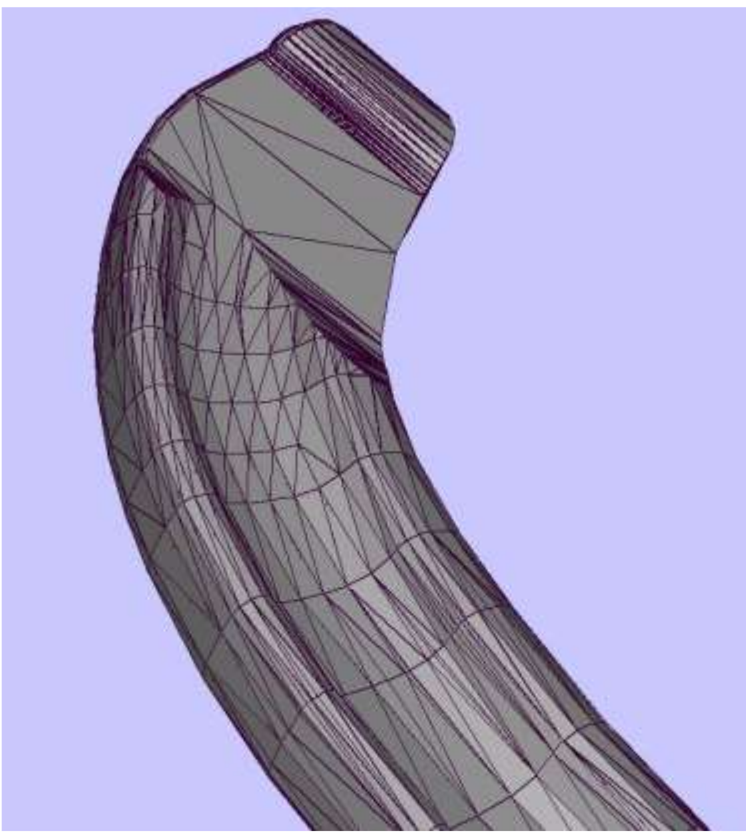
This is quite common and produces unattractive parts. To achieve a smooth surface on the model, the distance between the mesh points should be less than 0.2 mm.

Check the parameters of the native CAD program that is used to export .STL files.

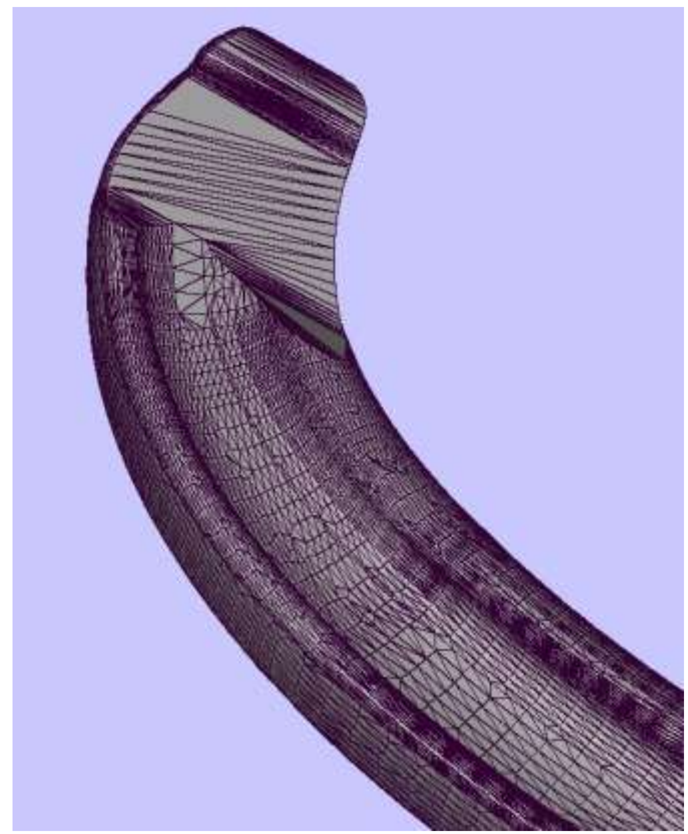
Principles and procedures in the design of production using additive technologies

The native CAD model is converted to .STL format with very low resolution, which results in rough, large flat areas on the model surface.

raw mesh

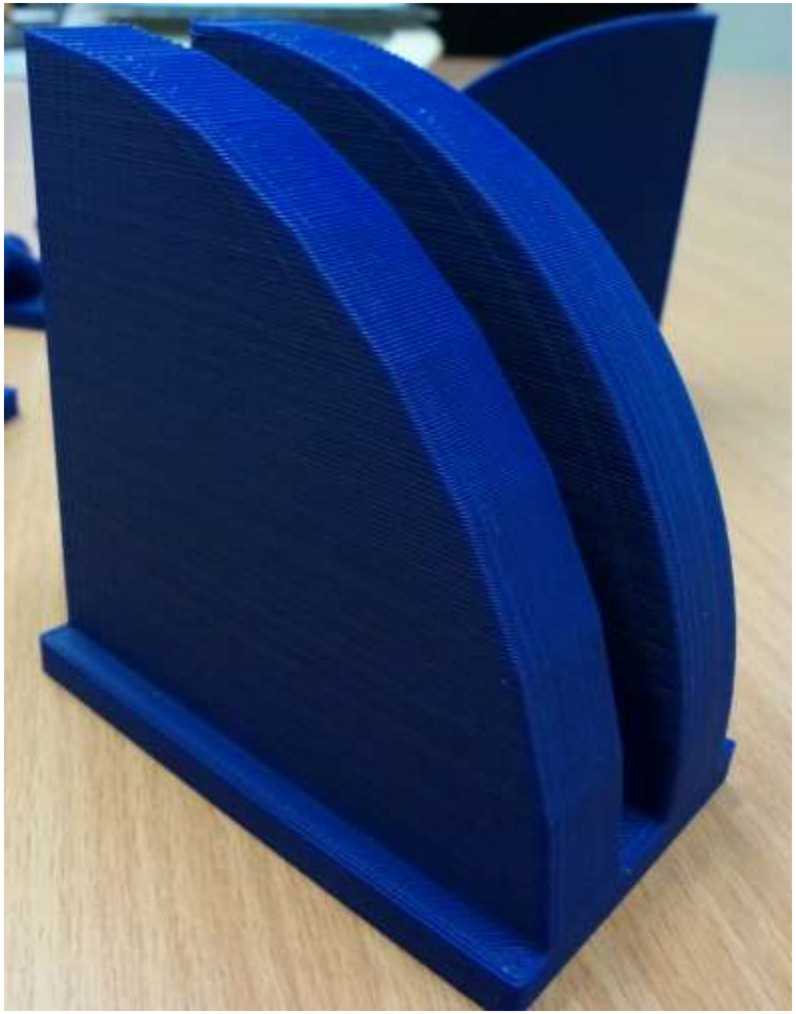


fine mesh



Principles and procedures in the design of production using additive technologies

The native CAD model is converted to .STL format with very low resolution, which results in rough, large flat areas on the model surface.



comparison of raw and fine mesh on the printed part
(CAD data were identical)

Principles and procedures in the design of production using additive technologies

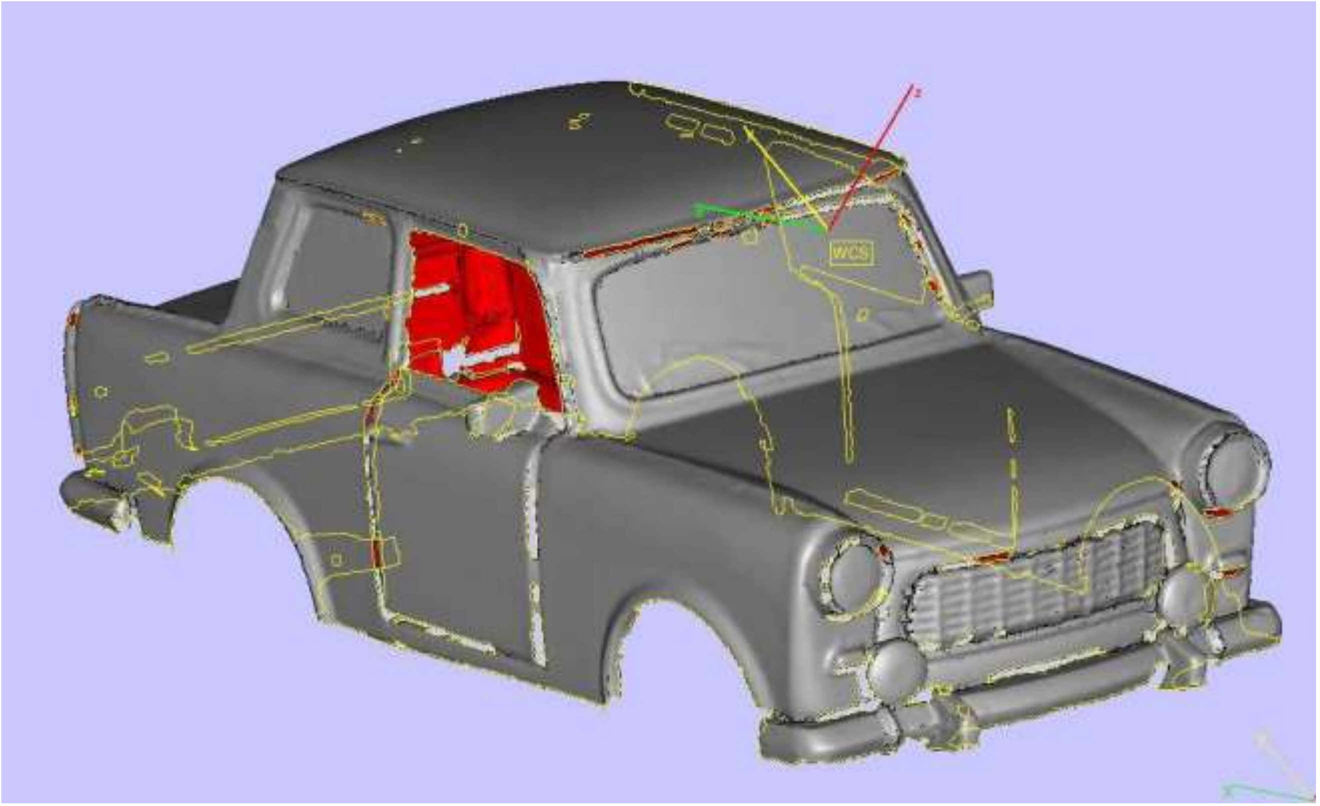
3. The original CAD data has many unconnected surfaces, which results in errors when converting to .STL format and subsequently also when printing.

Make sure that the surfaces in the original CAD model are ‘waterproof’ so that only volumes are modelled.

It is also better to check the .STL file to ensure that all dimensions, volumes and areas are in order.

Principles and procedures in the design of production using additive technologies

The original CAD data has many unconnected surfaces, which results in errors when converting to .STL format and subsequently also when printing.



Principles and procedures in the design of production using additive technologies

4. Part of the design is a closed hollow space from which the supporting material cannot be removed.

Each enclosed hollow volume will contain support materials that cannot be removed.

This area can also be filled with unused resin or powder according to the chosen prototyping method. Design the cavities so that they are either full or the construction is done in parts to allow access to the enclosure, or add holes in the model to allow the removal of supporting material.

Principles and procedures in the design of production using additive technologies

Part of the design is a closed hollow space from which the supporting material cannot be removed.

Principles and procedures in the design of production using additive technologies

5. Assemblies, threads and mating surfaces are designed with incorrect clearance.

Standard tolerances for most AM technologies start at +/- 0.1 mm. It is therefore common for individual parts constructed in nominal dimensions to "not fit" into each other.

Typically, the interlocking parts should be designed with clearance (for FDM up to 0.4 - 0.5 mm, depending on the orientation).

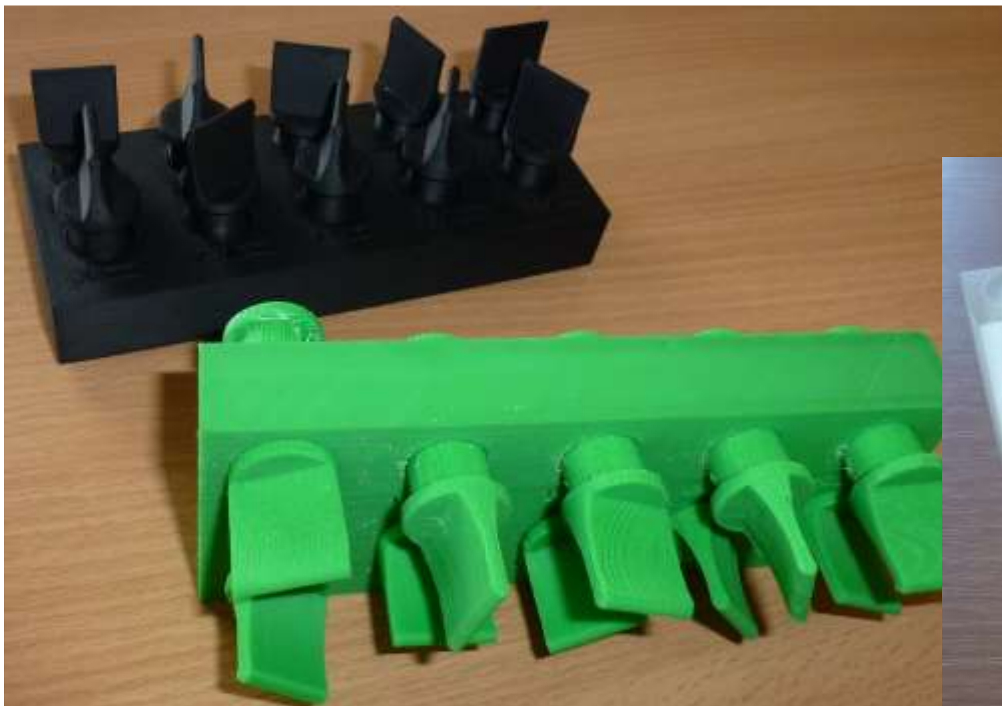
This is important to keep in mind for the success of the project. It depends on how well the different parts can or cannot be assembled together.

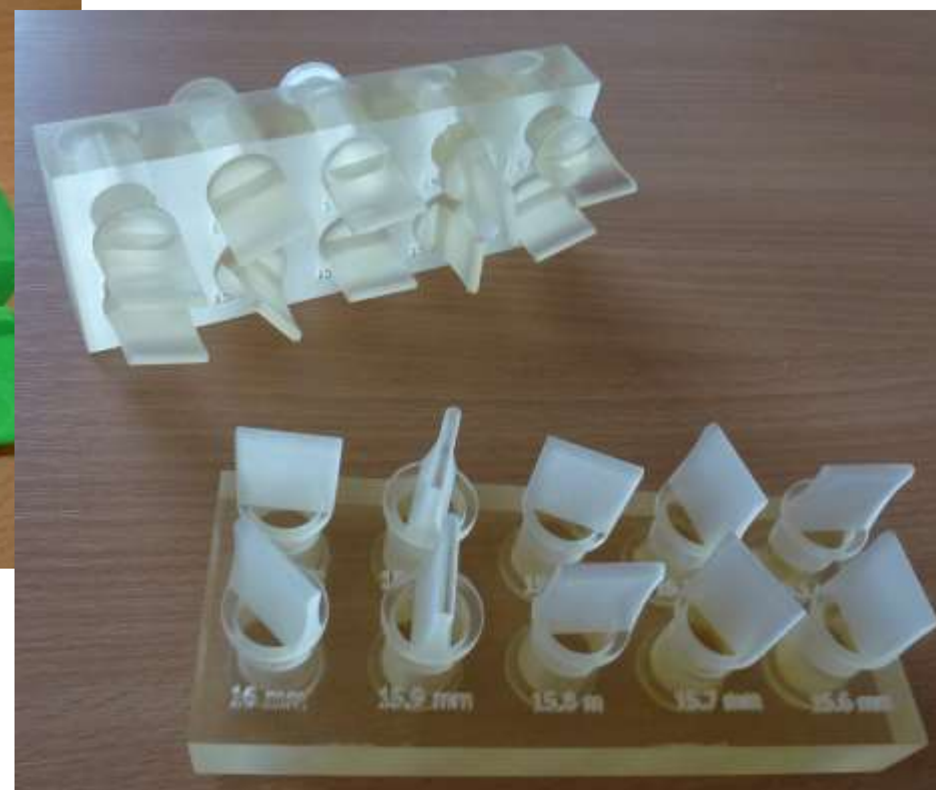
Principles and procedures in the design of production using additive technologies

Assemblies and mating surfaces were designed in this case with the right clearance – the mechanisms are functional.

Principles and procedures in the design of production using additive technologies

Assembly of base with holes and pins to verify the amount of clearances required for different orientations and different technologies (FDM and PolyJet)





Principles and procedures in the design of production using additive technologies

6. The design contains some special elements that are difficult to make by additive manufacturing. E.g. flexible hinges, clips etc. common to injection-molded parts.

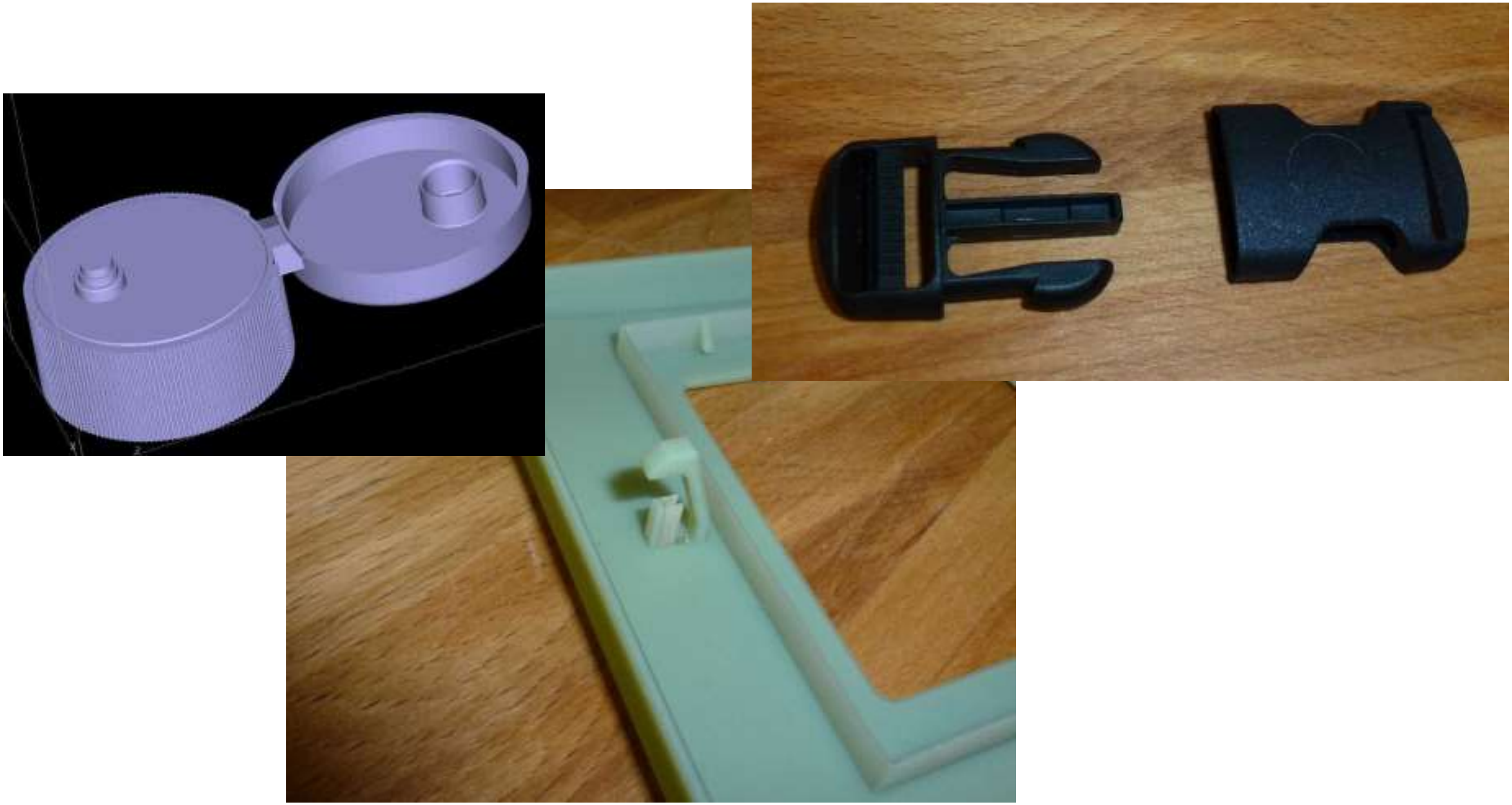
Designed hinges, clips etc. on most parts manufactured using AM technology usually do not work as intended.

The building material is often too rigid and breaks. However, several materials have been developed to meet this requirement (e.g. Duraform EX using the SLS process or flexible materials for PolyJet Printing).

The orientation of the model during construction is also important.

Principles and procedures in the design of production using additive technologies

The design contains some special features that are difficult to make by additive manufacturing. For example, flexible hinges, clips, etc.



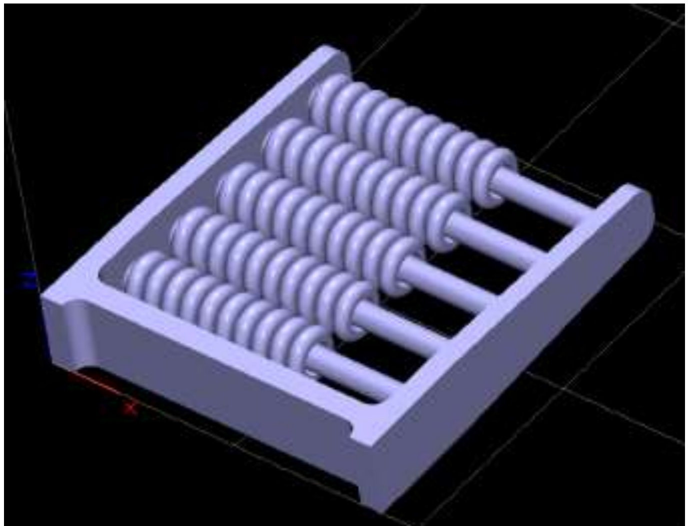
Principles and procedures in the design of production using additive technologies

7. Respect the area of the first layer. The first layer is fundamental for fixing the part in the printer's workspace throughout the whole building process.

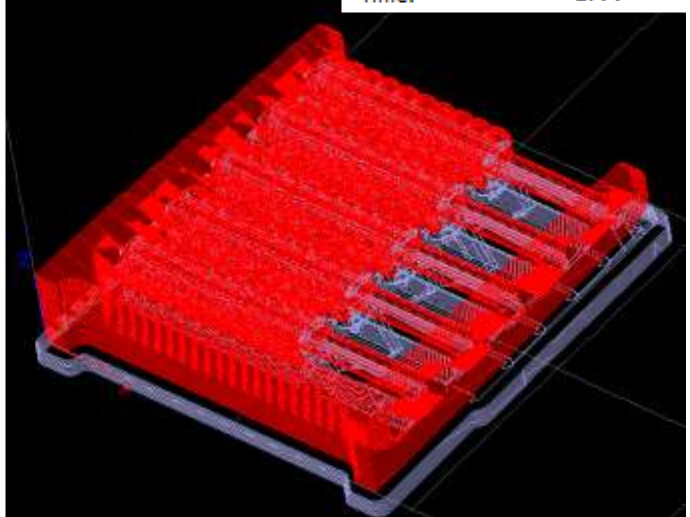
Orientation of the model during preparation is again important.

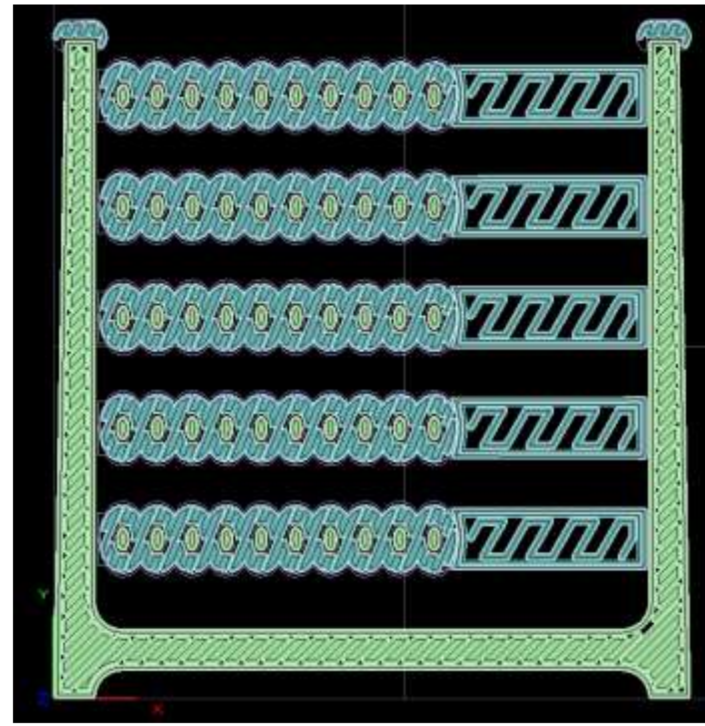
Principles and procedures in the design of production using additive technologies

Printing of the ball counter model.



Model Material:	7,13 cm³
Support Material:	4,07 cm³
Time:	1:44

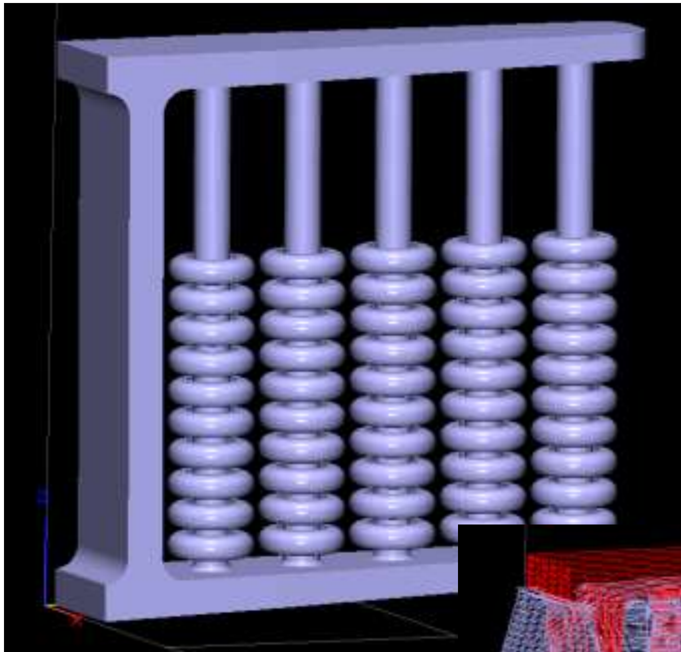




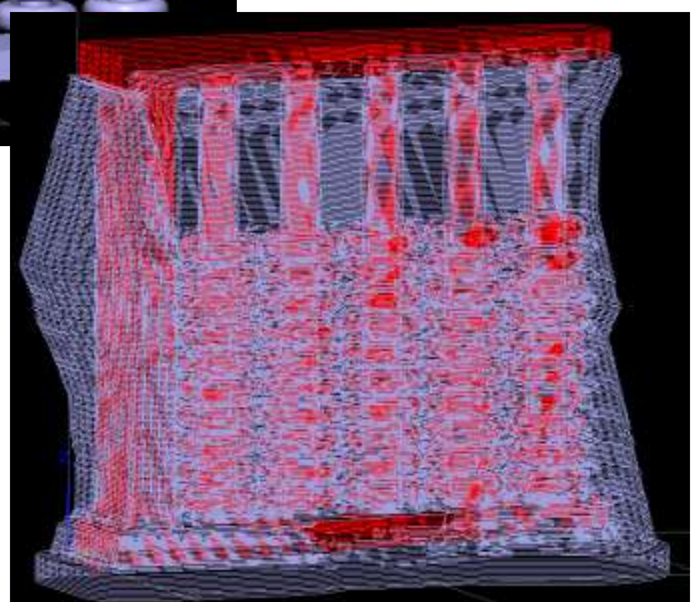
But the first layer areas of balls are too small – this is not optimal orientation!

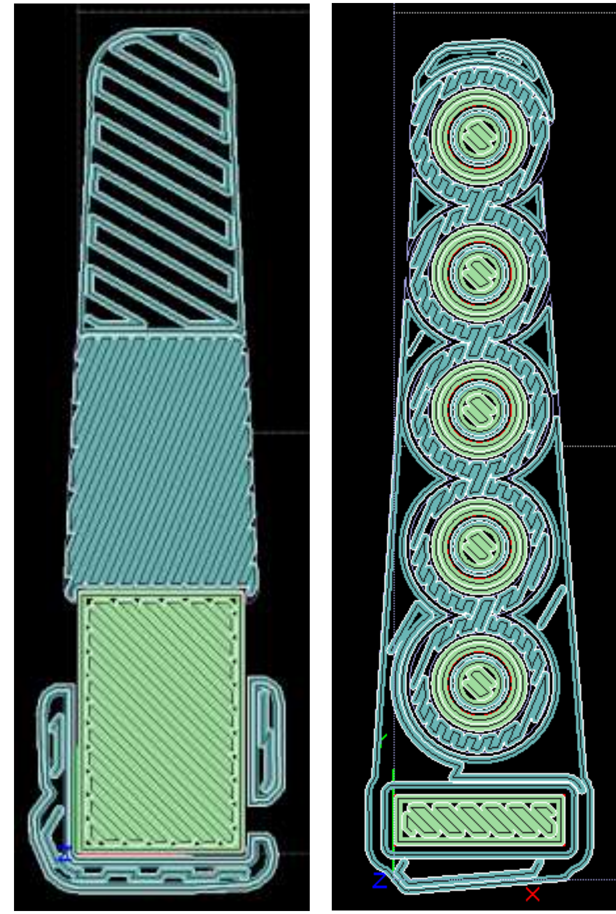
Principles and procedures in the design of production using additive technologies

Printing of the ball counter model.



Model Material:	6,93 cm³
Support Material:	7,66 cm³
Time:	3:04





Bigger the first layer areas – printing was OK.

Principles and procedures in the design of production using additive technologies

8. The units of data in the .STL file are different from what was intended.

STL data is exported without units - the file contains only dimensionless coordinate numbers of points of the polygonal mesh.

Therefore, it is better to double-check the parameters of the .STL files to make sure that the correct units are selected.

This is especially true if more than one part is being built. Some CAD programs have default settings for exporting a .STL file to units other than those used during the design process (typically Inventor has exported STL data in cm in the past!).

Principles and procedures in the design of production using additive technologies

The units of data in the .STL file are different from what was intended.

```
solid Default
  facet normal 9.965138e-01 8.302967e-02 8.140126e-03
    outer loop
      vertex 3.846057e+01 1.691150e+01 1.327663e+00
      vertex 3.846057e+01 1.678188e+01 2.649771e+00
      vertex 3.868277e+01 1.426173e+01 1.153604e+00
    endloop
  endfacet
  facet normal 9.965144e-01 8.302087e-02 8.155012e-03
    outer loop
      vertex 3.868277e+01 1.426173e+01 1.153604e+00
      vertex 3.846057e+01 1.678188e+01 2.649771e+00
      vertex 3.868277e+01 1.414878e+01 2.303505e+00
    endloop
  endfacet
  facet normal 1.000000e+00 0.000000e+00 0.000000e+00
    outer loop
      vertex 3.868277e+01 1.414878e+01 2.303505e+00
      vertex 3.868277e+01 9.445481e+00 1.685040e+00
      vertex 3.868277e+01 1.426173e+01 1.153604e+00
    endloop
  endfacet
  facet normal 1.000000e+00 0.000000e+00 0.000000e+00
    outer loop
      vertex 3.868277e+01 1.426173e+01 1.153604e+00
      vertex 3.868277e+01 9.445481e+00 1.685040e+00
      vertex 3.868277e+01 9.528807e+00 8.443715e-01
    endloop
  endfacet
```

?

µm, mm, cm, m

or mills, inches ?

Principles and procedures in the design of production using additive technologies

9. Take advantage of additive technologies - parts can be designed more complex than for other production technologies. This makes it possible to simplify subsequent assembly.

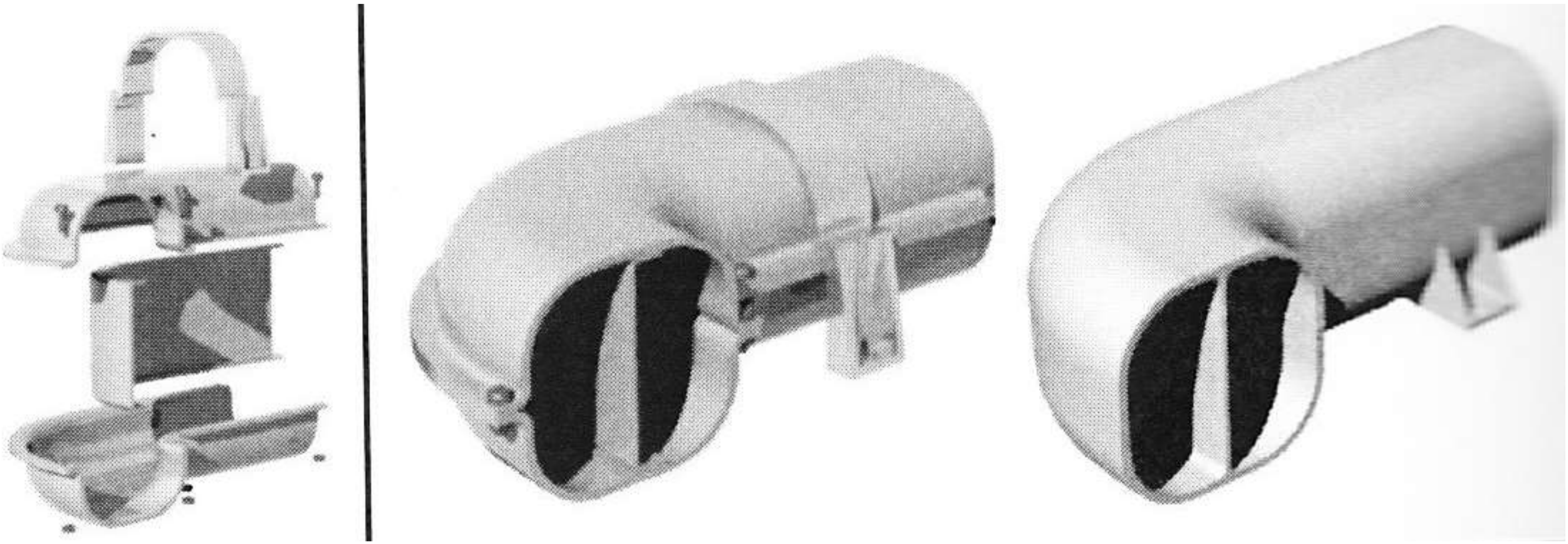
Additive technologies lead to a change in thinking and approach to component design.

It is possible to combine some parts into one final part and thus simplify assembly, subsequent maintenance, etc. - 'design for function'.

It is possible to produce parts that cannot be produced by other technologies.

Principles and procedures in the design of production using additive technologies

Take advantage of additive technologies – ‘design for function’.

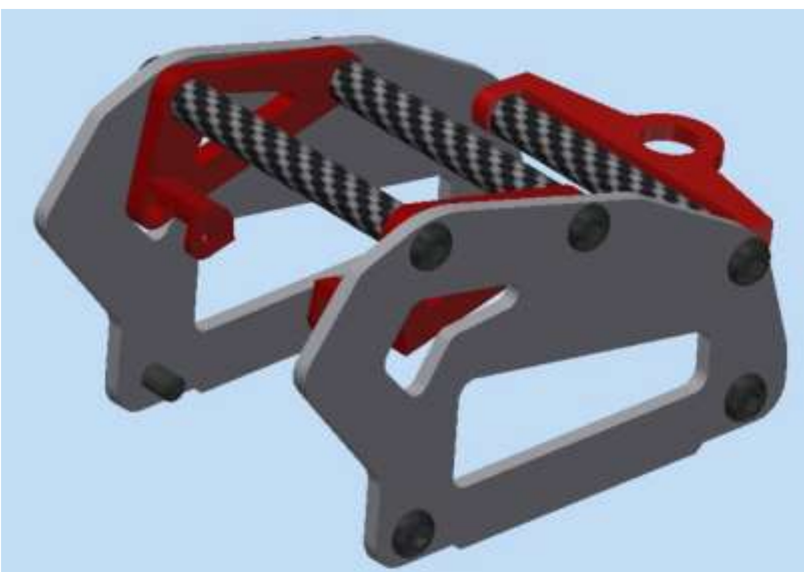


Principles and procedures in the design of production using additive technologies

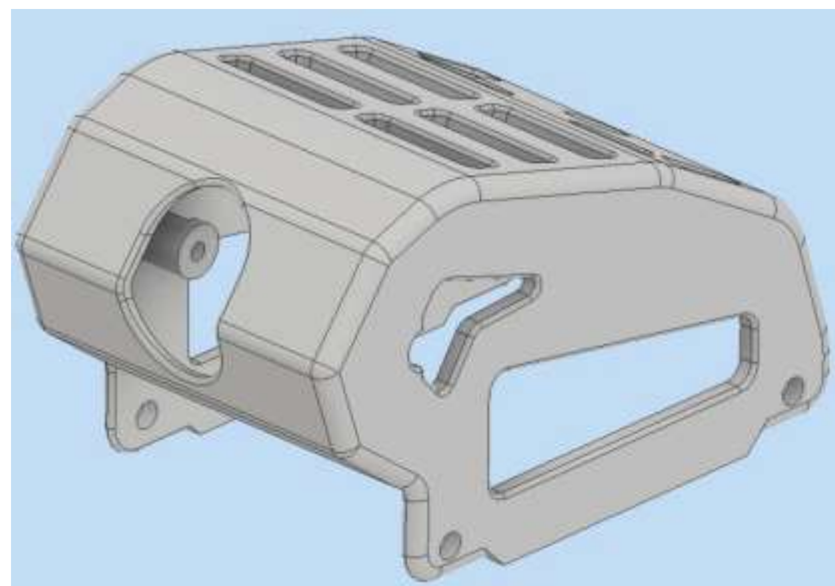
Take advantage of additive technologies – 'design for function'.

Example realized on KSA - electronics cover of modular FPV drone:

assembly of approx. 14 parts on the basis of milled side parts:



only one part for 3D printing by MJF technology:



Principles and procedures in the design of production using additive technologies

comparison of both versions of drones

	Machined version	3D printed version (MJF)
Base weight (without battery)	336 g	212 g
Base production cost	€ 23	€ 56
Number of base parts	12 + 10 screws M3	3 + 4 screws M3

Principles and procedures in the design of production using additive technologies

Summary:

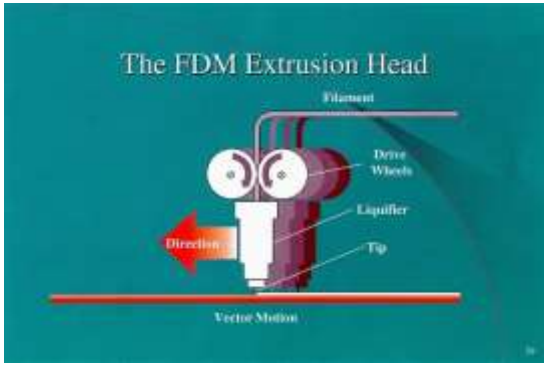
Keep these principles in mind when considering the use of additive manufacturing to build a part.

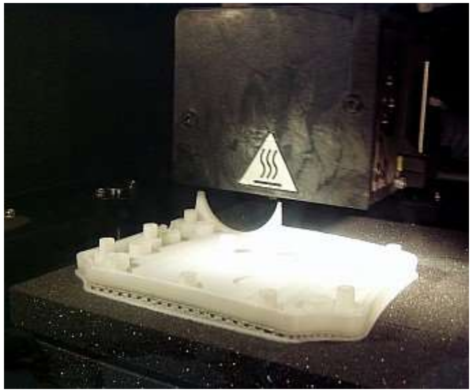
Pay attention to the integrity of the original CAD data, flexible elements (hinges), closed or hollow spaces, clearance between assembled parts, details or walls that are smaller or thinner than approx. 0.8 mm.

After exporting the .STL file from the native CAD file, verify that the overall resolution of the file is sufficient and that the selected units are selected correctly.

3D printing with FDM technology at KSA

System Dimension sst 768

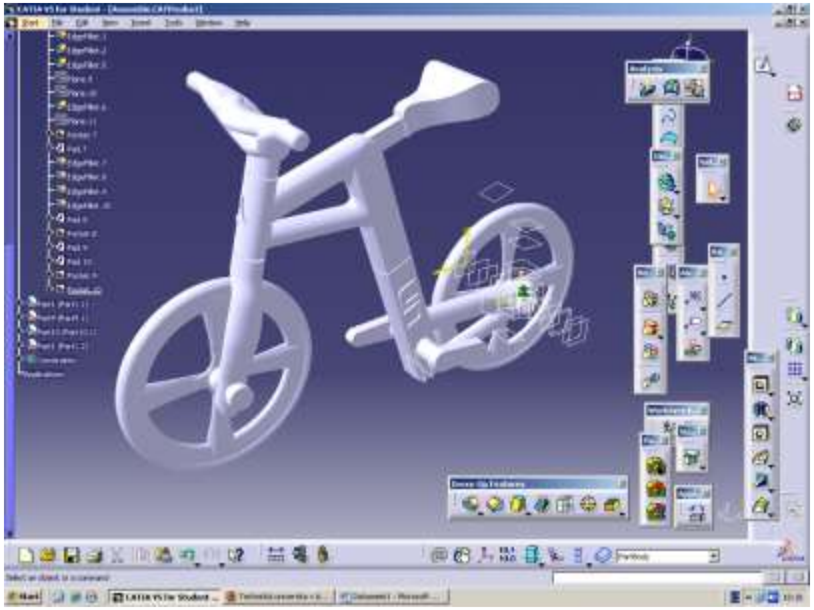


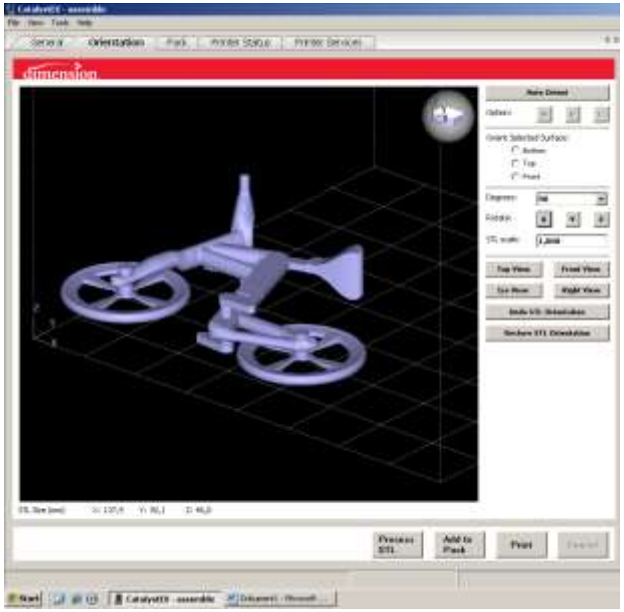


Equipment for fast manufacturing of functional models from ABS by FDM technology.

Working space: 203 x 203 x 305 mm

Prototype manufacturing procedure on Dimension sst 768

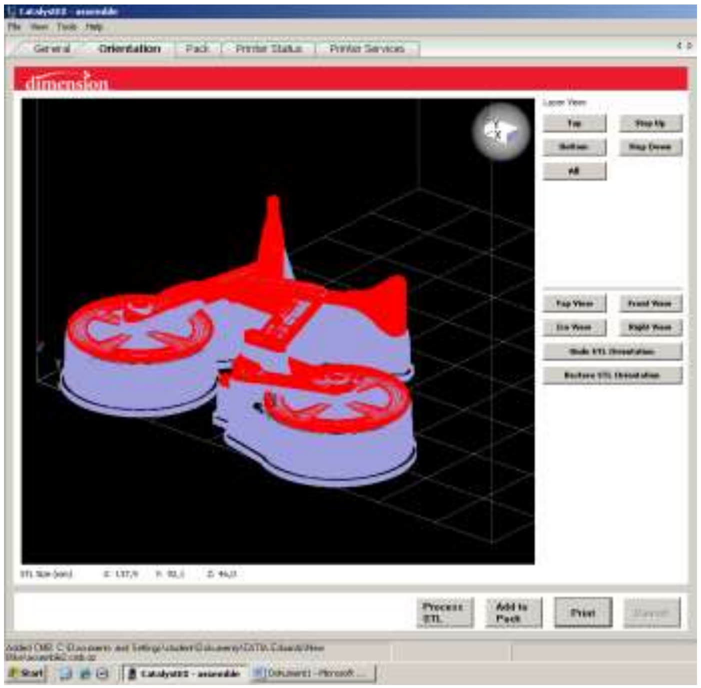


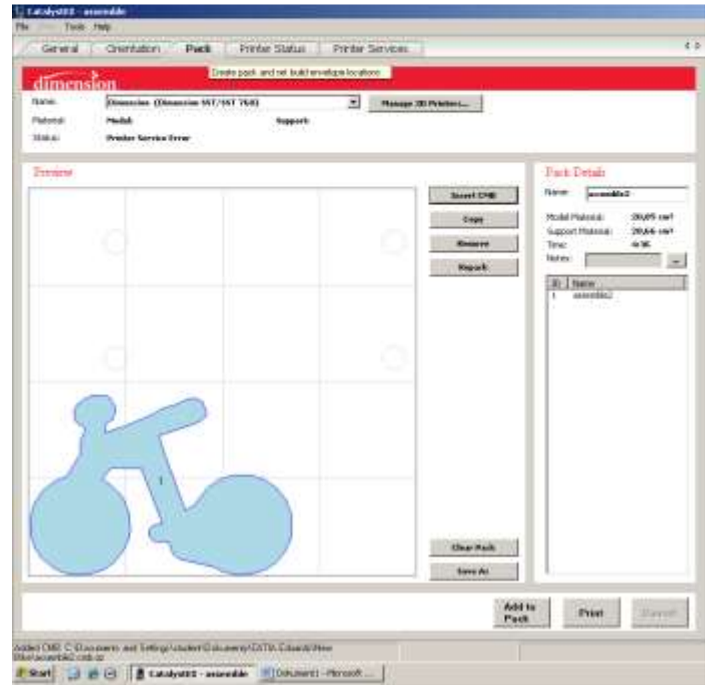


3D data – any CAD and data export to * .STL format

opening the * .STL file in CatalystEX software (Dimension machine accessory)

Prototype manufacturing procedure on Dimension sst 768





positioning the part and starting the process of division into layers and generating supports

placement on the pack, checking material and time consumption and sending it to the machine

Prototype manufacturing procedure on Dimension sst 768

machine

view into the working space of the machine during building

Prototype manufacturing procedure on Dimension sst 768

finished part, including supports

insertion into the liquid (solution with sodium hydroxide) to dissolve the supports

Prototype manufacturing procedure on Dimension sst 768

finished part

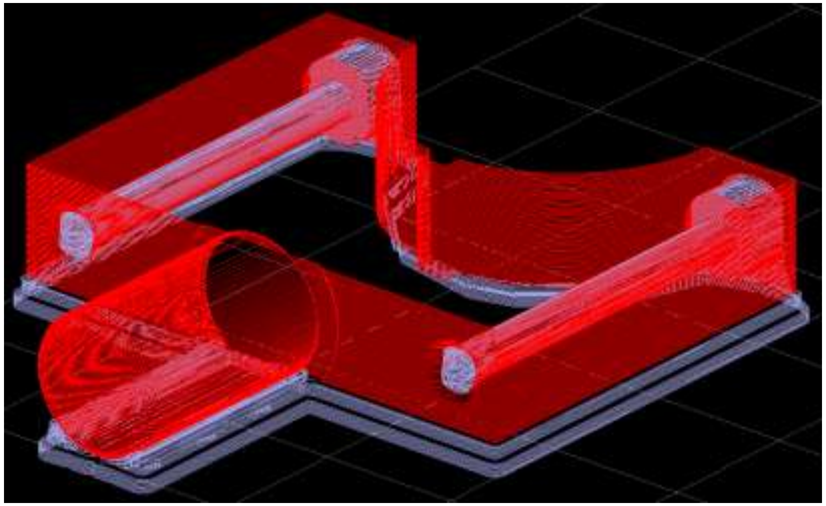
Samples of manufactured parts on the Dimension sst 768

Orientation of the part in the working space of the machine

- affects:

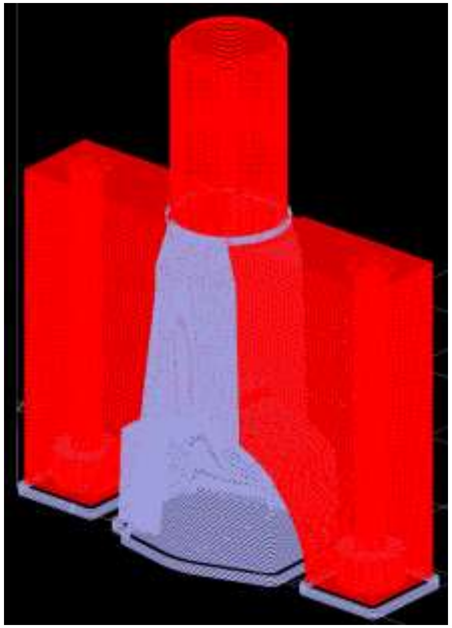
- consumption of material, in particular supporting
- the building time and thus the cost of building the part,
- the quality of the surface of the part and thus the complexity of finishing operations,
- last but not least, the mechanical properties - a number of additive technologies show inhomogeneity of parts in different directions (typically less strength in the planes of connection of individual layers)

Example of the effect of part orientation on the volume of material used



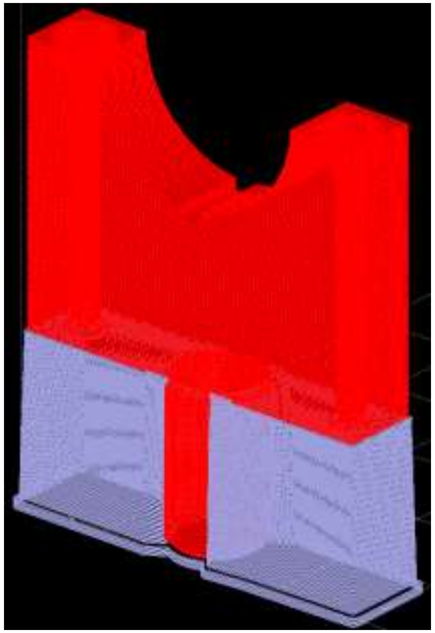
Model material:
131,8 cm^3

Support material:
16,6 cm^3



Model material:
131,3 cm^3

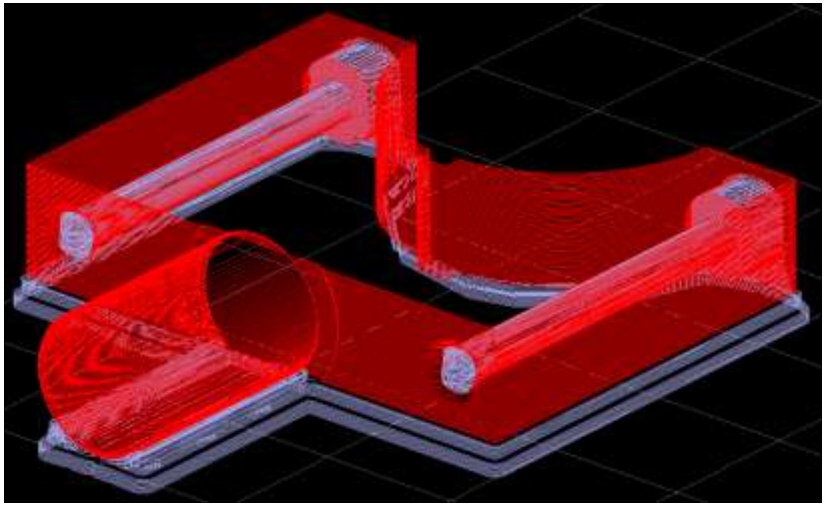
Support material:
12,0 cm^3



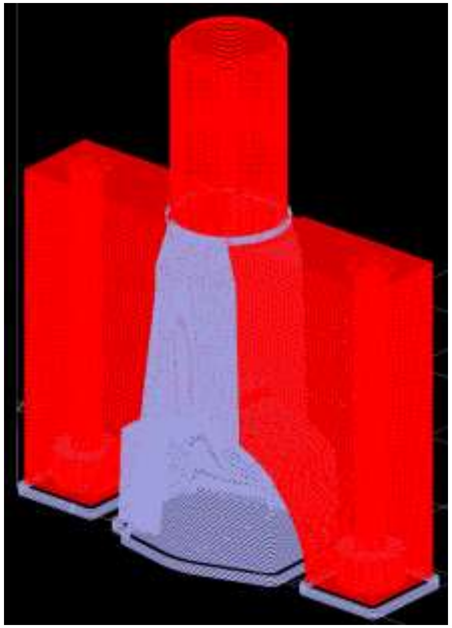
Model material:
131,2 cm^3

Support material:
15,8 cm^3

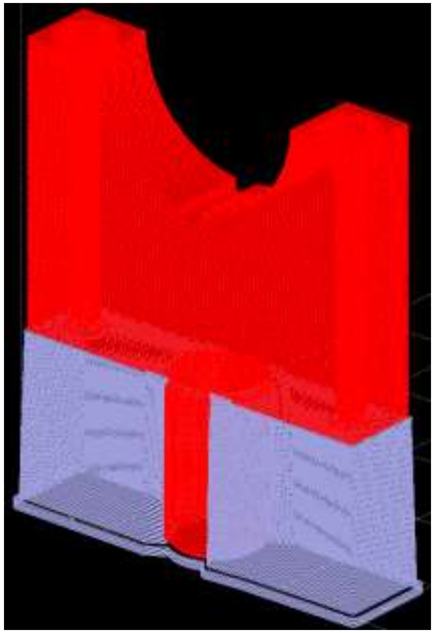
Example of the effect of part orientation on the building time



Estimated building time:
6:41 hours:min

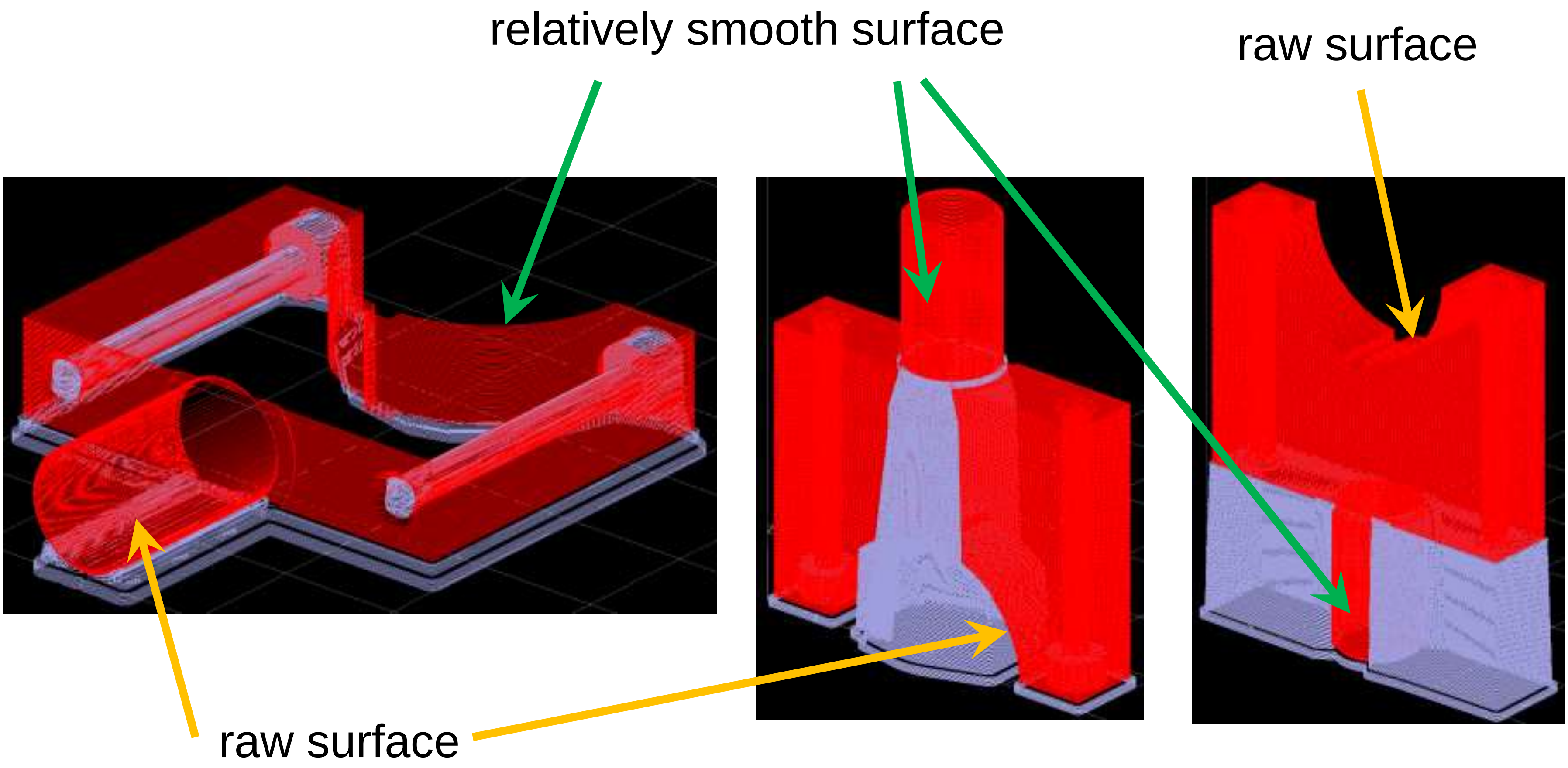


Estimated building time:
9:33 hours:min



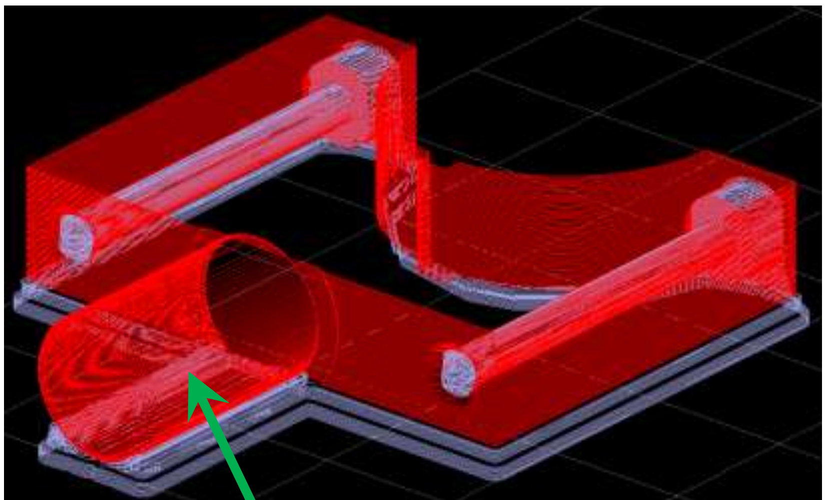
Estimated building time:
8:59 hours:min

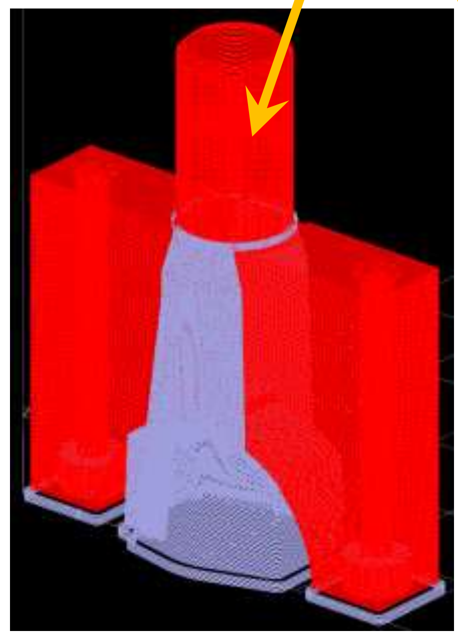
Example of the effect of part orientation on the surface quality

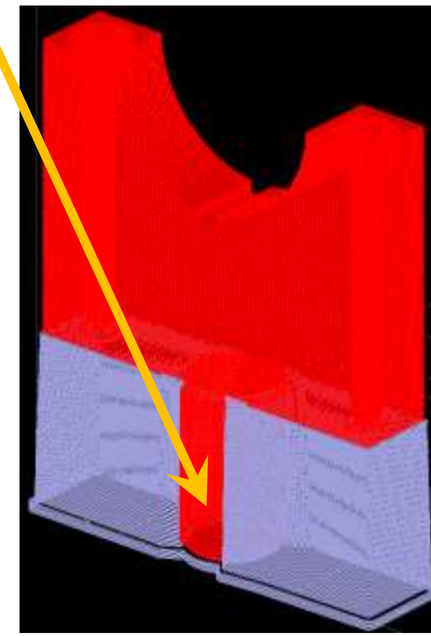


Example of the effect of part orientation on its strength

low strength when loading the pin (the force acts perpendicular to the plane of the layers)

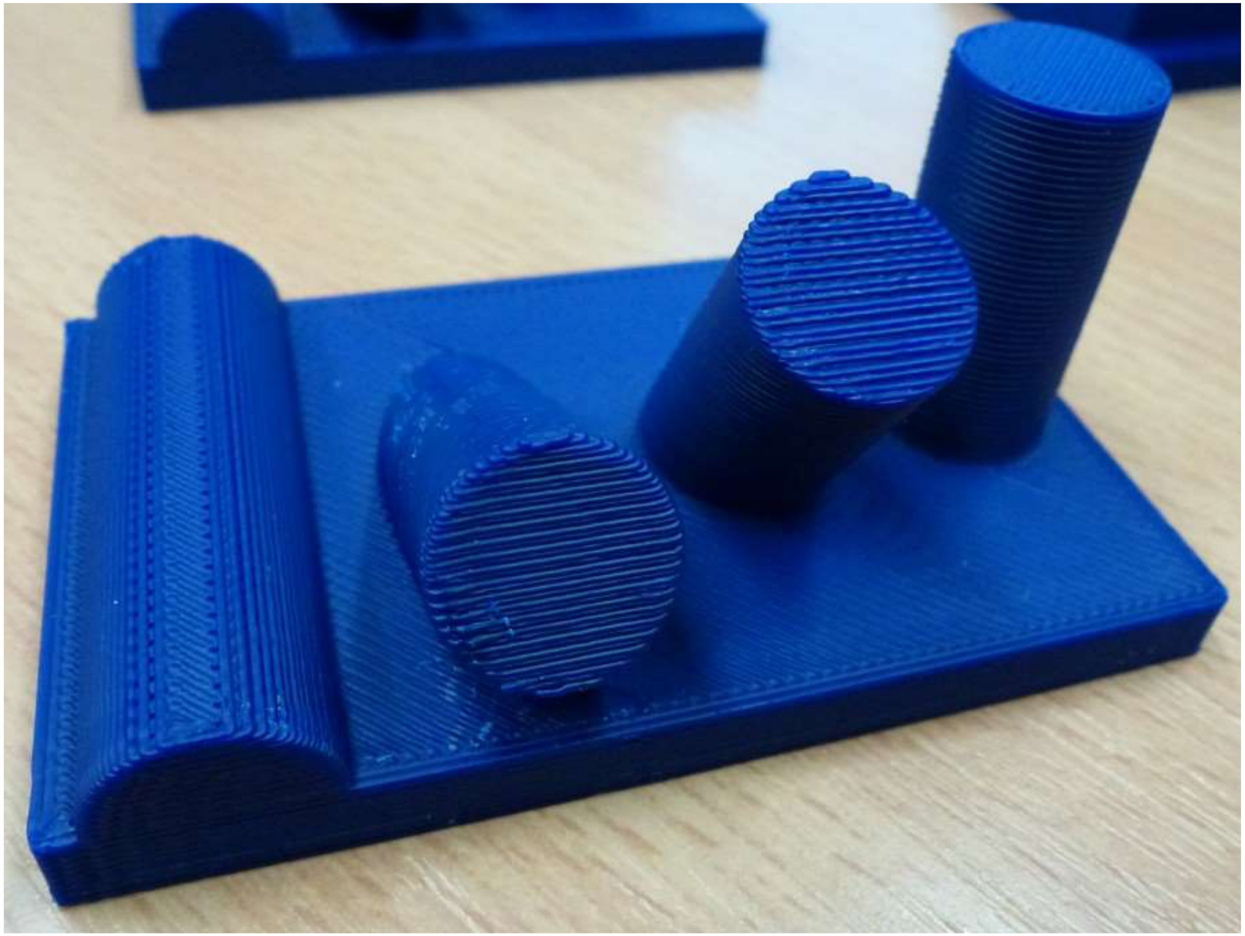






good strength of the pin under its load (the force acts parallel to the planes of the layers)

Example of the effect of part orientation on the surface quality

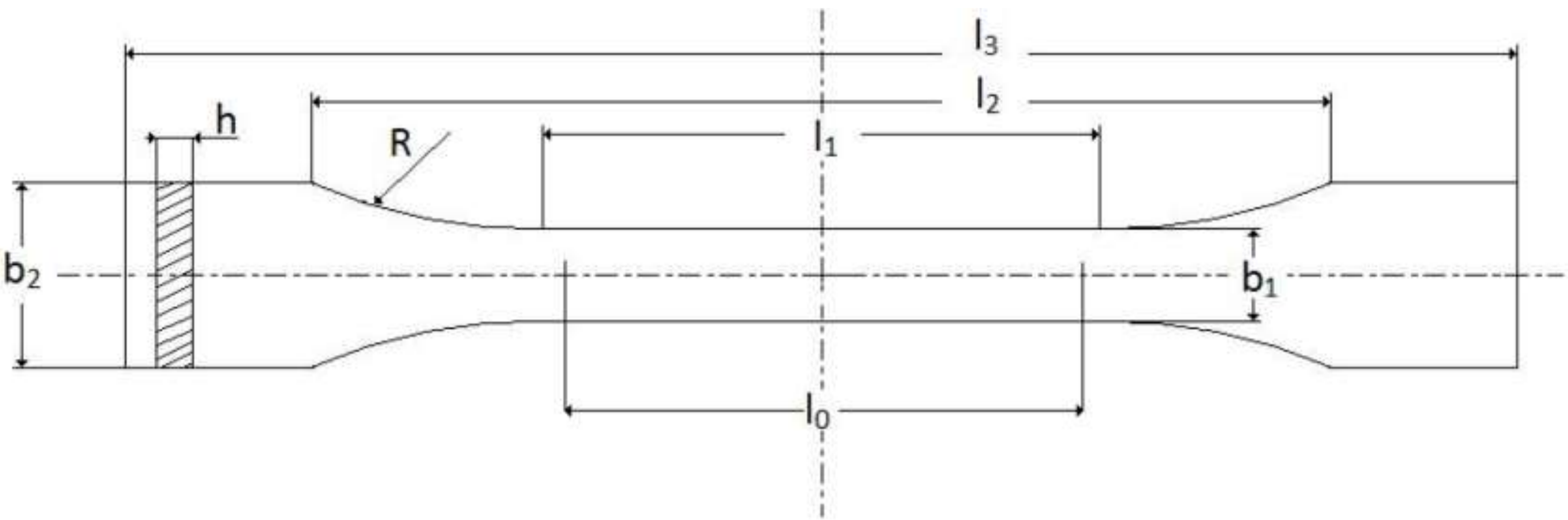


Experiment - the influence of different settings of printing parameters on the resulting properties of models

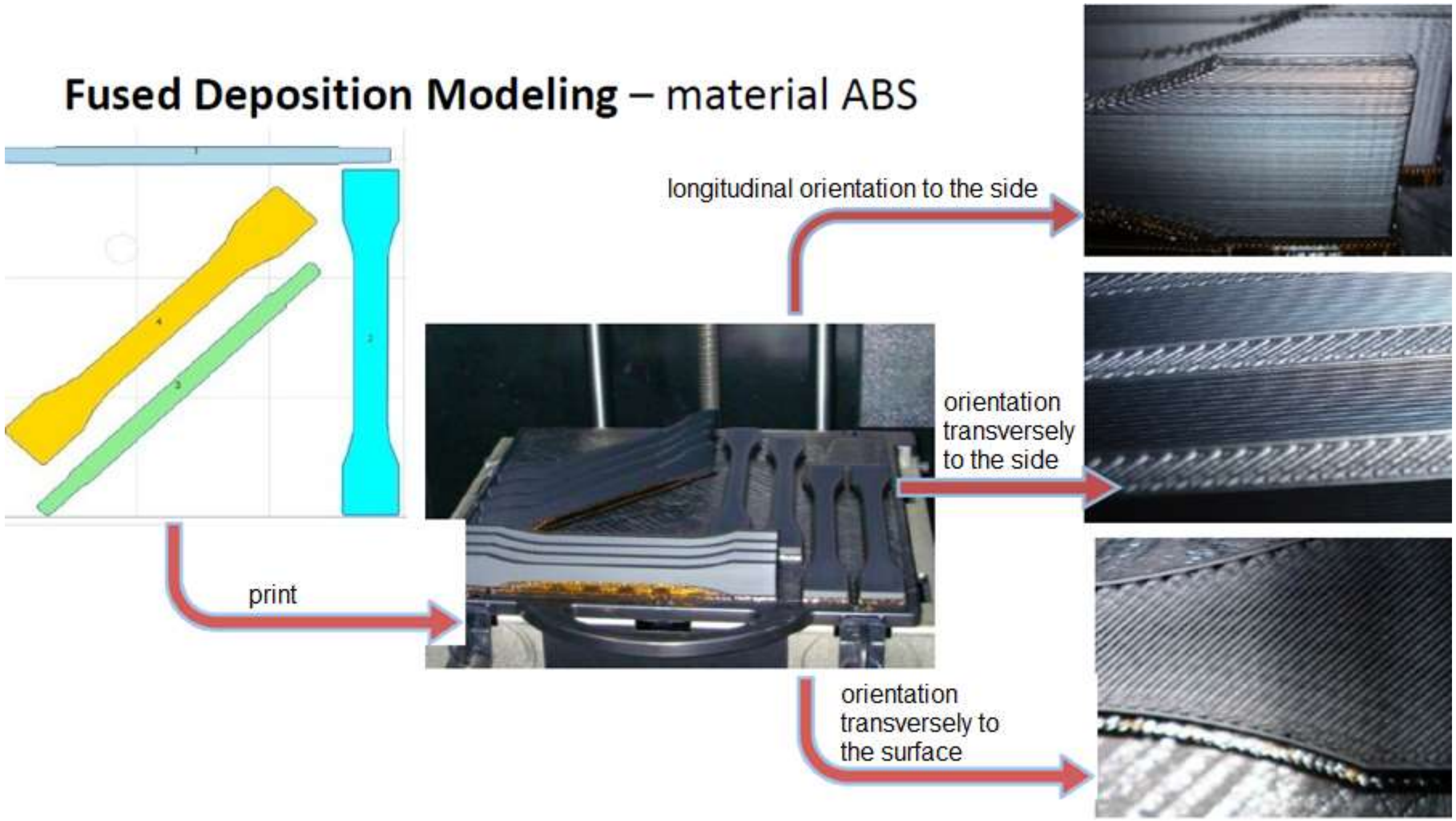
Experiment goals:

- Find out how much the orientation of the built part in the workspace of the 3D printer affects the resulting mechanical properties of the part.
- To determine the effect of subsequent heat treatment (tempering) of printed parts on mechanical properties.
- To determine the effect of natural aging of the printed part on its mechanical properties.
- Verify the material parameters specified by the manufacturer

Test specimen - according to ČSN EN ISO 527-2

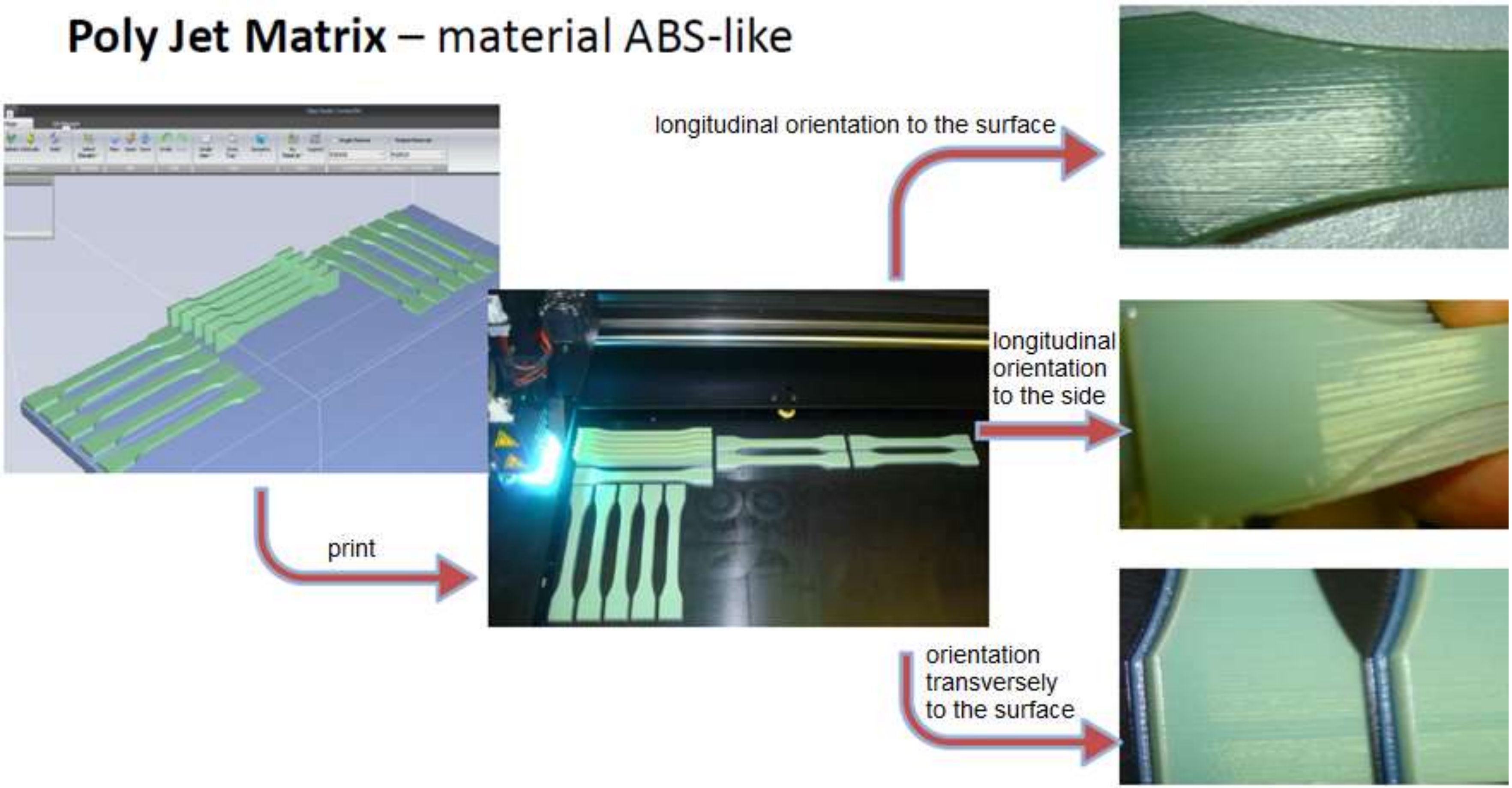


Methods of orientation and manufacturing of samples



Methods of orientation and manufacturing of samples

Poly Jet Matrix – material ABS-like



Methods of orientation and manufacturing of samples

Poly Jet Matrix – subsequent operations

- Tempering

Target temperature:
80°C
Time:
7 hours

Target temperature:
100°C
Time:
9 hours

process of tempering 1

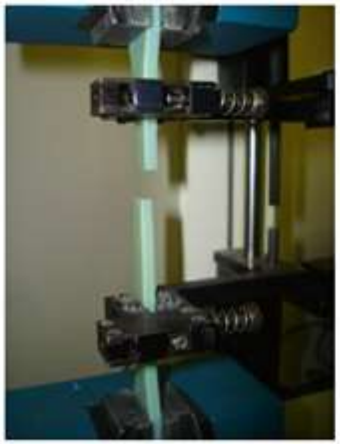
process of tempering 2

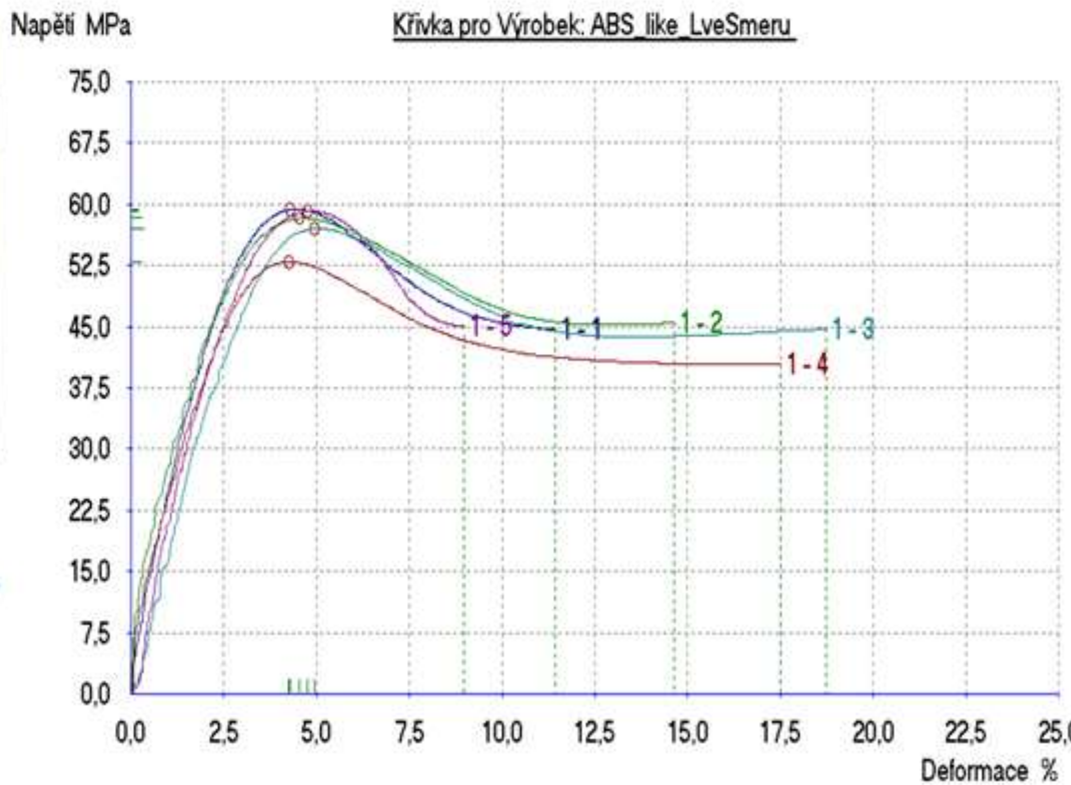
- Aging

Room temperature:
22°C
Time:
3 months

Tensile test

Hounsfield H10KT

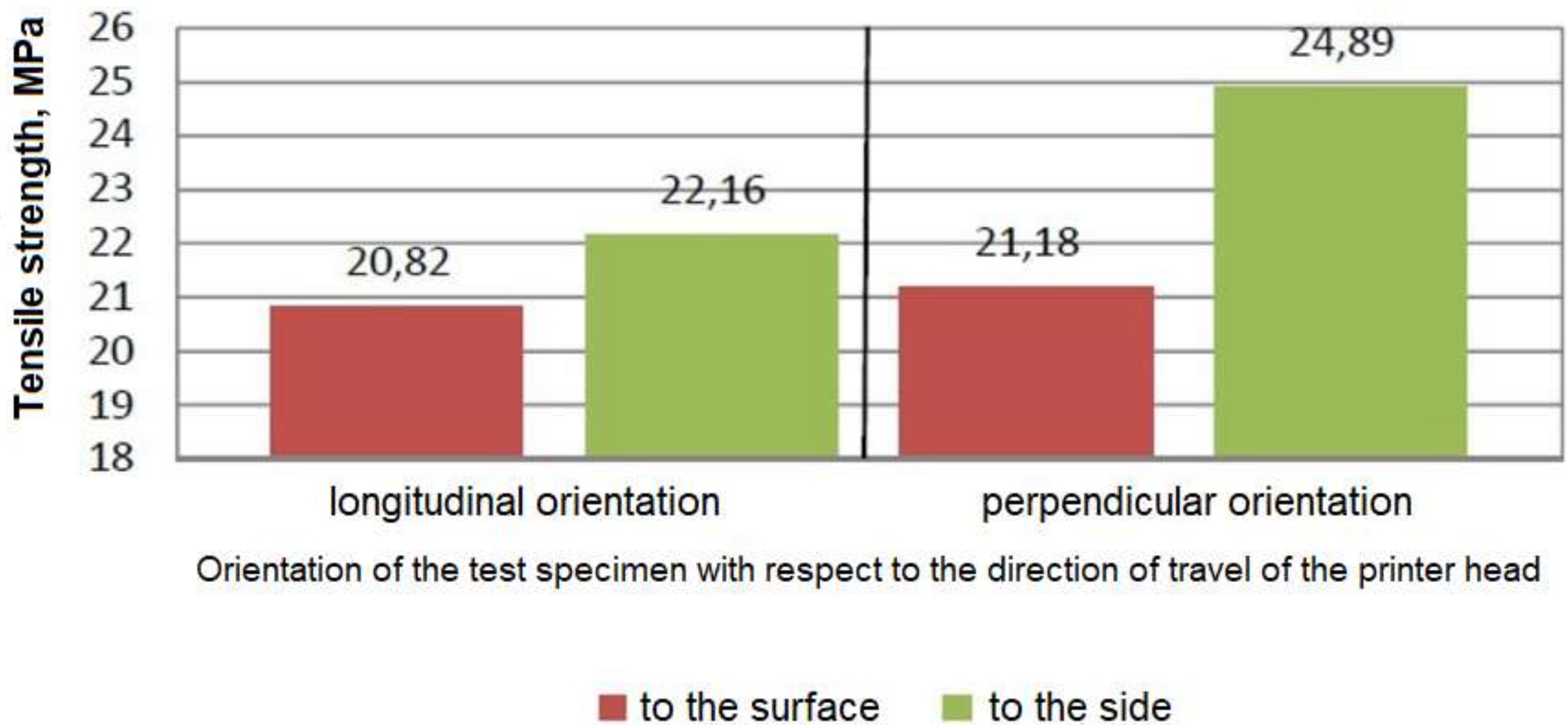




Results

Tensile strength stated by the material manufacturer: 34.5 MPa

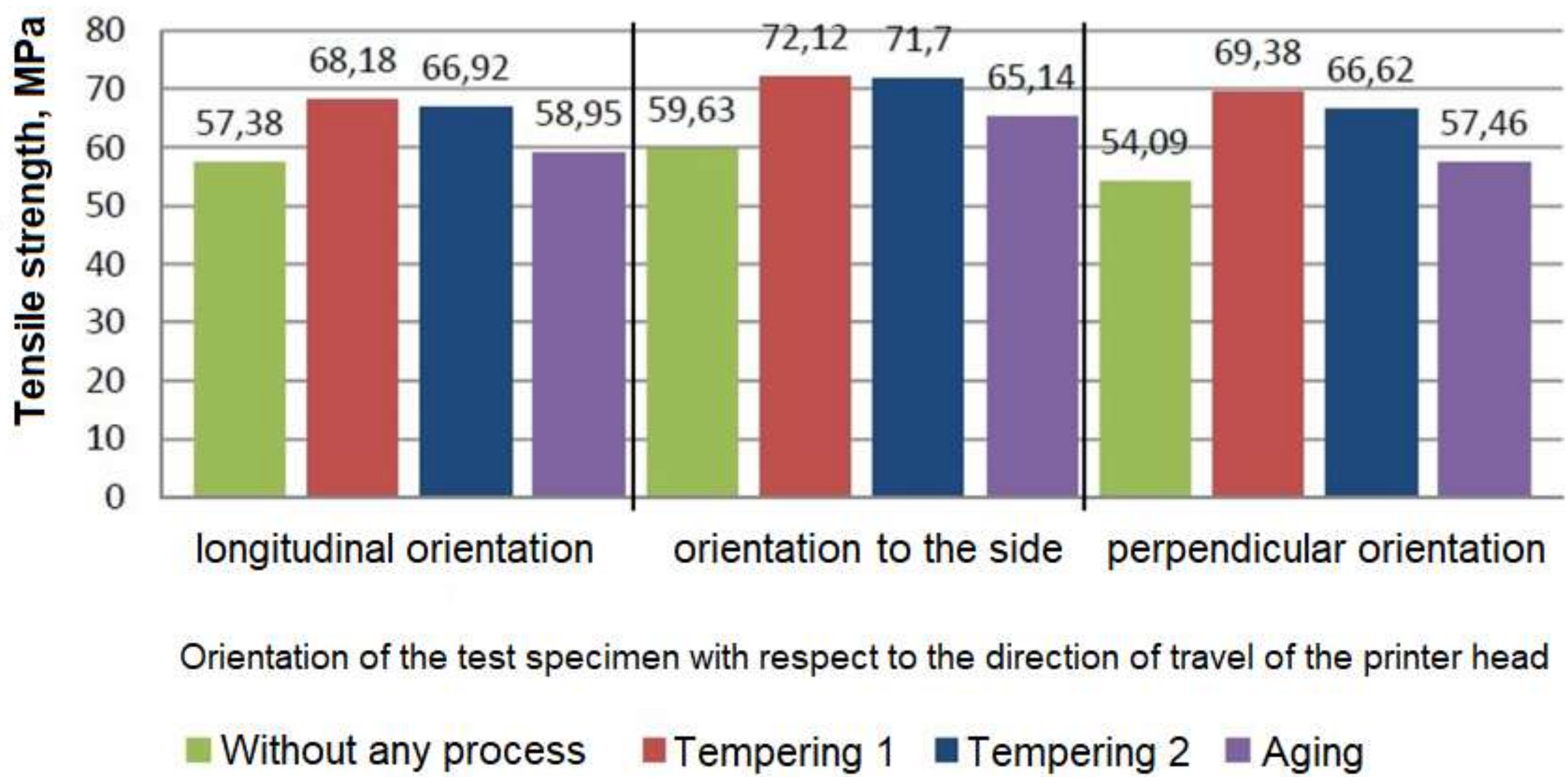
Tensile test results of ABS material from 3D printer Dimension SST 768 (FDM)



Results

Tensile strength stated by the material manufacturer: 55-60 MPa

Tensile test results of ABS-like material from 3D printer
Objet Connex 500 (PolyJet Printing)



Results – conclusion

- The orientation of the built-in part in the working space of the 3D printer has an effect on the resulting mechanical properties of the part in both tested additive technologies. Up to 20% tensile strength for FDM and up to 10% for PolyJet Printing.
- Subsequent heat treatment (tempering) of printed parts affects the mechanical properties. Up to 20% increase in tensile strength in ABS-like.
- The natural aging of a printed ABS-like part has an effect on its mechanical properties, but it is more pronounced only in the side orientation (approx. 10% increase in tensile strength).
- The material parameters specified by the manufacturer correspond to ABS-like and tensile strength was not achieved for ABS for FDM (30% difference in tensile strength).

Results – conclusion

- The results of experiments allow better decisions to be made in the preparation of production about the orientation of parts in the working space of the machine and thus increase the useful properties of manufactured parts.
- It will also make it easier to decide on the possible need to temper parts - without tempering, shorter production times.
- There is a comparison with the data of manufacturers in the material datasheets.

Sources:

ZELENÝ, P. a J. ŠAFKA, I. ELKINA. The mechanical characteristics of 3D printed parts according to the build orientation. *In. Applied Mechanics and Materials*, Vol. 474 (2014), Trans Tech Publications, Switzerland, pp 381-386 ISSN 1660-9336

Elkina, I. Influence of different print settings on the mechanical properties prototype parts. Diploma work, TUL-MF-DMS, Liberec (2012)