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SAM
SECTOR SKILLS STRATEGY
IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Design for Material Extrusion

Welcome

22 JUNE 2021

Maria DIMOPOULOU – LMS

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Get to know us

Before we start....

Go to sli.do

#775614

Agenda

Day 1 (22.06.2021)

Welcome	09:00-09:15	15
Overview of Machines, Process Capabilities and Limitations	09:15-10:35	80
Break	*10:35-10:40*	*5*
Process Related Materials (Part 1)	10:40-11:55	75
Break	*11:55-12:00*	*5*
Process Related Materials (Part 2)	12:00-12:55	*55*
Lunch break	*12:55-13:40*	*45*
Specific Design Considerations (Part 1)	13:40-14:50	70
Break	*14:50-14:55*	*5*
Specific Design Considerations (Part 2)	14:55-16:00	55
Break	*16:00-16:10*	*10*
Specific Design Considerations (Part 3)	16:10-16:30	20

Agenda

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Day 2 (23.06.2021)		
Case study	09:00-10:20	80
Break	*10:20-10:30*	*10*
Wrap Up	10:30-10:50	20
Break/preparation	*10:50-11:30*	*40*
Assessment	11:30-12:00	30

LMS: Introduction

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The Laboratory for Manufacturing Systems & Automation (LMS) is oriented on research and development in cutting edge scientific and technological fields. LMS is involved in a number of research projects funded by the CEU and European industrial partners. Particular emphasis is given to the co-operation with the European industry as well as with a number of "hi-tech" firms. LMS employs approximately 100 researchers.

- Participation in more than **180 R&D Projects**
- Coordination of more that **50 EU Competitive R&D projects**
- Organization of more than **10 International conferences.**
- Publication of more than **700 Scientific articles**

LMS

Laboratory for Manufacturing Systems & Automation

LMS is organized in Three Different Groups

Manufacturing Processes

Manufacturing Automation, Robots & Virtual Reality Applications

Manufacturing Systems

SAM: The Project

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SAM is a European initiative that aims to address the workforce development for Additive Manufacturing (AM) by developing a shared skills vision and collaborative learning solutions for the sector at European level.

Objectives:

- Build a sector skills strategy in AM;
- Assess and anticipate skills (gaps and shortages) in AM;
- Support with data the AM European Qualification System and foster wideness of its scope;
- (Re)design professional profiles according to the industry requirements;
- Develop specific relevant qualifications to be delivered for the AM Sector;
- Increase the attractiveness of the sector to young people, whilst promoting gender balance;
- Strengthen education-research-industry partnerships and encourage creativity “in companies and relevant educational and scientific institutions”;
- Track students, trainees and job seekers and promote match making between job offer and search.

Please find out more info at: www.skills4am.eu/

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Course structure

- 2-Day event
- Active participation of audience is expected
- Follow-up exam/assessment on 2nd day
- SAM certificate of attendance awarded to participants
  - Need to attend both days and successfully complete assessment
  - Will be issued after fulfilling the Satisfaction feedback form - 1 month to be issued
  - Will contain information about the attended CU and accomplished Assessment.

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Assessment

- Multiple-choice questions directly related to the program of the Unit of Learning Outcomes / Competence unit
- Invigilator from EWF will give access to the exam the day of the exam, using MS Teams Forms as supporting tool for the assessment
- Students are advised to have good internet connection and cameras on to access the exam
- The students must wait for permission to initiate the exam (and access the link)
- Questions/doubts during the exam shall be addressed in the chat box ONLY
- In order to pass the exam, the student must reach at least 60% correct answers
- Failing the exam, the student will be entitled to a maximum of 3 reassessments
- If case of failing 3 times, the student must attend the CU again before repeating the exam
- Students who feel that the evaluation process was unfair have the right to appeal directly to EWF.
- The results of the exam will be released 1 week after the exam occurrence

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Evidences

- To prove attendance and participation, evidences will be collected during each training course
- Evidences include
  - Attendance list (including your names and e-mails)
  - Photographic evidence/screenshots
  - Results of the assessment
  - Results of the feedback surveys
- **Participating in the training course means that you automatically accept the aforementioned data collection policy!**

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

skills4am.eu

Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Design for Material Extrusion

SESSION 01: Overview of Machines, Process Capabilities and Limitations

22 JUNE 2021

Harry BIKAS – LMS

Outline

- Introduction to AM
  - Introduction
  - AM applications
  - AM process families
- Material Extrusion
  - Material Extrusion Process
  - Material Extrusion Materials
  - Applications
  - Machines
  - Parameters
- Quality related challenges
  - Repeatability
  - Divergence between design & execution
  - Warping
  - Surface roughness
- Post-processing methods
  - Support removal
  - Sanding
  - Priming & painting
  - Polishing
  - Vapor smoothing
  - Epoxy coating
  - Media blasting
  - Debinding & sintering
- Design for AM
- Cost factors
- Conclusions

Introduction

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Learning Outcomes

- Basic **understanding** of the Material Extrusion process.
- **Familiarization** with the Material Extrusion process **applications** and the basic **machine types** of the process.
- Brief **overview** of the basic **design rules** for Additive Manufacturing.
- **Understanding** of the **post processing needs** for Material Extrusion and the **quality related challenges** of the process.
- Brief overview regarding the **cost parameters** of Material Extrusion process.

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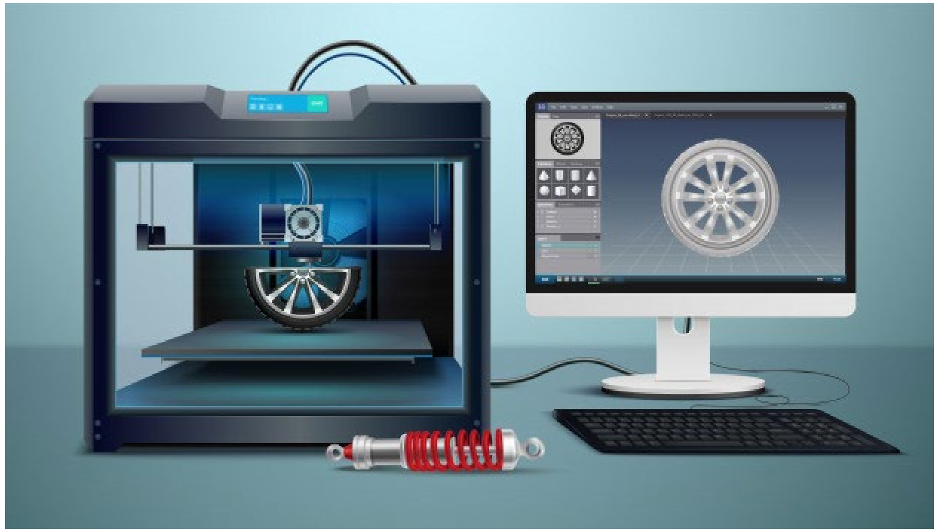
Additive Manufacturing – AM is using data computer-aided-design (CAD) software and directs the hardware in order to deposit the material, layer upon layer, in precise forms. AM is joining materials to make objects, hence it could be classified as a subcategory of joining processes.

AM competitive advantages:

- Able to manufacture complex structures
- Enable integrated design
- Enable lightweight design & structures
- Minimization of production & post-processing steps
- Elimination of jigs & tooling
- Zero changeover cost & setup time
- Optimum utilization of raw material



https://www.freepik.com/free-vector/isometric-composition-with-computer-3d-printing-process-vector-illustration_6933105.htm

Ideal technologies for manufacturing unique products with complex shapes and with low cost in relatively small volumes

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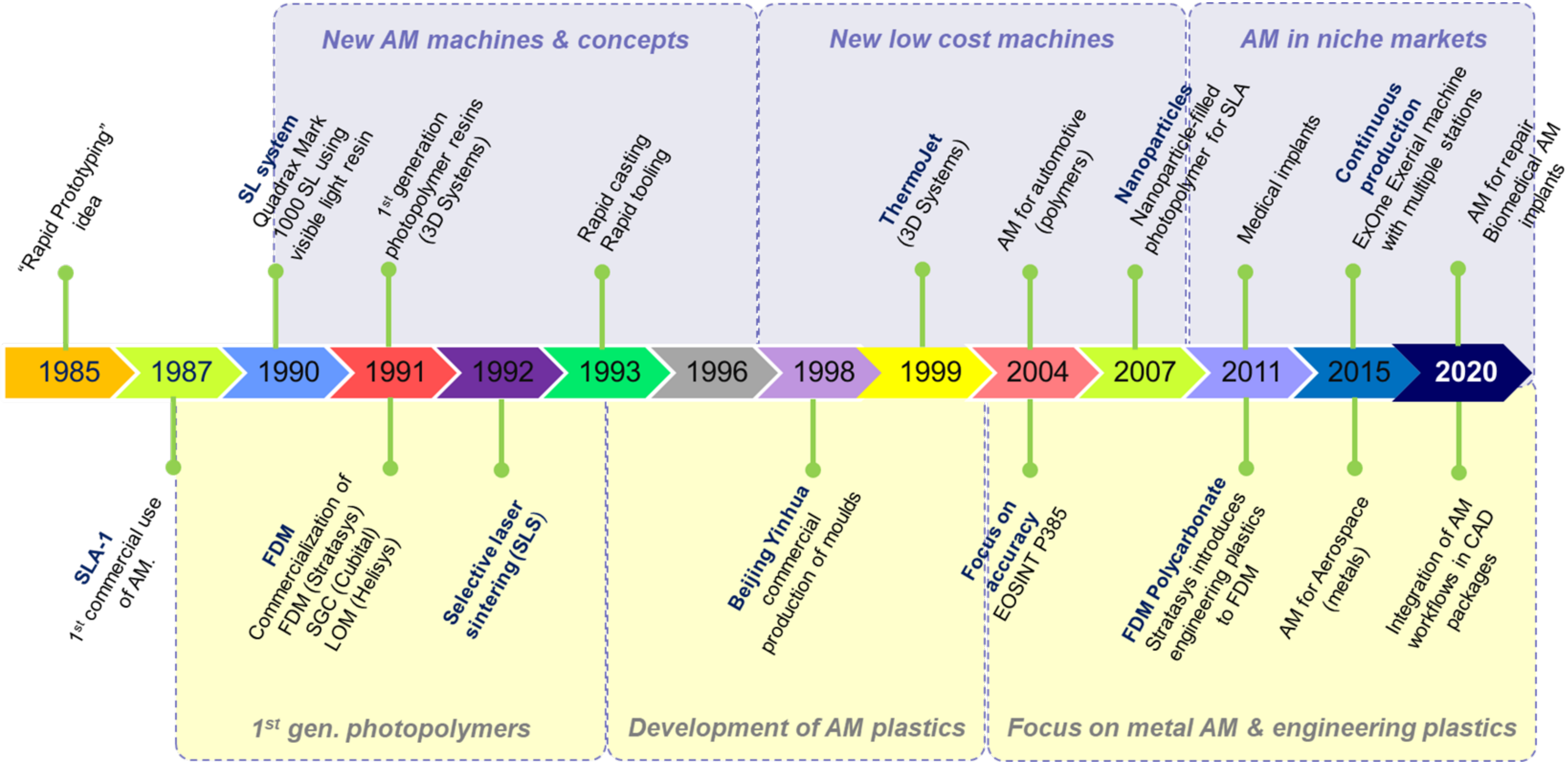


AM applications

Domestic



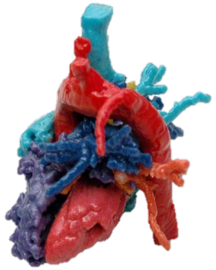


- ✓ Design freedom
- ✓ Customization
- ✓ Personalization
- ✓ Low volume manufacturing

Education

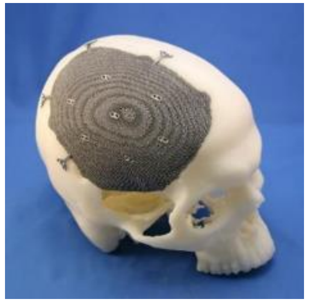






- ✓ Creativity
- ✓ Better understanding
- ✓ Tactile learning

Medical

- ✓ Biocompartible structures
- ✓ Personalization
- ✓ Miniaturization
- ✓ Aesthetics

AM applications

Industrial

Prototyping

- ✓ Quick turnaround
- ✓ Availability
- ✓ Design flexibility

Non-structural

- ✓ Design freedom
- ✓ Function integration
- ✓ Simplified manufacturing
- ✓ Mass reduction

Structural

- ✓ Design freedom
- ✓ Topology optimization
- ✓ Mass reduction
- ✓ Economic low volume manufacturing

Market Trends

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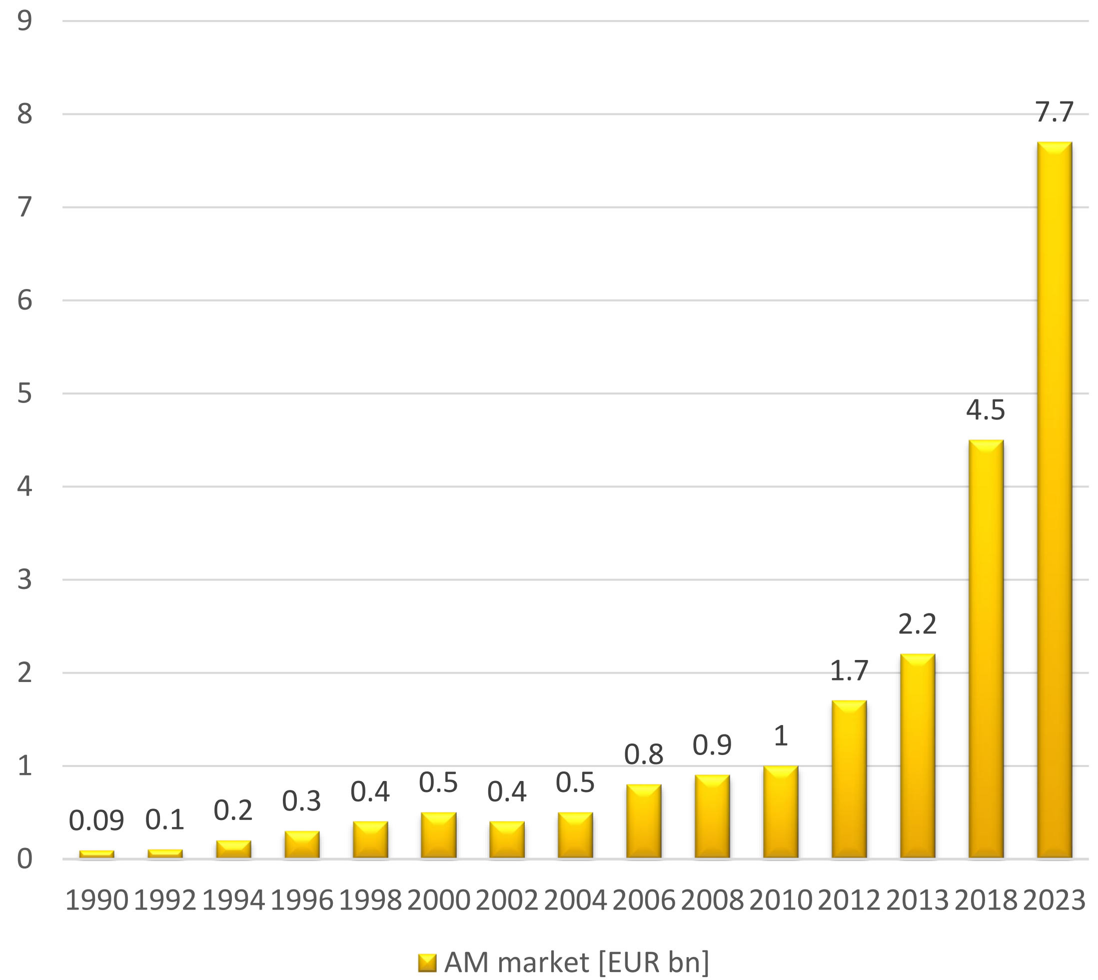
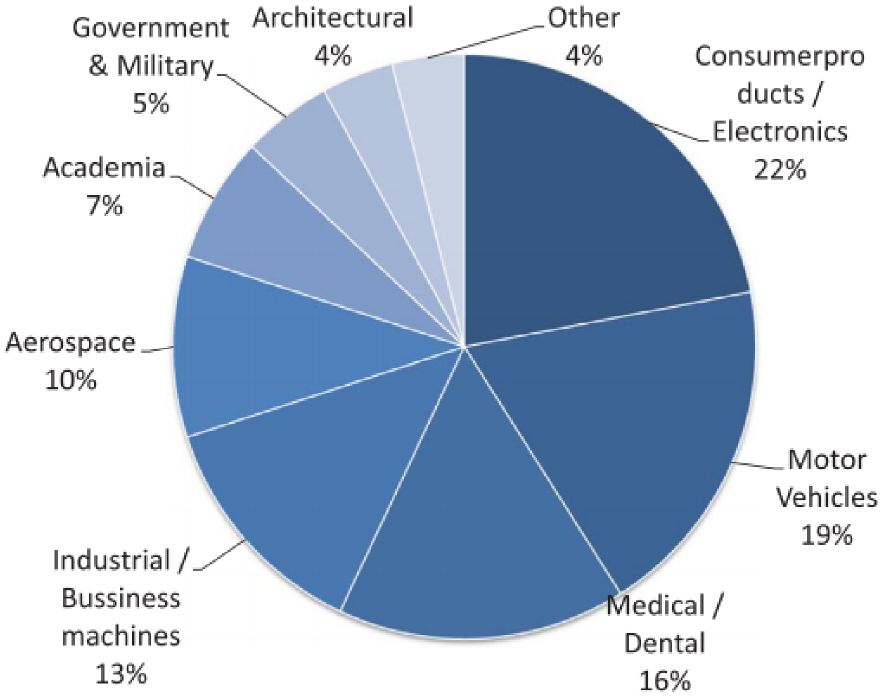




- ~ 25 % yearly increase
- > 30.000 polymer AM machines
- > 1.500 metal AM machines

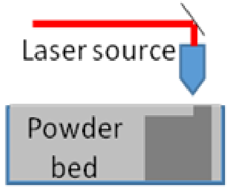
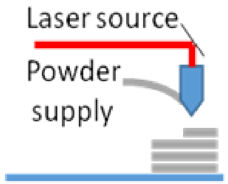
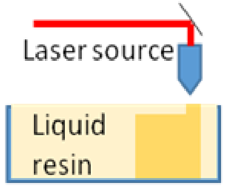
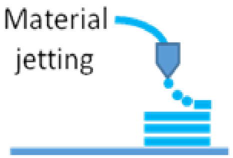
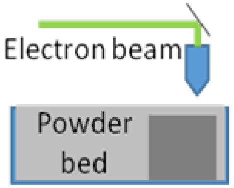
Verhoef, Leendert A., et al. "The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach." *Energy Policy* 112 (2018): 349-360.

Additive Manufacturing Process Families

- Seven main process families
- Different process mechanism of joining the layer with the previous ones

Process	Primary process mechanism	Main materials
Vat polymerization	Photopolymerization of liquid resin	Photo-polymers
Extrusion	Melting, extrusion, deposition and solidification of thermoplastics	Thermoplastics, often filled with particles
Material jetting	Melting, jetting and solidification	Wax
Binder jetting	Joining of powder particles through binder (adhesive)	All materials in powder form, mainly plastics, ceramics, metals
Powderbed fusion	Melting and solidification of powder particles in a powderbed	Thermoplastics, metals
Direct energy deposition	Melting and solidification of material (powder or wire) directly in the process head	Metals
Sheet Lamination	Cutting of sheets of material in an appropriate shape per layer and adhesive bonding	Paper, composites

Additive Manufacturing Process Families

Additive Manufacturing (AM) Processes							
Process	**Laser Based AM Processes** — ***Laser Melting***		***Laser (Vat) Polymerization***	**Material Extrusion**	**Material Jetting**	**Sheet Lamination**	**Electron Beam**
Process Schematic							
Name / Material	SLS	DMD	SLA	FDM	3DP	LOM	EBM
	SLM	DMLS	SGC	Robocasting	IJP	SFP	
	LENS	DMLM	LTP		MJM		
		LPD	BIS		BPM		
		SLC	HIS		Thermojet		

Bulk Material Type	Powder	Liquid	Solid

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Material Extrusion

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Process Definition:

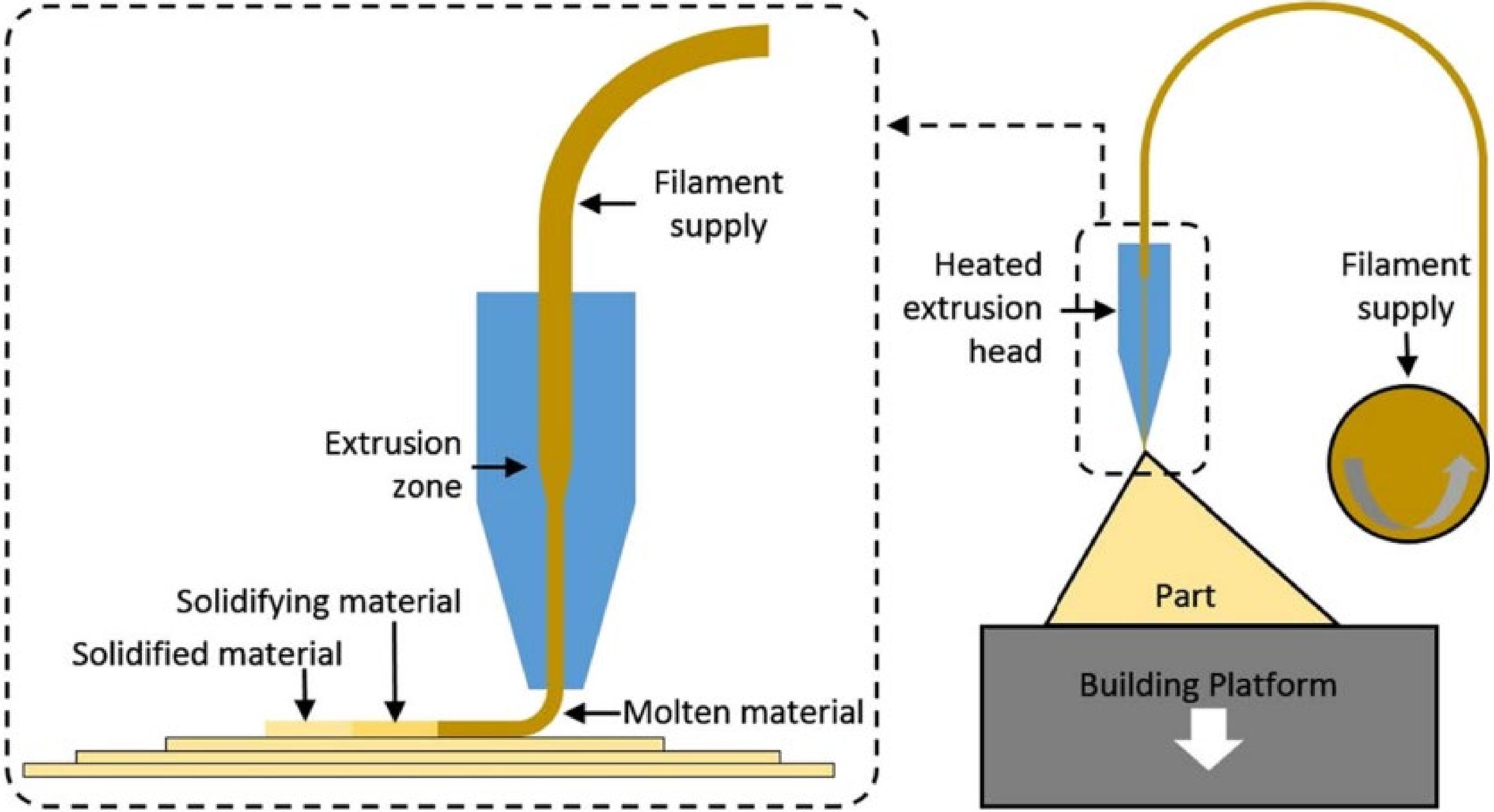
“Additive Manufacturing process in which material is selectively dispensed through a nozzle or orifice” [1]

Process steps:

1. First layer is built as nozzle deposits material where required onto the cross sectional area of first object slice
2. The melted material is extruded in thin strands and is deposited layer-by-layer in predetermined locations, where it cools and solidifies
3. To fill an area, multiple passes are required
4. When a layer is finished, the build platform moves down (or in other machine setups, the extrusion head moves up) and a new layer is deposited
5. Layers are fused together upon deposition as the material is in a melted state
6. This process is repeated until the part is complete

[1]: ISO 17296-2, Additive manufacturing – General principles – Part2:Overview of process categories and feedstock

Material Extrusion Process



Material Extrusion Materials

Processable Materials:

- Thermoplastics (PLA, ABS, PC, TPU, PA, HIPS, PEEJ, PEI)
- Particle filled polymers (MarkforgedOnyx, StratasysNylon 12CF)
- Fiber filled polymers (CF, Fibreglass, HT Fibreglass, Kevlar)
- Metal powder filled polymers (Stainless Steel, Tool Steel, Aluminium, Inconel, Titanium, Cu, Inco625)
- Concrete
- Clay

Feedstock Form:

- Solid filament/wire
- Pellets
- Paste

Build Volume:

- Typical: 200x200x200 mm^3
- Maximum: 1000x1000x1000 mm^3

Source: www.hubs.com, https://www.3dnatives.com/

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Production Capabilities:

- Extrusion speed range of 5 mm/min < Va < 80 mm/min. *(Va: extrusion speed)*
- Low volume production
- Printing tolerance of +/- 0.1mm (+/- 0.005")

Typical machine costs

- Entry level/hobbyist polymer machines: €200 – €500
- Professional grade polymer machines: €500- €1500
- High-temperature specialized machines: €1000- €5000

Typical material costs

- Relatively cheap compared to other AM processes
- Prototyping materials, e.g. PLA: €15- €25/kg
- Functional materials, e.g. ABS, PC, PETG: €35- €80/kg
- High-performance engineering materials, e.g. PEEK, PEKK: €150- €500/kg

Material Extrusion Capabilities

Advantages:

- Wide selection of print materials
- Easy and user-friendly process
- Low initial and running costs
- Small equipment size compared to other AM processes
- Lower production costs (particularly in metals)
- Suitable for small, highly complex parts (50-200 mm)
- Suitable for small series production

Limitations:

- Limited complexity (overhangs, bridges)
- Waste due to supports
- Post-processing requirements
- Toxic print materials (some thermoplastics)
- Sintered shrinkage (in metals)
- Limited wall thickness (in metals: 5-10 mm)

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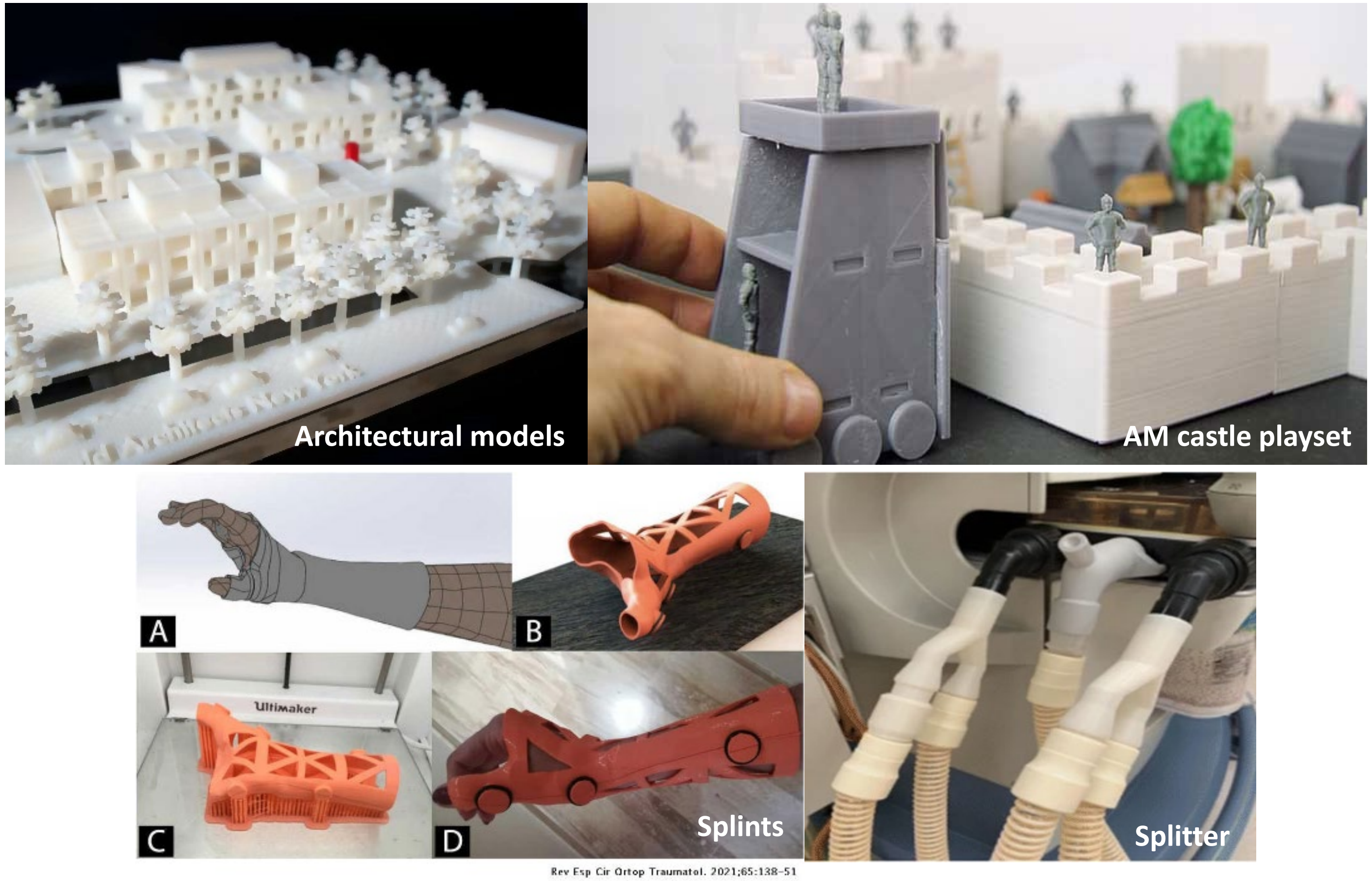
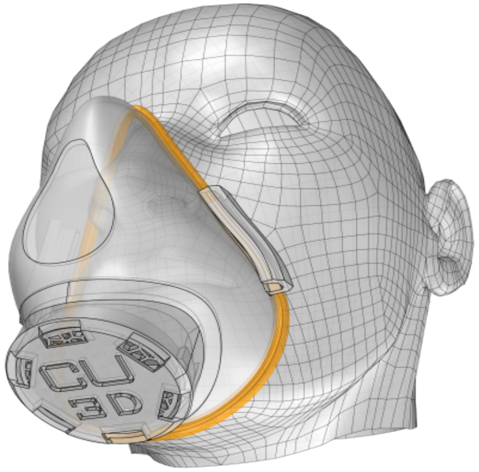
Material Extrusion Applications

- Prototypes
- Medical applications
  - Prosthetics
  - Pre-surgical models
  - Splints
  - Splitter
- Industrial applications
  - Aerospace
  - Automotive
  - Manufacturing
- Architecture
  - Architectural models
- Household Items
  - Clips
  - Mobile covers
  - Keychains
  - Idols
  - Games



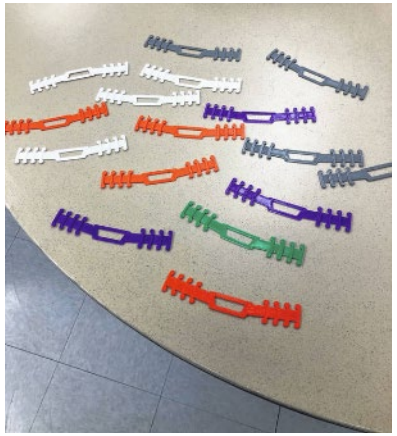
Aydin, Ayca, et al. "3D printing in the battle against COVID-19." Emergent Materials (2021): 1-24.
https://elearning.tki.org.nz/Technologies/Hardware-for-learning/3D-printing,
https://diyconnect.net/popular-applications-of-Material Extrusion-3d-printing-technology/

- Applications in COVID-19
  - Personal protective equipment
  - Face masks
  - Face shields
  - Mask extender
  - Auxiliary accessories
  - Diagnostic tools
  - Swabs
  - Ventilator devices
  - Splitters



Face masks


Face shields


Mask extender


Face shields


Swabs

3D Printing application for Healthcare Industry: The produce of a variety of products including face shields, masks, etc [https://www.3dapac.com/nanohack,,https://www.freepik.com/free-vector/realistic-plastic-face-shield-protection_8299835.htm],

Material Extrusion Machines

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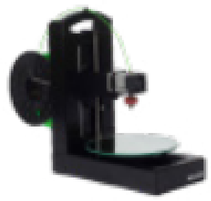
	Cartesian 3D Printer	Polar 3D Printer	Delta 3D Printer	Robot arm Printer
	3 Axis	*3 Axis*	*3 Axis*	*3 Axis*
Printing Time	◑	◑	○	◑
Surface Quality	◑	◑	◑	◑
Investment Costs	○	○	◑	●
	Examples			
				
	Ultimaker S3[1]	*Polar 3D*[2]	*Delta Go*[3]	*Yizumi SpaceA*[4]

Graduation:
- high ●
- middle ◑
- low ○

Sources:
1) https://ultimaker.com/en/products/ultimaker-3/specifications
2) https://polar3d.com/
3) https://www.deltaprintr.com/product/delta-go/
4) https://www.yizumi-germany.de/spacea-additive-fertigung/

Kampker, Achim, et al. "Review on machine designs of material extrusion based additive manufacturing (AM) systems-Status-Quo and potential analysis for future AM systems." Procedia CIRP 81 (2019): 815-819.

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Cartesian machine

Advantages:

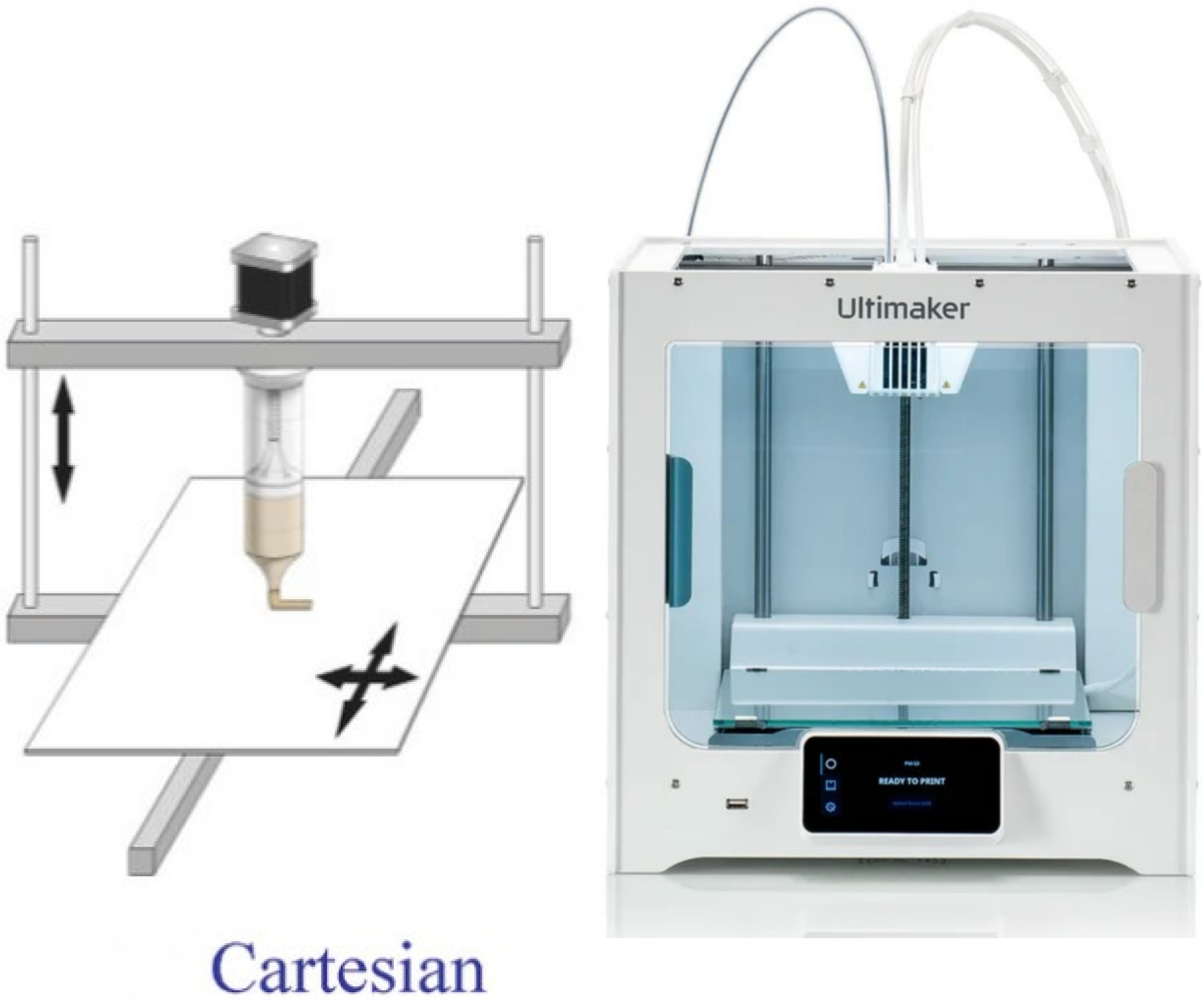
- Relatively cheap
- Simple to understand and implement
- Comparatively easy to upgrade and fix
- Lots of community support

Limitations:

- Large and heavy frame
- Relatively slow
- Limited print height

Price:

€200- €5.000



https://ultimaker.com/3d-printers/ultimaker-s3

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Polar machine

Advantages:

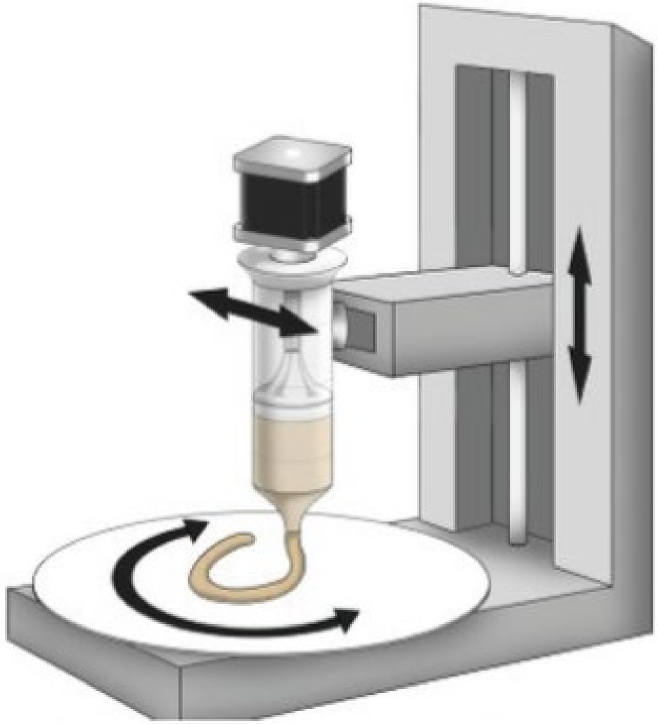
- Relatively inexpensive
- Fewer motors and less noise

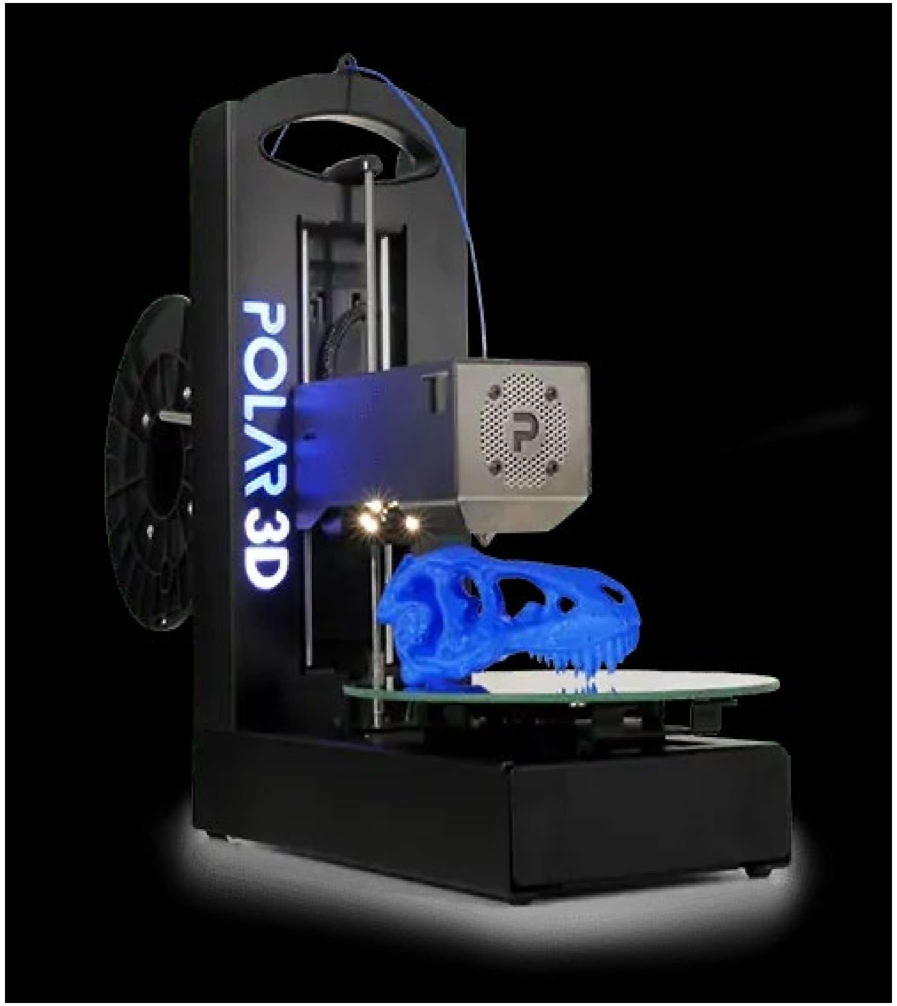
Limitations:

- Low print quality
- Relatively slow low
- Relatively obscure
- Limited community suppor

Price:

€150- €800





https://polar3d.com/

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Delta machine

Advantages:

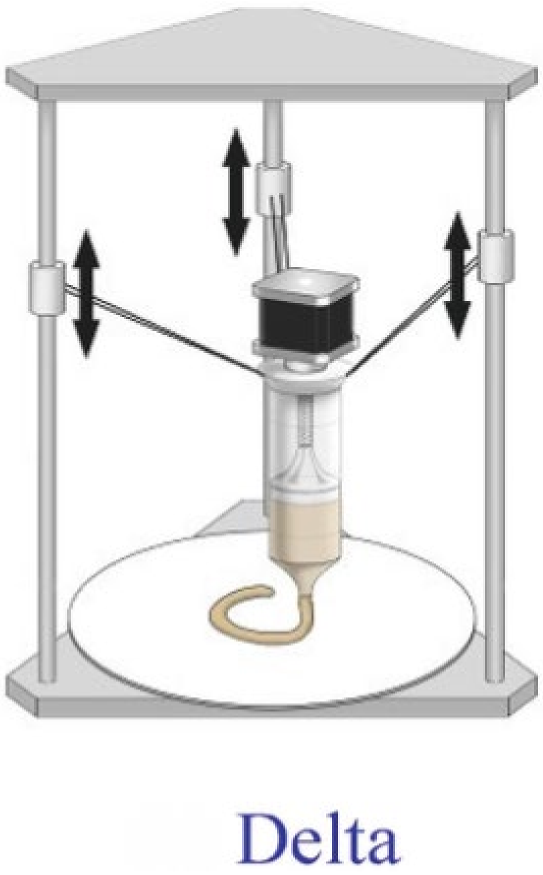
- Relatively fast
- High print quality
- Generally capable of tall prints

Limitations:

- Difficult to fix and upgrade
- Less compatible with direct drive extrusion
- Typically small build volume

Price:

€250- €3.000



https://www.deltaprintr.com/

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Robot arm machine

Advantages:

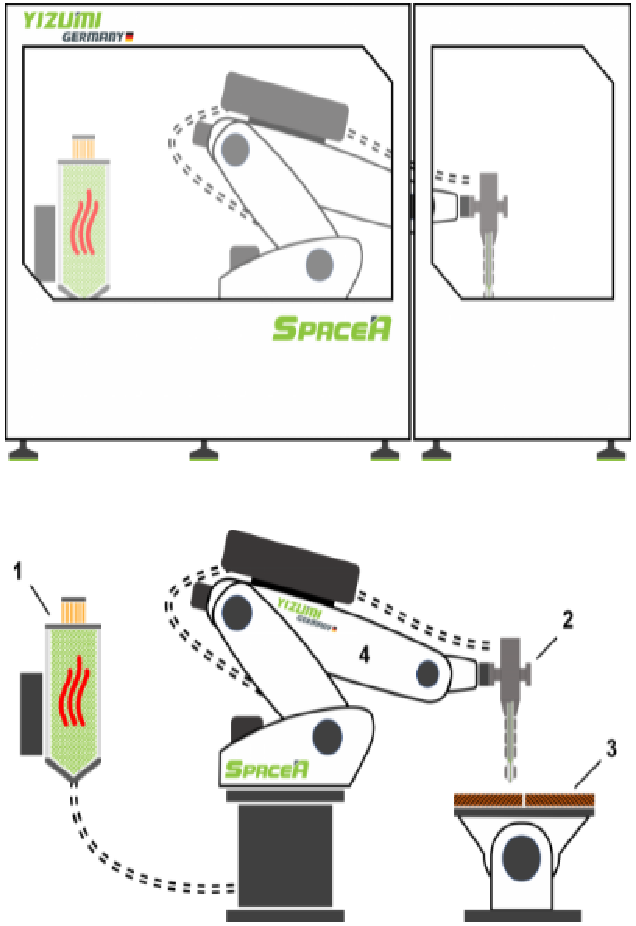
- Good for industrial printing
- Relatively fast

Limitations:

- Relatively imprecise
- Relatively obscure
- Limited community support
- High cost

Price:

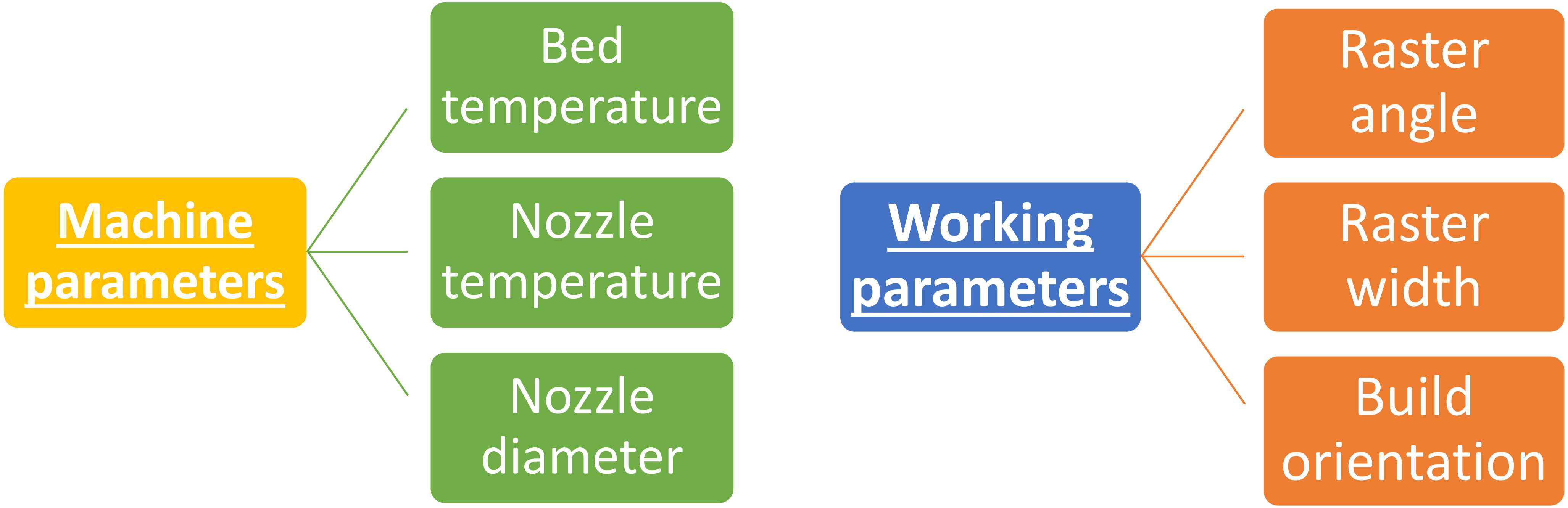
€10.000- €100.000



*https://*www.yizumi-germany.de/en/products/additive-manufacturing/

Parameters That Affect The Printing Process

- The parameters of the **Material Extrusion machine**
- The working parameters



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When is support needed in Material Extrusion?

With Material Extrusion printing, each layer is printed as a set of heated filament threads which adhere to the threads below and around it. Each thread is printed slightly offset from its previous layer. This allows a model to be built up to **angles of 45°,** allowing prints to expand beyond its previous layer's width.

When a feature is printed with an overhang beyond 45°, it can sag and requires **support** material beneath it to hold it up.

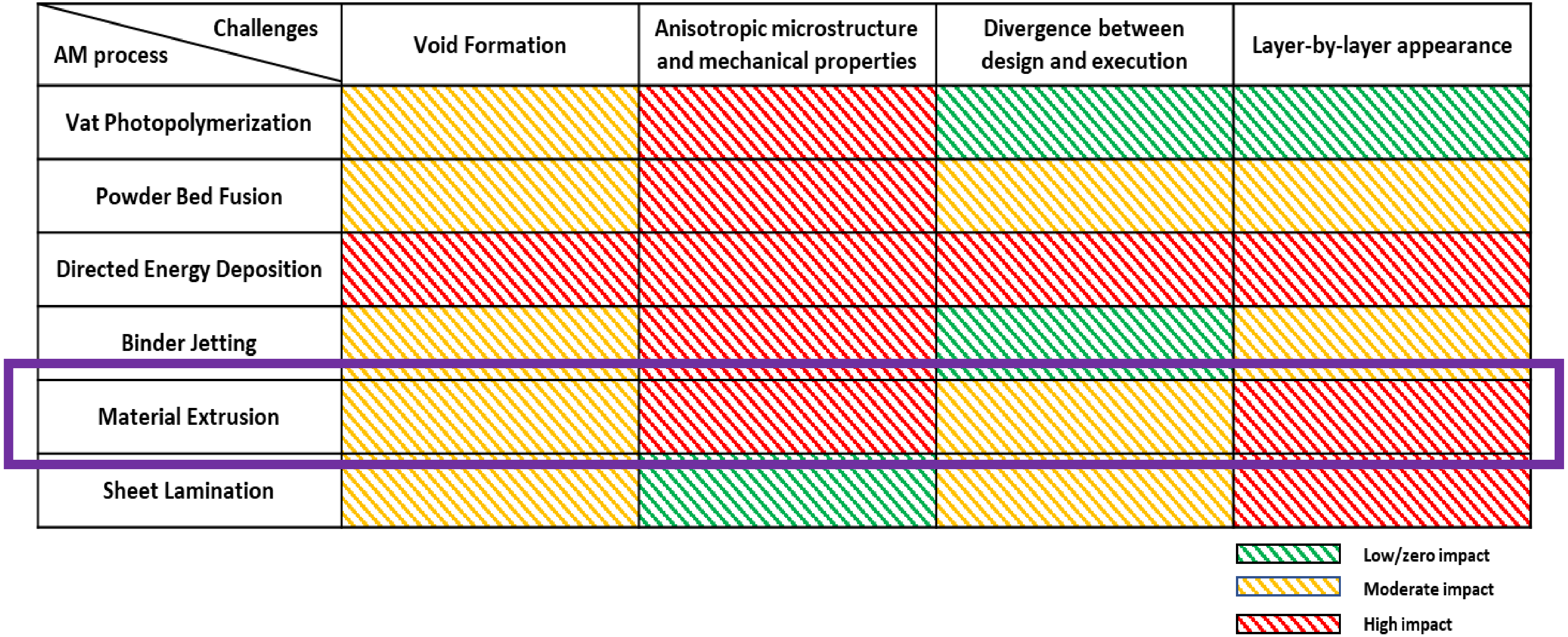
Honeycomb Support - Material Extrusion

Space tree support - Material Extrusion

Quality Related Challenges

MEx quality related challenges

The following figure provides an overview of the impact of each quality-related challenges in the categories of Additive Manufacturing.



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Repeatability

Repeatability refers to the variation in repeated dimensional measurement from part to part in a single build on a single machine.

Material Extrusion process is highly capable additive manufacturing process in producing highly accurate product with good repeatability and reproducibility.

Material Extrusion Parts

source: 3DHubs

Material Extrusion Parts

source: 3DHubs

Co-funded by the Erasmus+ Programme of the European Union

Divergence between design and execution

- Printing process parameters such as extrusion pressure and orientation of the filaments influence the appearance and the mechanical properties of the parts.
- This phenomenon lies on the process mechanism of AM
- To plan and find the optimum orientation of the part.
- Outer surface of AM parts can also be influenced by the need to create external support, which is not always easy to remove.
- Divergence between design and execution depends mainly on:
  - Process resolution (layer and track thickness)
  - Wall thickness of the part
  - Temperature
  - Speed of printing

Part as designed and as built (left).
Design compensation (right).

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Warping – effect on dimensions

- Warping is one of the most common defects in Material Extrusion:
  - When the extruded material cools, its dimensions decrease.
  - As different sections of the print cool at different rates, their dimensions also change at different speeds.
  - Differential cooling causes the buildup of internal stresses that pull the underlying layer upwards, causing it to warp.

A warped Material Extrusion part printed in ABS

Source: Hubs.com

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Surface roughness

- Layer by layer appearance manifests as surface roughness
- Surface roughness is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form.

The following dominant factors for surface roughness in Material Extrusion:

- Layer height
- Wall thickness

The layer lines of an Material Extrusion part are generally visible

Source: Hubs.com

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Surface roughness – effect of material feedstock

The following factors related to the material feedstock affect surface roughness:

- The morphology (size and shape) of the material
- Quality of the material
- Feedstock type

Material Extrusion printed parts

Source: Hubs.com

Post-processing Methods

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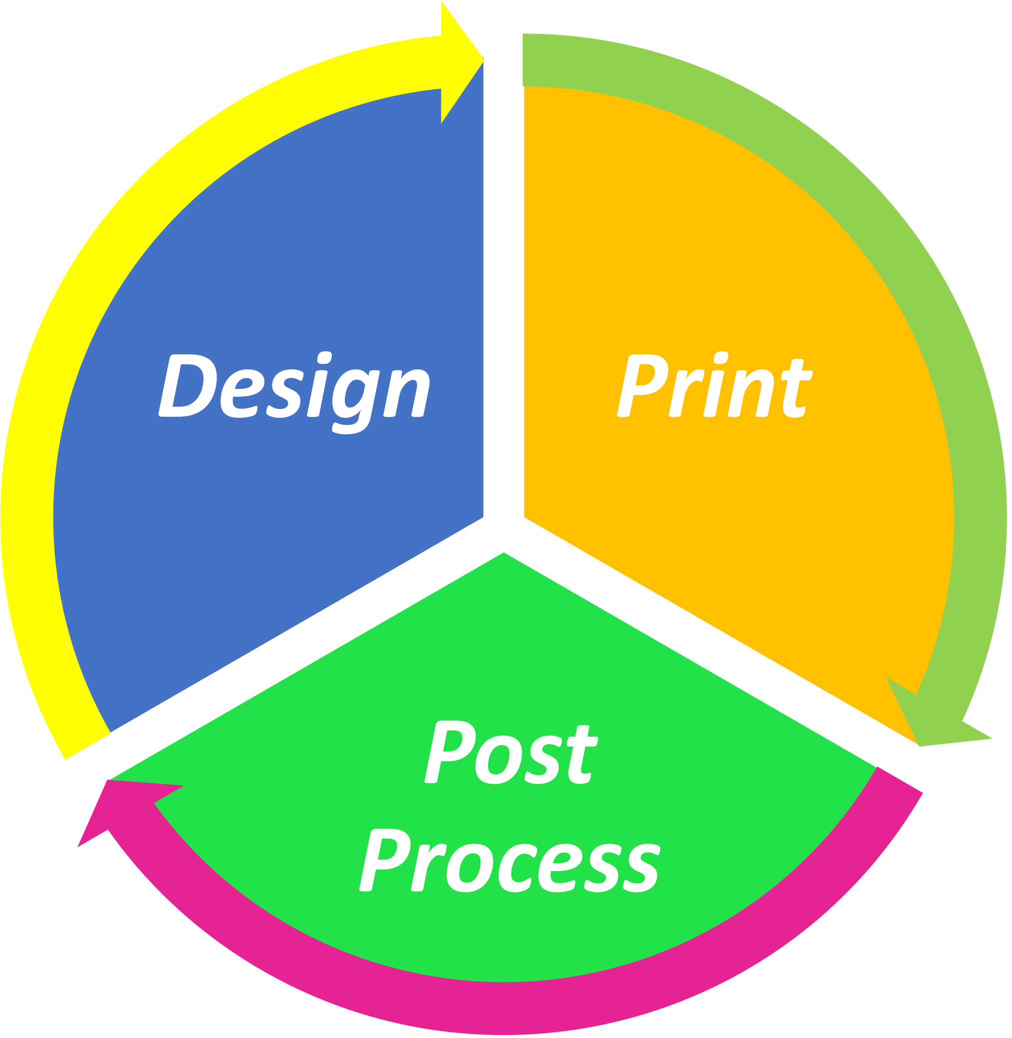

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Post processing needs in Material Extrusion- Additive Manufacturing

- The post processing needs of AM components include:

- *Support Removal*
- *Sanding*
- *Polishing*
- *Priming & Painting*
- *Vapor smoothing*
- *Epoxy coating*
- *Debinding & Sintering*

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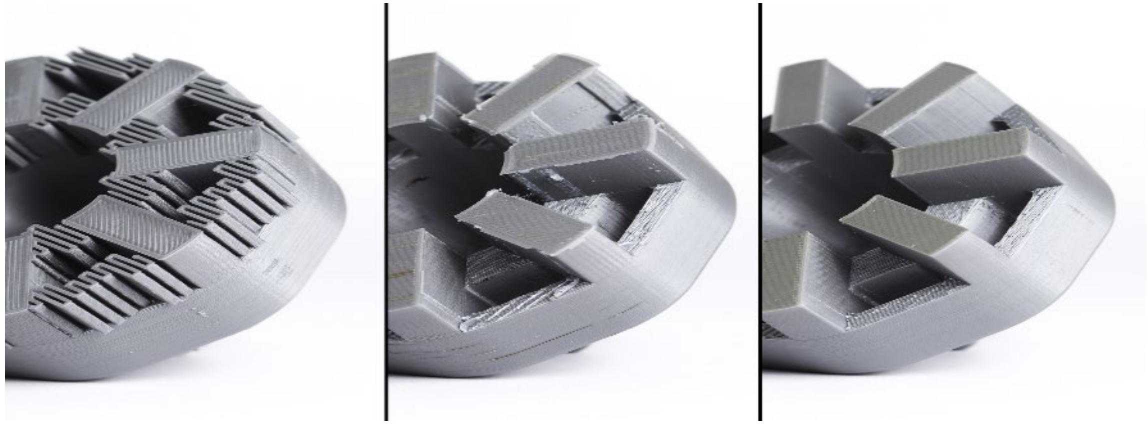
The Support Removal process

Main characteristics of the Support Removal process:

- Support is separated into two categories:
  - Standard
  - Dissolvable
- Support removal the first stage of post-processing for AM printing technologies that require support to accurately produce parts.
- Support removal is a mandatory requirement and does not produce an improved surface finish.



Original print with support attached, poor support removal and good support removal (left to right)

Source: Hubs.com

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The Sanding processes

- Main characteristics of Sanding processes:
  - Sanding helps to smooth the part and remove any obvious blemishes
  - Produces extremely smooth surface finish.
  - Makes additional post-processing (such as painting, polishing, smoothing, and epoxy coating) very simple.

A sanded grey print

Source: Hubs.com

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The Priming & Painting processes

- Main characteristics of The Priming & Painting processes:
  - Produces professional results with attention to detail and some practice.
  - Allows for complete flexibility of the visual appearance of the final product, independent of the material/color the object was originally printed in.

A grey PLA Material Extrusion print spray painted black

Source: Hubs.com

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The Polishing processes

- Main characteristics of Polishing processes:
  - Polishes the print without the use of any solvents that can warp the print and alter tolerances.
  - Produces a mirror-like finish if properly sanded and polished, which mimics injection molded plastics.
  - Plastic polish and cleaner is highly economical making this method very cost effective for the quality of the finish.

Source: Hubs.com

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The Vapor smoothing processes

- Main characteristics of the Vapor smoothing processes:
  - Smooths many small blemishes and diminishes the layer lines present in a print without any additional work.
  - Produces a very smooth “shell” around the exterior of the print.
  - Very quick, and can be done with commonly sourced materials.

A smoothed black hemi-sphere print

Source: Hubs.com

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The Epoxy coating processes

- Main characteristics of the Epoxy coating processes:
  - Very thin layer of epoxy will not impact the tolerances of the print all that greatly (unless the print is sanded first).
  - Provides an outer protective “shell” around the print.

A black print showing half coated with epoxy and half unprocessed

Source: Hubs.com

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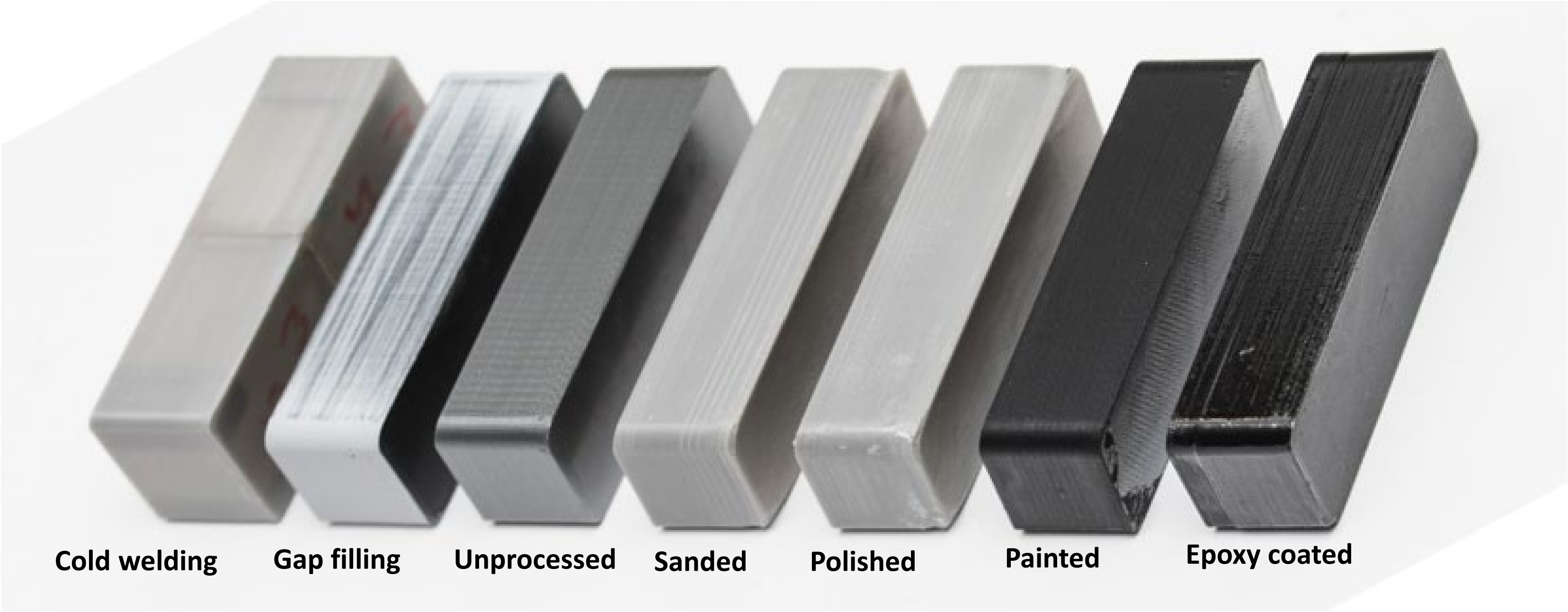
Media Blasting

- Media blasting is an inexpensive and quick solution.
- Media blasting can be used to smooth concept models, prototypes, and end-use parts.
- It can also be used in surface preparation for painting, and mold masters.

Source: https://grabcad.com

MEx post-processing methods



Post processed Material Extrusion prints (from left to right): Cold welding, gap filling, unprocessed, sanded, polished, painted and epoxy coated.

Source: Hubs.com

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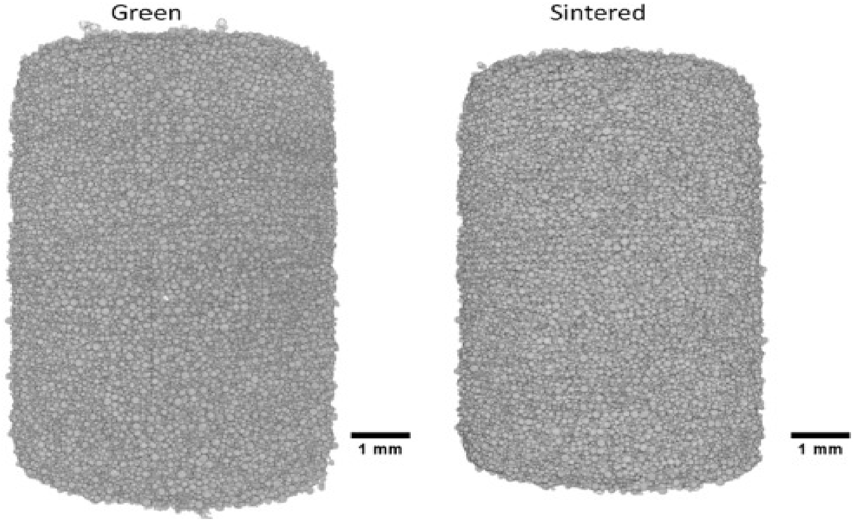
Debinding And Sintering

- Material extrusion can be used for producing metal specimens when combined with debinding and sintering.
- Material extrusion was first developed for polymeric filaments, metal specimens can be produced using a filament made of a polymeric binder system highly-filled with metal particles, debinding and subsequent sintering.
- Sintering is the process of fusing particles together into a solid mass by using a combination of high pressure and high temperature without reaching the liquefaction point of the material.



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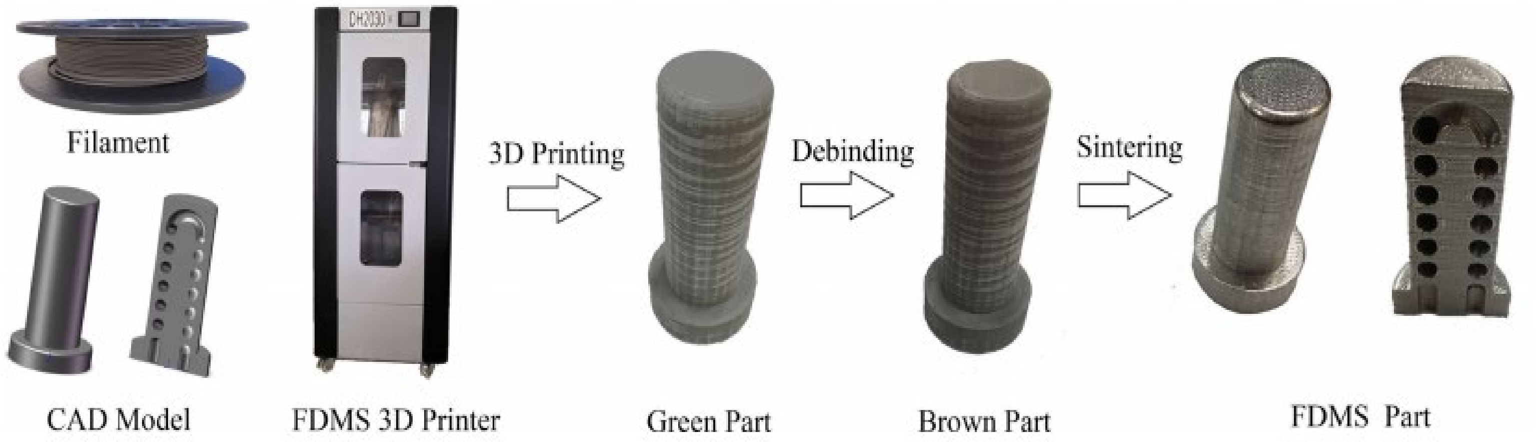
Debinding And Sintering

- For metal parts produced with Material Extrusion usually the main binder has to be removed from the component before sintering in order to prevent bubble formation on the sintered part.
- It is an economical way for the production of steel parts to combine Material Extrusion process with de-binding and sintering.
- Shrinkage is significant (10-20%) and should be compensated for.



Liu, Bin, et al. "Creating metal parts by fused deposition modeling and sintering." Materials Letters 263 (2020): 127252.

Gonzalez-Gutierrez, Joamin, et al. "Shaping, debinding and sintering of steel components via fused filament fabrication." CIM. 2017.

Design for AM

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Design for X (Excellence)

Design for X (Excellence) are extensive design frameworks including engineering rules and guidelines that aim to reach specific goals. The X may represent several traits or features including manufacturability, power, variability, cost, yield, or reliability or a combination of the above.

The most popular frameworks are:

- DfM: Design for Manufacturability (refers to conventional manufacturing)
- DfA: Design for Assembly
- DfI: Design for Inspection
- DfAM: Design for Additive Manufacturing

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Introduction to DfAM

- Design for AM refers to **design optimization** following certain **rules and guidelines**, aiming to improve **AM manufacturability**
    - Manufacturability is not a duality nature of can-or-cannot be manufactured
    - Manufacturability is used to describe the ease to implement a manufacturing technology to realize a part design
    - Manufacturability for AM requires identification of the Design Aspects of the part and their comparison with AM capabilities
- Current design optimization methods (TO) generate highly complex parts that are appealing for AM
- Most complex geometries display low AM manufacturability
- Modifications are required on a second stage to address problematic aspects of the design (post-processing)

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AM Manufacturability

Part's features not aligned with DfAM Rules → Post-Processing Workload → Reach Part Requirements

Part Conventional Designer or Redesign for AM

Part features aligned with DfAM Rules → Post Processing Workload → Reach Part Requirements → Production Gains

Part Designer for AM

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Determining AM part's Manufacturability

#Step	Indicator	
1. Part's geometric features recognition	[from CAD/.STL file]	
2. Crosschecking Design features with the AM process capabilities	[Limit of Overhangs, etc.]	0 1
3. Crosschecking Design Considerations with Part Specifications	[Surface roughness, porosity]	0 1
4. Magnitude of feature alternation to achieve manufacturable features	[Feasible-Impractical-Add Supports]	
5. Determine the actions for excess material removal	[Few-Numerous Supports]	
6. Post-processing to reach parts requirements (post-treatment)	[Minimal-Major]	

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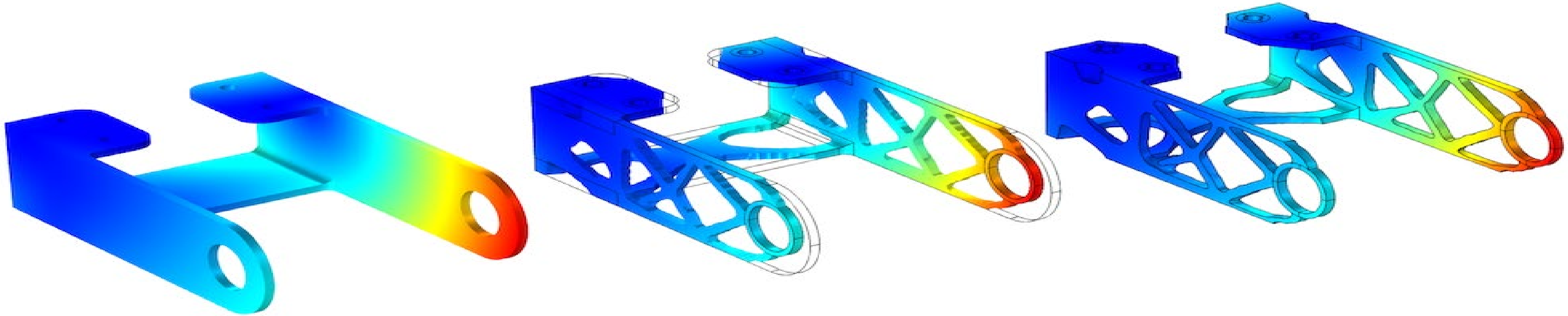
- Several design optimization techniques with respect to different targets (structural, thermal, fluid dynamics) exist:
    - Topology optimization
    - Generative design
    - Etc.
- However, these methods do not take into account manufacturability constraints
- Although AM is the enabler of design freedom, it is not guaranteed that all designs can be built **effectively**
- It is important to create an algorithmic approach of engineering the geometry of a part design that results in an **optimum material distribution** and **optimised manufacturability** of the AM buildability restrictions



Cost factors

Cost of Material Extrusion

Parameters that affect the cost:

- **Filament cost**
  - PLA
  - PC
  - ABS HT
  - PA12 Nylon
  - PA6 Nylon
  - PETG
- **Electricity cost**
- **Printer depreciation**
- **Preparation labor cost**
  - Model preparation (Fixing, CAD)
  - Slicing (Supports, Parameters)
  - Material change
  - Transfer & Start
- **Post-processing cost**
  - Job removal
  - Support removal
  - Additional post processing (sanding, painting)
- **Consumables**
  - Miscellaneous

Conclusions

Conclusions

- The **history of AM** dates back to the early 1980s, and in forty years has grown from a new process used by a select few to a mainstream technology adopted by everyone from hobbyists and engineers to manufacturers and researchers.

- Additive manufacturing refers to **several technologies** that produce parts by depositing material layer-by-layer.

- Additive Manufacturing Technologies:
  - ✓ Vat polymerization
  - ✓ **Material Extrusion**
  - ✓ Material jetting
  - ✓ Binder jetting
  - ✓ Powder-bed fusion
  - ✓ Direct energy deposition
  - ✓ Sheet Lamination

- Depending on the part characteristics required, **AM technologies** are used to directly produce the parts or in indirect processes in combination with traditional manufacturing techniques.

Conclusions

- Material Extrusion **Advantages**:

  - ✓ Wide selection of print material (plastics)
  - ✓ Easy and user-friendly process
  - ✓ Low initial and running costs
  - ✓ Small equipment size compared to other AM
  - ✓ Lower production costs (in Metals)
  - ✓ Suitable for small, highly complex parts (50 mm)
  - ✓ Suitable for small series production

- Three main **types** of materials are used in Material Extrusion :
  - ✓ Polymers (thermoplastics)
  - ✓ Metals
  - ✓ Construction materials (concrete, clay)

- **Additive Manufacturing** in general will continue to **evolve** as engineers, designers, and researchers find new ways to leverage its power for exciting applications in medical, aerospace, automotive, and consumer goods.

Conclusions

- Adoption of AM in the **industrial market** will continue to grow, with one report estimating that advancement in technologies and an increase in awareness can drive the value of industrial AM market to around 6 billion euros in 2024.

- AM is being used for pandemic-related (**COVID-19**) purposes by producing a variety of products including face shields, masks, ventilator components, hands-free door openers and nasal swabs.

- Material Extrusion Industrial **Applications**:
  - ✓ Rapid Prototyping
  - ✓ Automotive
  - ✓ Healthcare

- The basic categories of the **Material Extrusion machines** are:
  - ✓ Cartesian
  - ✓ Polar
  - ✓ Delta
  - ✓ Robot arm

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Conclusions

- **Quality related challenges** in Material Extrusion:
  - ✓ Void Formation
  - ✓ Anisotropic microstructure
  - ✓ Divergence between design and execution
  - ✓ Surface roughness
  - ✓ Warping – effect on dimensions
  - ✓ Infill and shell thickness effect

- **Post processing** needs in Material Extrusion:
  - ✓ Support Removal
  - ✓ Sanding
  - ✓ Polishing
  - ✓ Priming & Painting
  - ✓ Vapor smoothing
  - ✓ Epoxy coating

Conclusions

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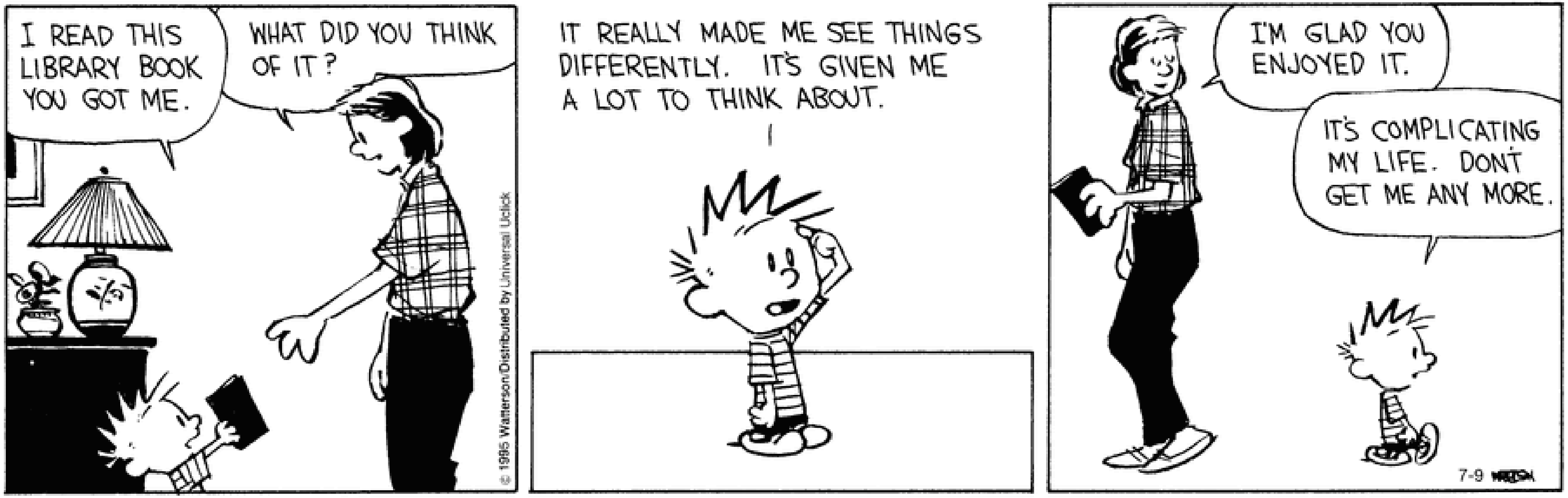
- Some of the parameters that affect the **cost of Material Extrusion** process are
  - ✓ Filament cost
  - ✓ Electricity cost
  - ✓ Printer depreciation
  - ✓ Preparation labor cost
  - ✓ Post-processing cost
  - ✓ Consumables

- Material Extrusion overall **costs** increase as part complexity increases due to higher post-processing time/labor.

- Material Extrusion low **costs** due to part set-up time.

Questions?


I READ THIS LIBRARY BOOK YOU GOT ME.
WHAT DID YOU THINK OF IT?
© 1985 Watterson/Distributed by Universal Uclick
IT REALLY MADE ME SEE THINGS DIFFERENTLY. IT'S GIVEN ME A LOT TO THINK ABOUT.
I'M GLAD YOU ENJOYED IT.
IT'S COMPLICATING MY LIFE. DON'T GET ME ANY MORE.
7-9

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S4M
SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

skills4am.eu

LMS

Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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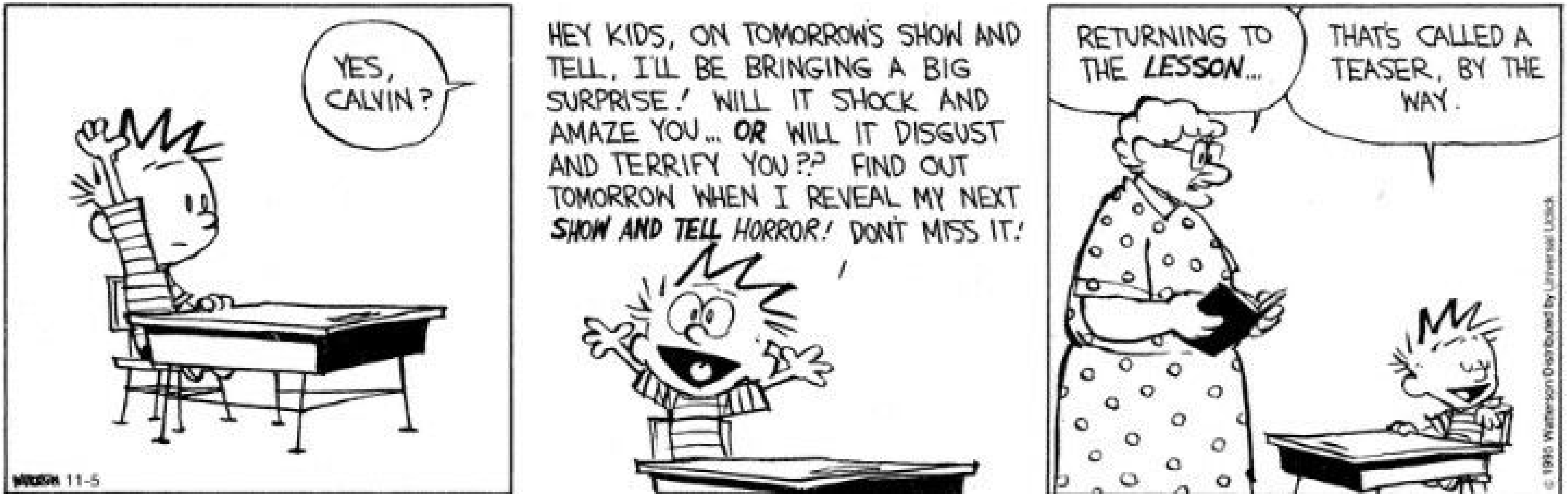
Welcome Back!



Watterson, Bill. The Essential Calvin and Hobbes: A Calvin and Hobbes Treasury. , 1988. MLA (7th ed.)

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Design for Material Extrusion

SESSION 02: Process Related Materials

22 JUNE 2021

FOTIS STAMATOPOULOS - LMS

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Agenda

- Learning Outcomes and Introduction
- Material Properties Overview
- Polymers in MEX Overview
- Metal Filled, Fiber Filled Polymers and Continuous Fiber Fabrication
- Material Selection
- Biocompatibility
- Summary

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Learning Outcomes

- ✓ Basic understanding of all Material Properties important for the MEX printing process
- ✓ Familiarization with the most common Polymer Materials and their respective properties and applications
- ✓ Brief overview of high end applications through the use of Metal Filled Polymers, Fiber Filled Polymers and Composites
- ✓ Ability to choose the right material for every MEX application
- ✓ Introduction to Biocompatible Materials and Applications

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Overview of MEX compatible Materials

Standard Materials	Specialty Materials
a. ABS/ASA b. PLA c. Polycarbonate d. ABS/Polycarbonate Blends e. Nylon f. PPSF/PPSU g. ULTEM 9085, 1010 h. Metal filled polymer filaments (bronze, steel, stainless steel, copper, Inconel etc.)	i. Clay/Brick/Wood filled polymer ii. Concrete iii. Chocolate iv. Polyurethane foam v. Silicone vi. Epoxy vii. Biomaterials viii. HPA/PCL ix. Fiber filled polymer filaments

- MEX printing process is very adaptable => broad range of materials can be extruded
- Most common materials being **thermoplastics**

A **thermoplastic**, or **thermo-softening plastic**, is a plastic polymer material that becomes pliable or moldable at a certain elevated temperature and solidifies upon cooling.

Thermoplastics have a simple molecular structure comprising chemically independent macromolecules. Upon heating, they are softened or melted, then shaped, formed, welded, and solidified when cooled. Multiple cycles of heating and cooling can be repeated, allowing reprocessing and recycling.

- Thermoplastics have been in use long before Additive Manufacturing was invented
- Injection molding and plastics were invented in parallel, while AM is 100 years younger => Most plastics designed with molding in mind

Thermoplastics Reprocessing

SAM: Materials in MEX Introduction

- The Material Extrusion (MEX) printing process is incredibly adaptable—however, it doesn't work for every plastic.
- MEX requires tight constraints to precisely extrude plastic out of a tiny nozzle, so traditional plastics originally optimized for injection molding do not print easily.
- The plastics that are printable, however, cover a massive range of compositions, print constraints, and material properties.
- Additive Manufacturing Material market is rapidly evolving and sees the regular emergence of radically new materials

MEX Polymer Spool Filaments

Source: 3DNatives

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Agenda

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Material Properties Overview

- Material properties describe how a specific material will behave under certain conditions
- Different categories of properties such as: chemical, optical, mechanical, thermal, electrical etc.
- As quantitative metrics, these attributes can help you assess the benefits of one material versus another for a specific use case.

In the following, we'll provide a brief overview of:

- the most useful material properties linked with MEX printing
- their importance for specific applications

MECHANICAL PROPERTIES			
Tensile stress at yield and break	ISO 527	N/mm^2	45
Elongation at break	ISO 527	%	25
Tensile modulus of elasticity	ISO 527	N/mm^2	2500
Compression test			
- 1% strain after 1,000 hrs	ISO 899	N/mm^2	17
Charpy impact strength - Notched	ISO 179-1/1eU	KJ/mm^2	14
Charpy impact strength - Unnotched	ISO 179-1/1eA	KJ/mm^2	no break
Ball indentation hardness	ISO 2039	N/mm^2	85
Shore hardness D	ISO 2039	D	82
Coefficient of frition to steel[12]	ISO 8295	-	0.5
THERMAL PROPERTIES			
Melting temperature	ISO 3156	°C	105
Thermal conductivity at 23°C	ISO 22007.2	W/9km)	0.15
Deformation temperature[15]	ISO 75	°C	85
Coefficient of linear thermal expansion			
- average value between 23 and 60°C	ISO 11359	m(m.K)	90
Max. allowable service temperature in air			
- Continuously[17]	-	°C	90
- Short periods[18]	-	°C	100
Minimum service temperature[19]	-	°C	-20
Flamability			
- Oxygen index	ISO 4589	%	19
- according to UL 94 (3/6 thickness)	UL94	-	HB
ELECTRICAL PROPERTIES			
Dilectrical constant at 1 MHz	ISO 250	-	3.3
Dielectric strength	ISO 243	KV/mm	20
Volume resistivity	ISO 93	Ωcm	10^{15}
Dissipation factor tan Δ at 1 MHz	ISO 250	-	0.02

Source: plastim.co.uk

SAM: Material Properties Overview

Common Mechanical and Thermal Properties

- Tensile Strength
- Young's Modulus
- Elongation
- Flexural Strength
- Fatigue Strength
- Flexural Modulus
- Impact Strength
- Indentation Hardness (Shore)
- Compression Set
- Water Absorption
- Heat Deflection Temperature
- Vicat Softening Point
- Thermal Expansion

Other Useful Material Properties

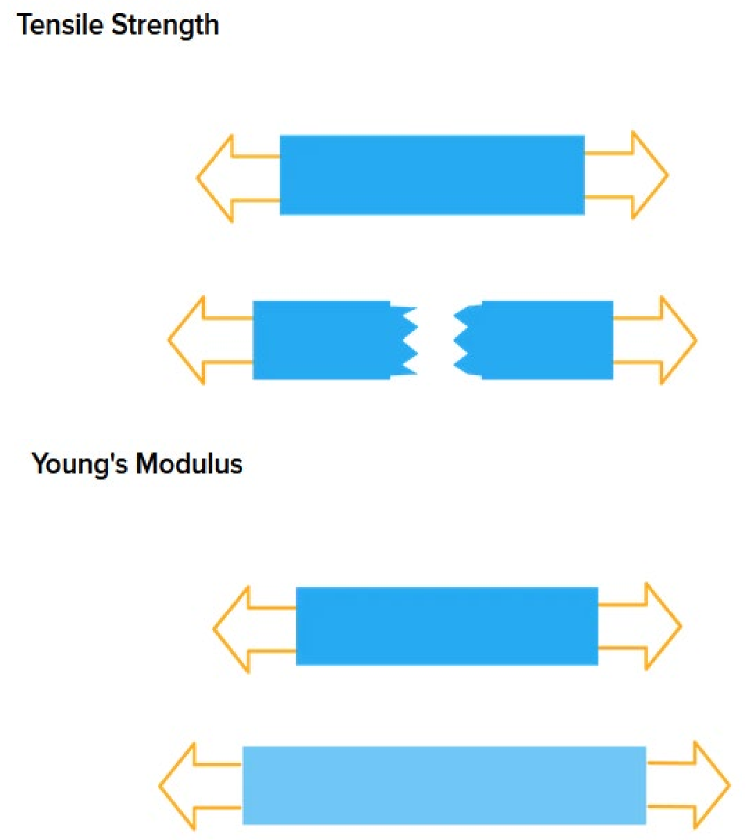
- Chemical Resistance
- Electrical Properties
- Machinability
- Ease of Printing
- Layer Adhesion
- Optical Properties
- Recyclability/Biodegradability
- Biocompatibility

Tensile strength: Resistance of a material to breaking under tension

- Fundamental property that shows the ultimate strength of a part. High tensile strength is important for structural, load bearing, mechanical or statical parts

Young's Modulus: Resistance of a material to stretch under tension (stiffness)

- Good indicator for either the stiffness (high modulus) or the flexibility (low modulus) of a material
- Important for structural parts that are expected to remain inside their geometric specifications under load



Source: Formlabs

Elongation: Resistance of a material to breaking when stretched

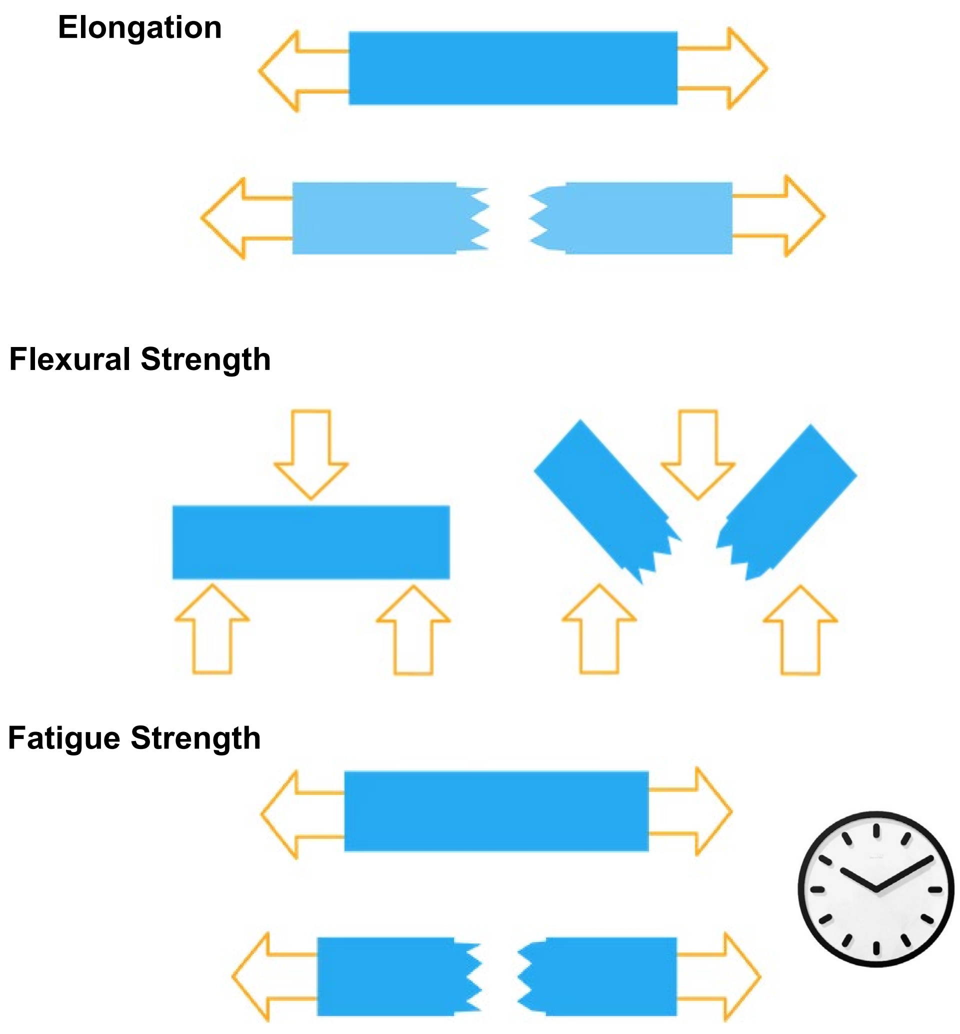
- helps you compare flexible materials based on how much they can stretch
- indicates if a material will deform first, or break suddenly

Flexural Strength: Resistance of a material to breaking when bent

- strength versus bending loads
- good indicator if a material is isotropic (homogeneous)

Fatigue Strength: highest stress that a material can withstand for a given number of cycles without breaking

- indicator of durability
- important on repeated loads



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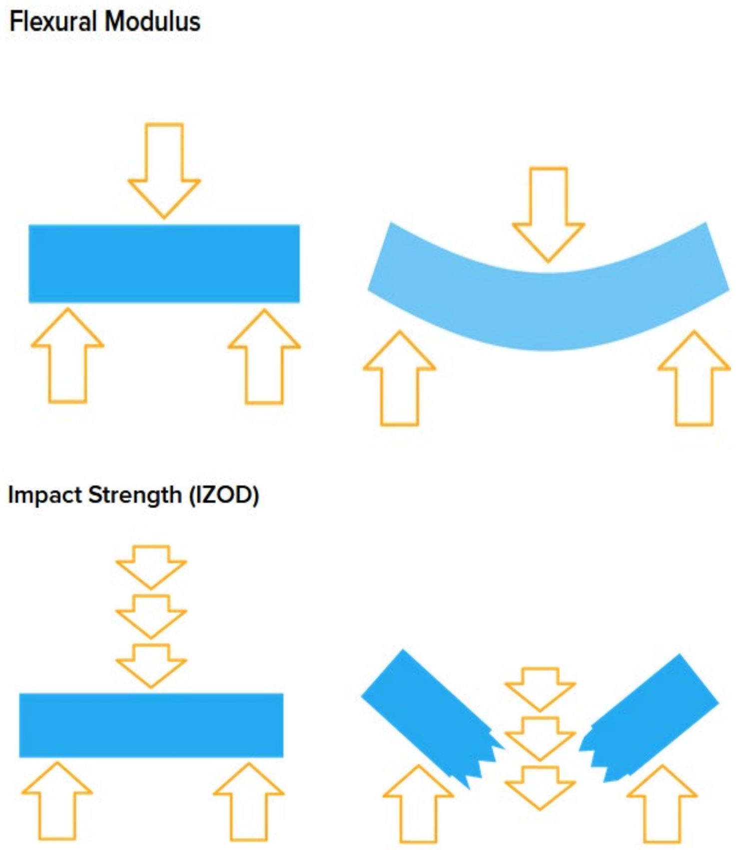
Flexural Modulus: Resistance of a material to bending under load

- indicator for either the stiffness (high modulus) or the flexibility (low modulus) of a material

Impact Strength: Ability of a material to absorb shock and impact energy without breaking

- indicates toughness, helps you figure out if a part will survive when dropped on the ground or crashed into another object
- Important for applications like safety goggles



Source: Formlabs

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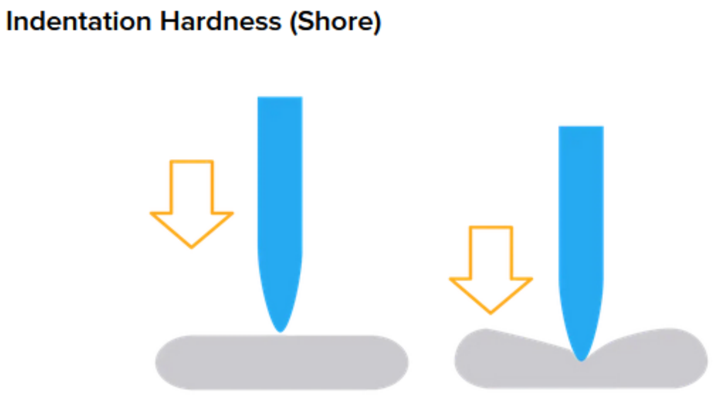
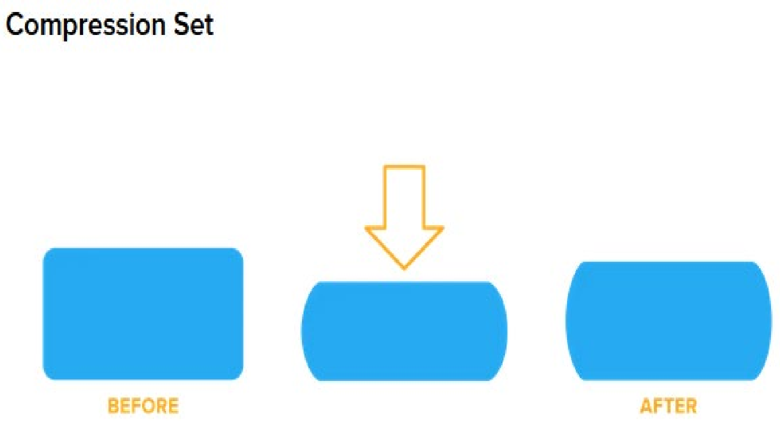
Indentation Hardness (Shore): Resistance of a material to deformation

- in practice synonymous with scratch resistance as well as resistance to indentation and elastic deformation
- helps you identify the right “softness” for rubber and elastomers for certain applications

Compression Set: Permanent deformation remaining after material has been compressed

- important for elastic applications, tells you if a material will quickly spring back into its original shape





Source: Formlabs

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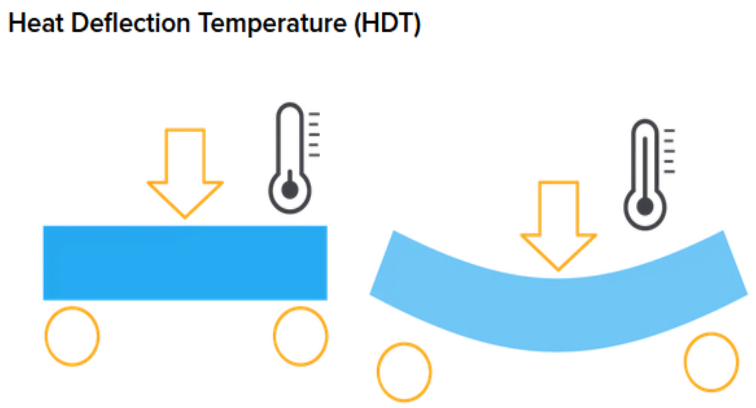
Water Absorption: Amount of water absorbed under specified conditions

important during the processing of the raw material, high water absorption or humidity can lead to hydrolysis, which cracks long molecule chains into shorter ones and weakens the material properties

Heat Deflection Temperature: Temperature at which a sample deforms under a specified load

indicates if a material is suitable for high temperature applications such as enclosures and mounts for heating elements, components which come in contact with hot liquids or gasses such as tooling for injection molds, fluidic connectors, valves, and nozzles.



Source: Formlabs

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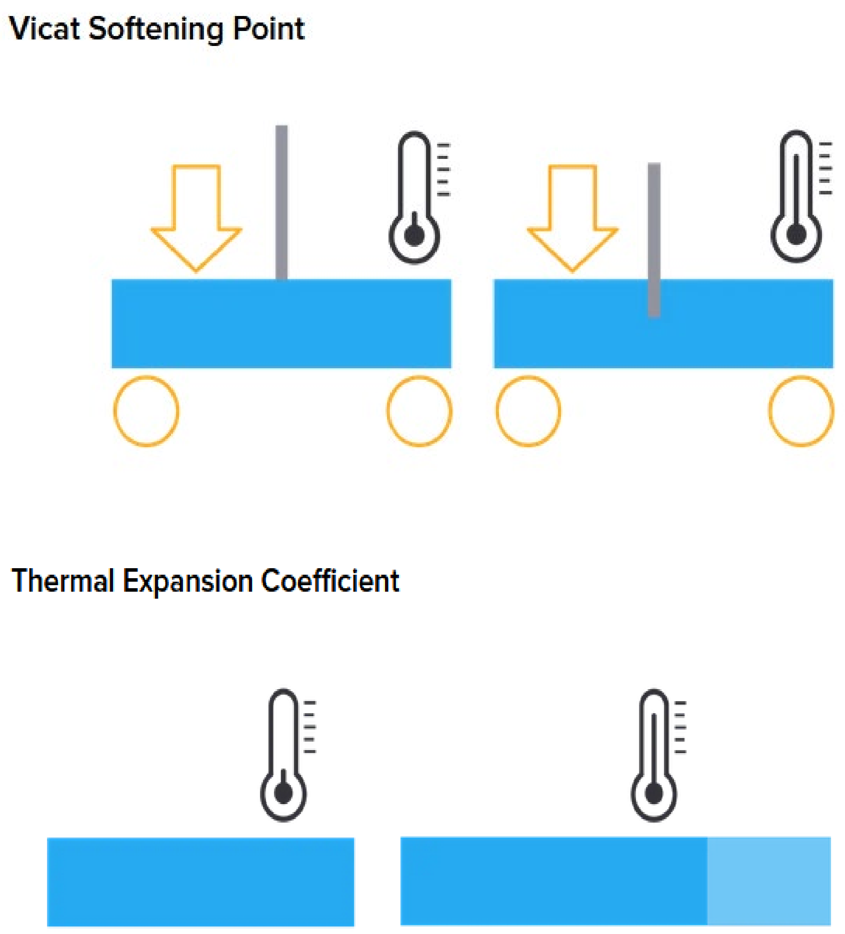
Vicat Softening Point: Temperature at which the material becomes noticeably soft

- used for materials that have no definite melting point. For high temperature applications it helps determine the upper temperature limit for continuous use

Thermal Expansion: Tendency of a material to expand (or shrink) in response to a change in temperature

- important for applications where a shape change in response to temperature is unacceptable or desirable
- if not taken into account can cause thermal phenomena such as hoop shrinkage, curling, and warping during printing



Source: Formlabs

Comparing Material Properties: Datasheets and Spider Web Diagrams

Description

PLA (Polylactic Acid) is a biodegradable, sustainable and food safe polymer made from organic sources.

It is the most common used filament in FFF 3D printers for its ease of use and awide range of applications, especially those not mechanically or thermally demanding. Definitely a good starting point to learn about the 3D Printing manufacturing process.

Properties

- Detailed and glossy surface quality
- Good tensile strength
- Rigid, fragile behaviour
- Good UV resistance
- Withstand operating temperatures up to 50 °C.
- Odor-free, ideal for educational and office environments
- Compatible with PVA supports
- Low humidity resistance

Recomendations

Plastics absorb moisture from the air. For long periods of time without printing, it is recommended to keep the PLA spools in a box or airtight container with desiccant to keep them dry.

PLA emits low levels of gasses and particles when printed. We recommend printing it in a well-ventilated area to ensure a healthy environment.

Filament specifications	
Diameter	∅ 2.85 mm
Max roundness deviation	≥ 95%
Net filament weight	750 g
Specific gravity (ISO 1183)	1.24 g/cm³

Mechanical properties		
	Typical value	Test method
MFR 210°C/2.16 kg	9.56 gr/10 min	ISO 1133
Tensile strength at yield	70 Mpa	ISO 527
Strain at yield	5 %	ISO 527
Strain at break	20 %	ISO 527
Tensile Modulus	3120 MPa	ISO 527
Impact strength-Charpy method 23°C	3.4 kJ/m²	ISO 179
Moisture absorption	1968 ppm	ISO 62

Thermal properties		
	Typical value	Test method
Melting temp.	115±35°C	ISO 11357
Vicat softening temp.	60 °C	ISO 306
Glass transition temp.	57 °C	ISO 11357

Printing settings	
Extruder temperature	190 °C - 220 °C
Bed temperature	65 °C
Speed	10-70 mm/s
Retraction speed	40 mm/s
Retraction distance	4 mm
Cooling fan	Yes
Minimum layer height	0.05 mm

Source: bcn3d.com

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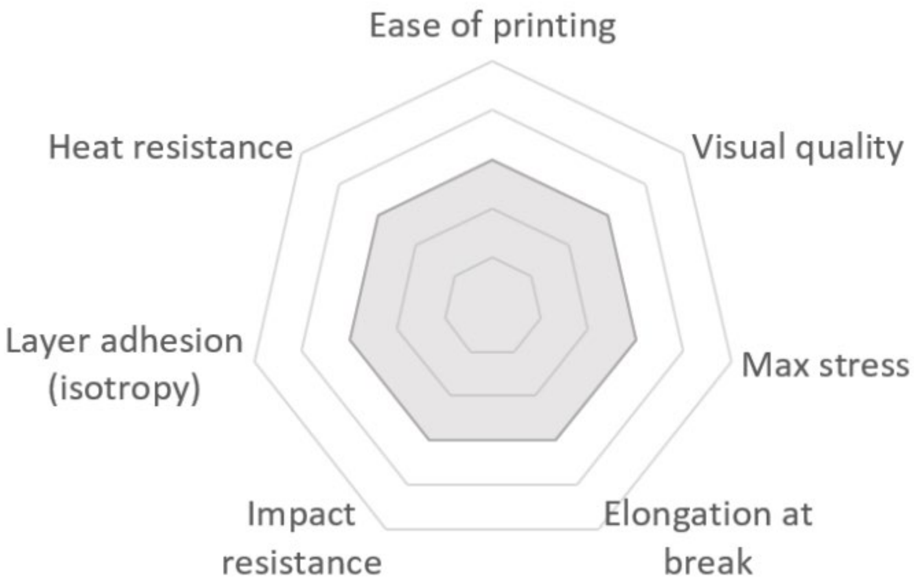
Evaluating Thermoplastics for Manufacturing

3 major categories

- Mechanical Performance
- Durability and Robustness
- Printability/Print quality

Additional properties to be considered

- Cost/Availability
- Chemical resistance
- Humidity resistance



Material Properties Spider Web Graph

Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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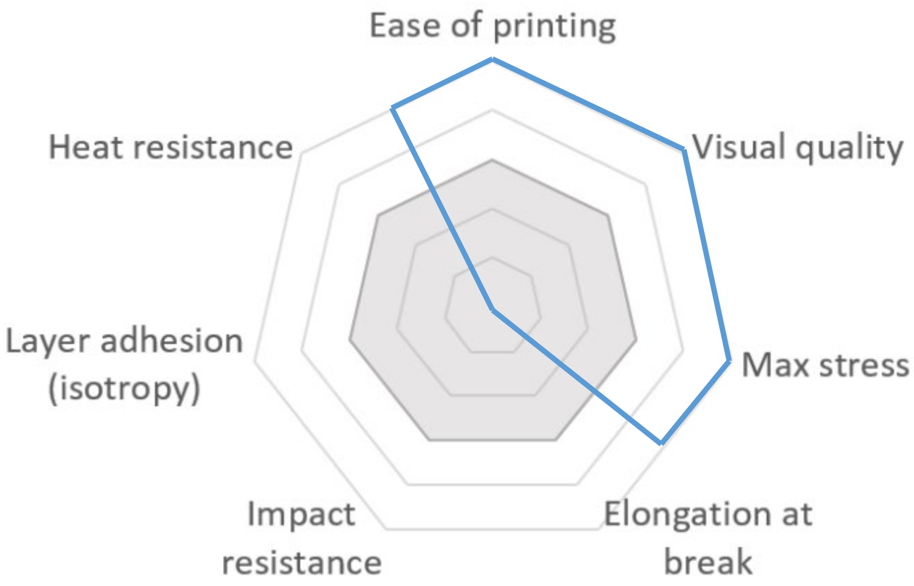
Visible/Tactile Attributes

- **Ease of printing:** How easy it is to print a material (bed adhesion, max printing speed, frequency of failed prints, flow accuracy, ease to feed into the printer etc.)
- **Visual quality:** How good the finished object looks
- **Max stress:** Maximum stress the object can undergo before breaking when slowly pulling on it



Material Properties Spider Web Graph

Adapted from: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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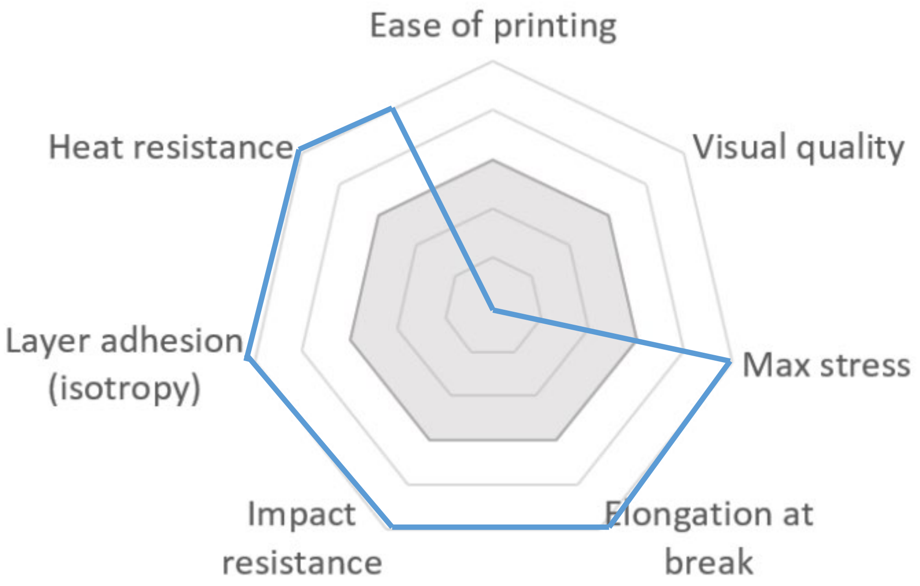
Mechanical Properties

- **Max stress:** Maximum stress the object can undergo before breaking when slowly pulling on it
- **Elongation at break:** Maximum length the object has been stretched before breaking
- **Impact resistance:** Energy needed to break an object with a sudden impact
- **Layer adhesion (isotropy):** How good the adhesion between layers of material is
- **Heat resistance:** Max temperature the object can sustain before softening and deforming



Material Properties Spider Web Graph

Adapted from: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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Agenda

- Introduction
- Material Properties Overview
- **Polymers in MEX Overview**
- Metal Filled, Fiber Filled Polymers and Continuous Fiber Fabrication
- Material Selection
- Biocompatibility
- Summary

Polymers in MEX Overview

- As AM has expanded rapidly, so has the variety of printing filaments
- Despite this boom, most MEX AM printable thermoplastics fit into three categories:
    - **Basic thermoplastics**
    - **Niche thermoplastics**
    - **Engineering-grade polymers**

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Overview of Polymer Materials in MEX

PLA - Hobbyist material
ABS - Low grade industrial material
PETG - Low grade industrial material

→ Basic thermoplastics

Nylon - Tough, flexible niche material
TPE - Flexible niche material
Polycarbonate - Medium Grade industrial material

→ Niche thermoplastics

PEEK/ULTEM - Superplastics, ideal for industrial uses

→ Engineering Grade Polymers (Superplastics)

Chopped Fiber Reinforced Plastics - Superplastics, ideal for industrial uses
Continuous Fibers - Composite materials, ideal for industrial uses

→ Specialty Industrial Grade "Composite" Materials

SAM: Polymers in MEX Overview

Basic thermoplastics: These plastics don't have any excellent qualities, but are the most popular printing thermoplastics available.

- **PLA**: the most common printing plastic, prints well and possesses decent mechanical properties—however, its complete lack of heat resistance and its low durability makes it impossible to use in industrial environments.
- **ABS:** good heat resistance, but not particularly strong and reacts poorly with most manufacturing chemicals.
- **PETG**: is a cross between the two: a bit stronger than ABS and a bit more heat resistant than PLA, but still not robust enough for most manufacturing environments.

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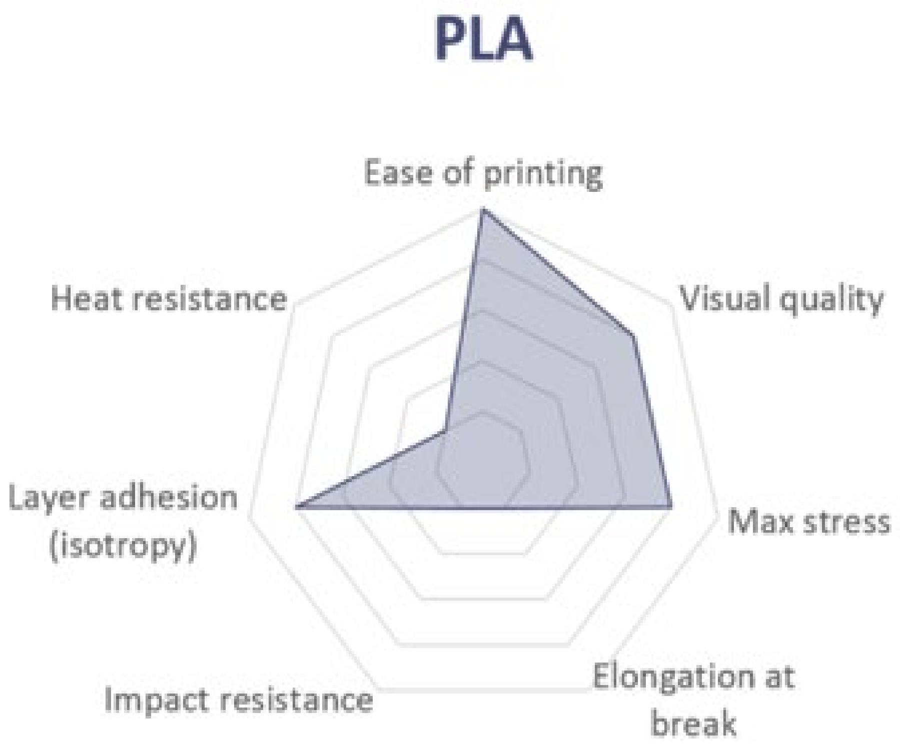
PLA

Pros

+ Easiest polymer to print and provides good visual quality
+ Very rigid and actually quite strong, but very brittle
+ Odorless
+ Bio-sourced and biodegradable
+ Can be post-processed with sanding paper and painted with acrylics
+ Good UV resistance
+ Cheapest

Cons

- Low humidity resistance
- Can't be glued easily



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

ABS

Pros

+ Higher temperature resistance and higher toughness than PLA

+ Can be post-processed with acetone vapors for a glossy finish or sanding paper

+ Can be painted with acrylics

+ Acetone can also be used as strong glue

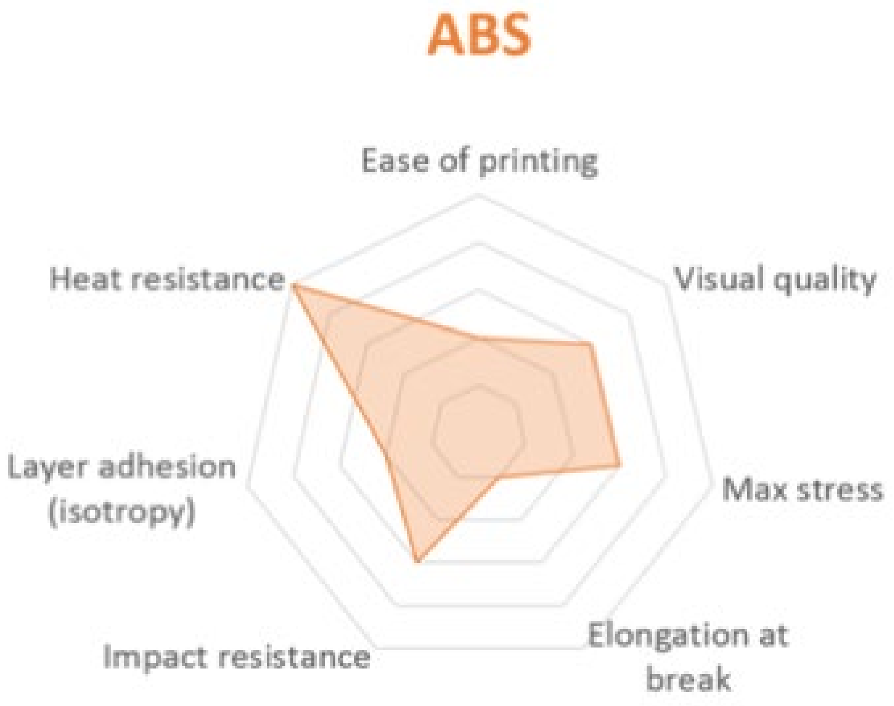
+ Good abrasion resistance

Cons

- UV sensitive

- Potentially high fume emissions/Odor when printing

- Low chemical resistance



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

PET/PETG

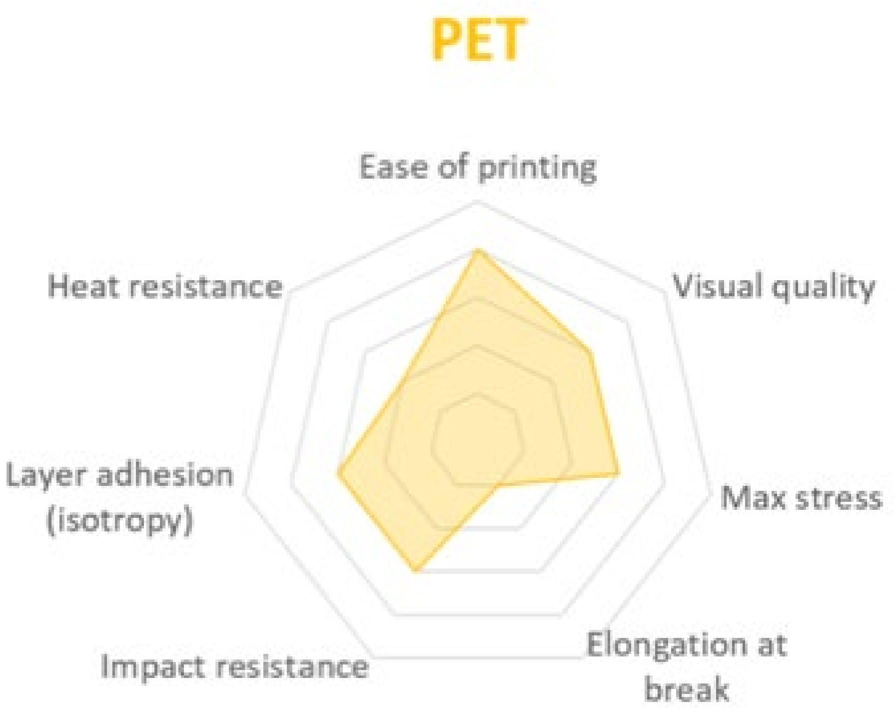
slightly softer polymer that is well rounded and possesses interesting additional properties with few major drawbacks.

Pros

+ Can come in contact with foods
+ High humidity/chemical resistance
+ Recyclable
+ Good abrasion resistance
+ Can be post-processes with sanding paper and painted with acrylics

Cons

- Heavier than PLA and ABS
- Not robust enough for manufacturing use



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

Niche thermoplastics: Niche thermoplastics have one or two excellent facets, making them very useful in specific applications.

- **Nylon:** not stiff or particularly strong and it carries virtually no heat resistance, but it's extremely durable and has remarkable chemical resistance.
- **TPU (or TPE):** an extremely ductile material that has similar properties to Nylon, with a bit more flexibility.
- **Polycarbonate (PC):** excellent plastic in many respects—quite strong and heat resistant—but is only moderately durable and chemically resistant.

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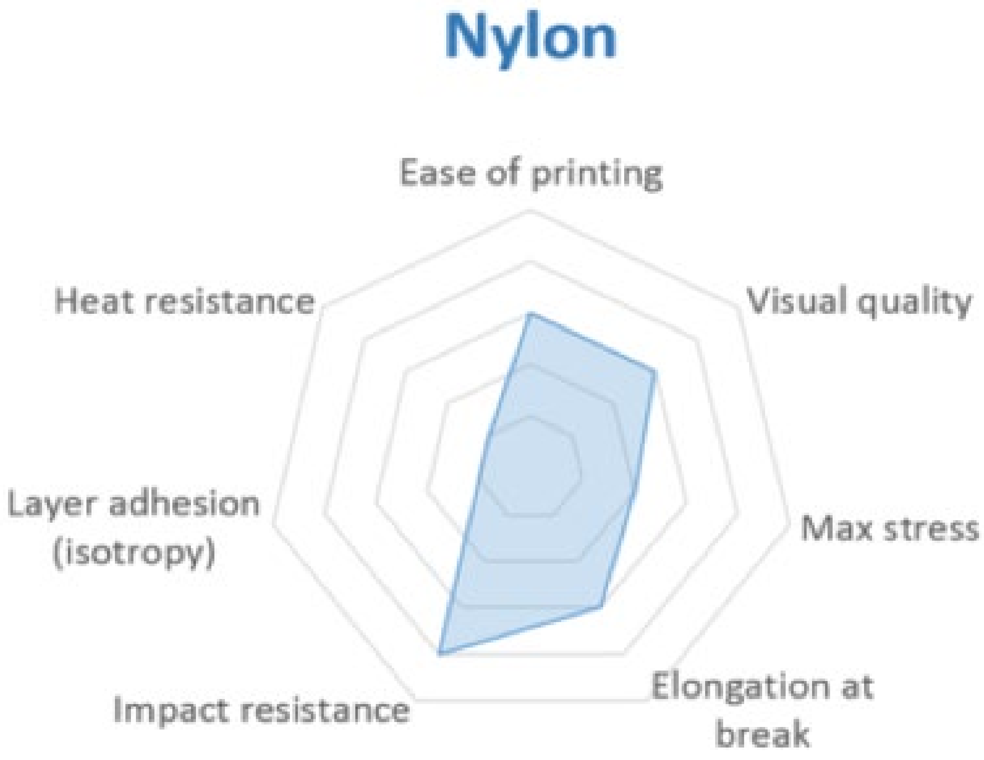
Nylon

Pros

+ Best impact resistance for a non-flexible filament
+ High Strength
+ High Durability
+ High chemical resistance

Cons

- Absorbs moisture
- Potential high fume emissions
- Not stiff or heat resistance enough to be usable alone in high load environments
- Challenging layer adhesion



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

TPU/TPE

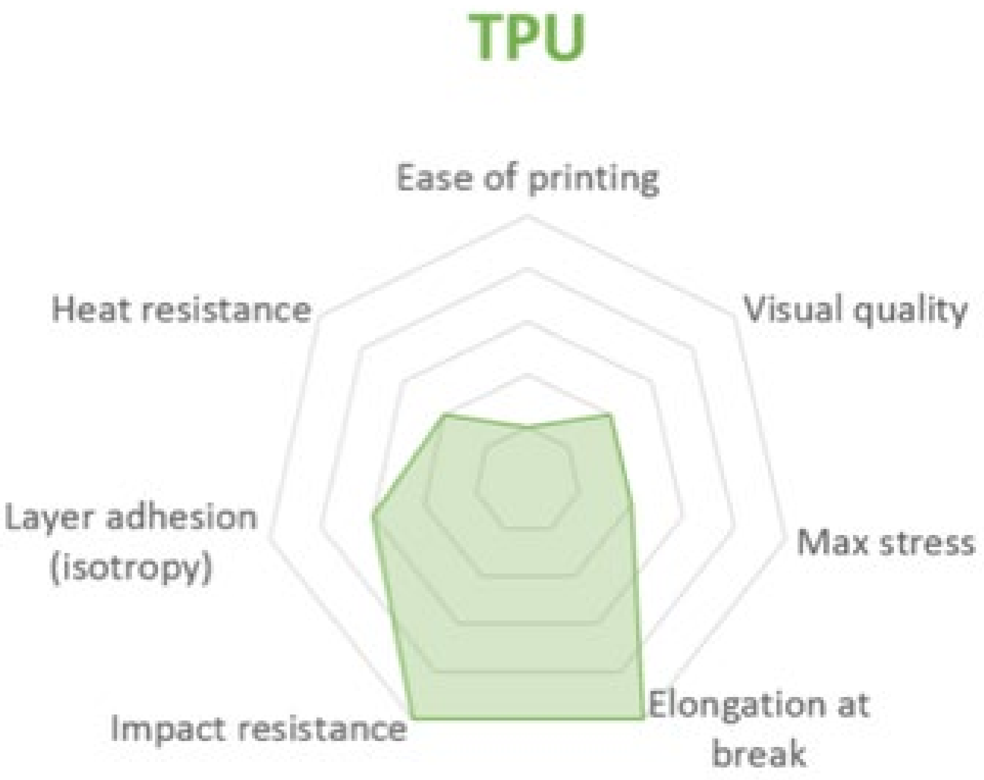
mostly used for flexible applications

Pros

+ Very high impact resistance
+ Good abrasion resistance
+ Good resistance to oil and grease
+ Highly flexible
+ Highly Durable

Cons

- Difficult to post process
- Can't be glued easily
- Not strong enough to used in base industrial applications



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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PC (polycarbonate)

the strongest conventional thermoplastic

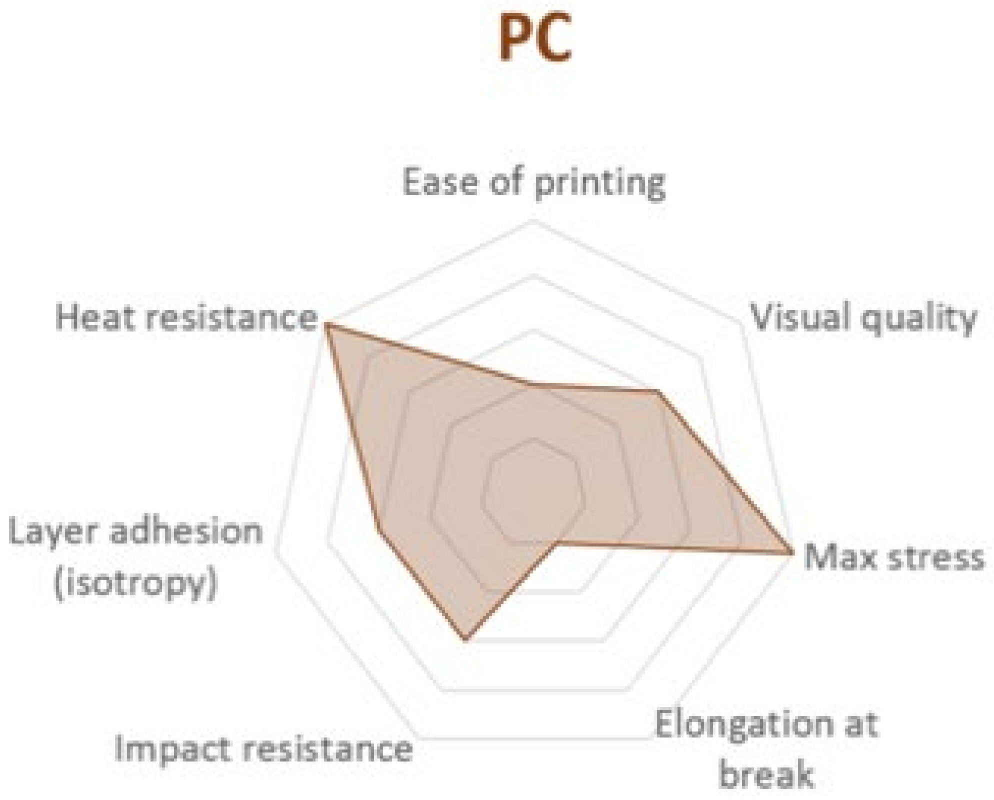
can interesting alternative to ABS (similar properties)

Pros

+ Very strong and stiff
+ Very high heat resistance
+ Can be sterilized
+ Easy to post-process (sanding)

Cons

- UV sensitive
- Few printers can print it due to high temperature required
- More expensive than ABS



Source: https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/#conclusion

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Engineering Grade Polymers: properties good enough for manufacturing environments

PEEK/ULTEM

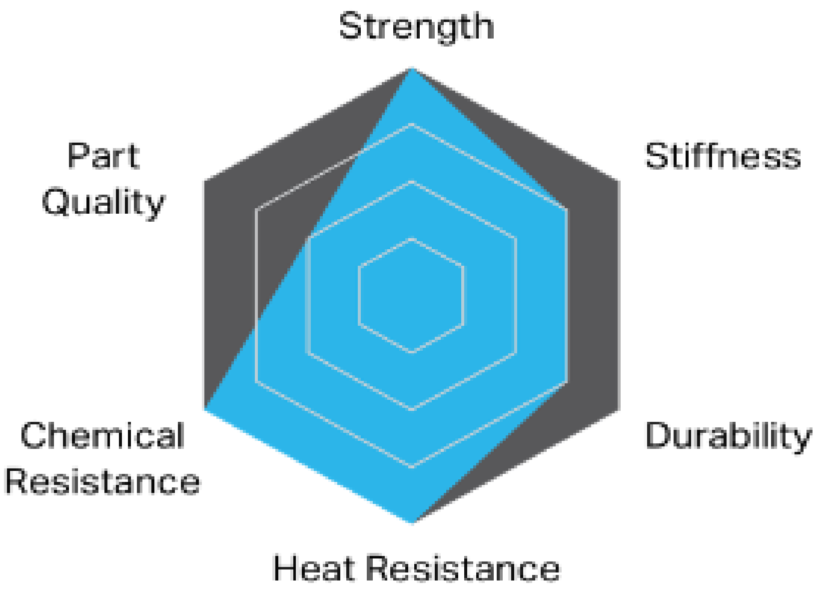
Pros

+ High grade plastics that posses good qualities across the board
+ Strong, stiff
+ Heat/chemically resistant
+ Machinable
+ Best for manufacturing environment

Cons

- Not commonly printed due to material cost and industrial printer cost
- Inaccessible
- Very expensive (both materials and printers required)

PEEK/ULTEM



Source: Markforged

SAM: Polymers in MEX Overview

Co-funded by the Erasmus+ Programme of the European Union

Properties	PLA	ABS	PET/PETG	Nylon	TPU/TPE	PC	PEEK
Tensile Strength (MPa)	37	27	55-75	40-50	26	55-75	90-100
Elongation	6	3.5-5	1.5	0.6-1.1	5.5-5.8	1.5	1.5
Flexural Modulus (GPa)	4	2.1-7.6	2.8-3.1	2.1	0.78	2.2-2.5	3.6
Density (g/cm³)	1.3	1.0-1.4	1.38-1.45	1.06-1.14	1.21	1.15-1.2	1.32
Melting Point (°C)	173	N/A (amorphous)	250	268	220	100-110	343
Glass Transition Temperature (°C)	60	105	81	70	-24	147	143
Biodegradable	Yes (under conditions)	No	No	No	Yes	No	No
Recyclable	Yes	Yes	Yes	Yes	Yes	Yes	No
Price (per kg)	15-30	15-45	20-60	50-100	90-100	40-90	200-400
Printability (1-10 scale)	9	8	9	8	3	4	4
Other Notable Properties	Biocompatible, Good for support structures, Resorbable	Impact Resistant	Chemically Resistant, Fatigue Resistant, Water Resistant	Flexible, Impact Resistant, Heat Resistant, Fatigue Resistant	Flexible	Impact Resistant, Heat Resistant, Fatigue Resistant	Biocompatible, Heat Resistant, Chemically Resistant, Machinable

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Factors Affecting Quality and Mechanical Properties of MEX AM printed Parts

Process parameters
- Air Gap
- Raster Angle
- Raster Width
- Infill Style
- Layer Thickness
- Contour Width

MEX Printer
- Nozzle Temperature
- Bed Temperature
- Chamber Temperature
- Nozzle Diameter
- Machine Calibration

CAD Model
- Quality of STL File

Final Part Quality and Mechanical Properties

Part Build Orientation
- Z direction
- Y direction
- Z direction

Raw Material
- Filament Quality
- Density
- Water Content
- Manufacturer

Environment
- Temperature
- Humidity
- Oxygen content

Real AM Printed Parts might have lower than expected mechanical properties

Agenda

- **Introduction**
- **Material Properties Overview**
- **Polymers in MEX Overview**
- **Metal Filled, Fiber Filled Polymers and Continuous Fiber Fabrication**
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Metal Filled Filaments

- Made by mixing a fine metal powder (such as Copper, Bronze, Brass, and Stainless Steel) into a base material (usually PLA) used for suspension
- The percentage of metal powder infused in each filament can vary (~80% or ~90% metal powder is common)
- Final parts have a unique metallic finish and added weight
- Provide an accessible MEX alternative to print metal parts compared to other AM metal printing processes
- End material can be
  a) **niche material**
  b) **engineering grade material**

Spool of Metal Filled Filament and Sample Prints

Source: BASF

Co-funded by the Erasmus+ Programme of the European Union

Properties and Applications

Final part properties depend on the type and concentration of metal powder used

Properties present in all metal filaments:

- Addition of a metallic finish to your prints (in a similar way to metallic car paints)
- Increase in weight (heavier than polymer materials - not as heavy as pure metal)
- Final part feels more solid than polymer parts, but is more brittle

a) Lower Metal Concentration => Niche Materials

- Look and feel like metal but and too fragile to be used in high load applications
- Used to print objects that don’t require the strength of real metal but do need to emulate it.

AM Printed and Treated Vase

Source: FormFutura

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Bronze and Copper Filled Applications

Commonly used 3D print sculptures and museum replicas.

- Copper's prints give modern sculptures a rustic appearance
- Bronze prints imitate the appearance of genuine ancient metal
- Ability to corrode (forming of patina allows for the creation of aged-looking models)

AM printed Replica of "Head of a Horse of Selene"

Source: 3dsourced

b) High metal concentration followed by de-binding and sintering => engineering grade material

- High Performance parts with metal like properties

Metal Filled Filament MEX Printed Sample Parts

Source: BASF

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Metal Filled Thermoplastics

Pros

+ Low entry barrier, simple, accessible and cost-effective printing of metal parts

+ Does not need high-temperature extruder

+ Aesthetically appealing metallic finish

+ Heavier than standard filaments (pro or con depending on the application)

+ Reduced potential hazard of handling fine metallic powders (when compared to SLM or Binder Jetting, due to immobilization of metal particles in the binder matrix)

+ Magnetic Ability

Cons

- Requires a wear-resistant nozzle (filaments tend to be very abrasive and wear the nozzle)
- Printed parts are very brittle
- Very poor bridging and overhangs
- Can cause partial clogs over time
- Heavier than standard filaments
- Expensive spools
- Require de-binding and sintering (to remove residual binder material and reach final properties)
- Sintering shrinkage needs to be accounted for

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Filled Thermoplastics- Chopped Fiber Reinforced Plastics

Combine the advantages of MEX AM with the superior material properties industrial grade fibers (such as carbon fiber, fiberglass)

Parts AM printed with these materials are

- engineering grade quality, ideal for industrial uses
- used when conventional thermoplastic properties are not sufficient
- excellent in a wide variety of applications
- easily be mistaken for parts that aren't printed

AM Printed Brake Pedal Assembly

Source: Stratasys

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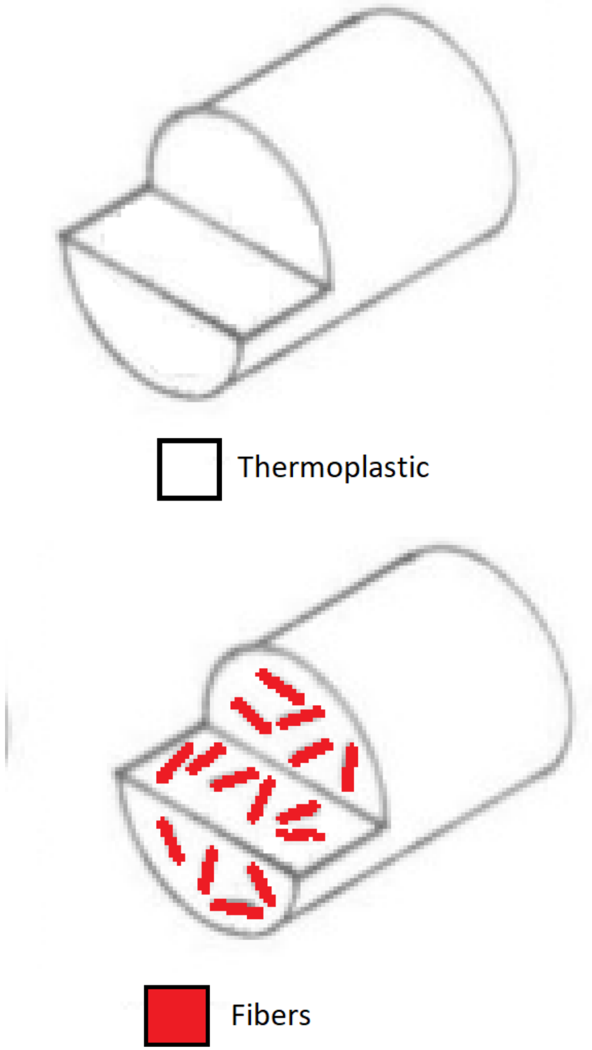
Fiber Filled thermoplastics are standard/conventional thermoplastics that are impregnated with tiny particles (fibers) of a second material

The concentration of the second material may vary, but it’s still primarily a thermoplastic by composition and material behavior

Not technically a composite material because the fibers are blended inside the plastic, rather than remaining distinct.



How Fiber Filled Thermoplastics are Printed

- Chopped Fibers are short-length fibers chopped into segments <1mm in length and mixed into traditional thermoplastics to form what is called a filled plastic.
- This combination, called a filled plastic, is extruded using a **standard MEX** printing process.

Close-up of chopped carbon fibers used in AM, taken on an SEM.

Chopped carbon fiber stool

Source: Markforged

SAM SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING
Co-funded by the Erasmus+ Programme of the European Union

Matrix Material Properties

- must extrude easily
- offer a smooth surface finish
- adhere well to itself as infill (so that it is stable under compression)
- not be brittle once it sets (to avoid risk of fracture)
- most importantly for embedded fibers, the matrix must be **ductile** enough to allow the fibers to be loaded.

Fiber Properties

- Main function is reinforcement, the primary factor is tensile strength (very important when parts are designed to maximize axial loading of the fiber)
- Fiber does not need to create a nice surface finish or hold stable under compression
- Qualities such as heat deflection and gradual yield modes distinguish one fiber from another

Remember that there is a **mutual dependence**: fiber requires the space created and held by the plastic in order to do its job, so both must work together to form a strong part.

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Advantages of Filled Thermoplastics

- Carbon fiber, fiberglass and other material have superior material properties to thermoplastics
- Adding tiny particles of strong material to a plastic matrix augments material properties, increasing yield stress and flexural strength
- Nylon most common, PLA , ABS and PC also exist
- **Note**: chemical resistance is still wholly dependent on the plastic

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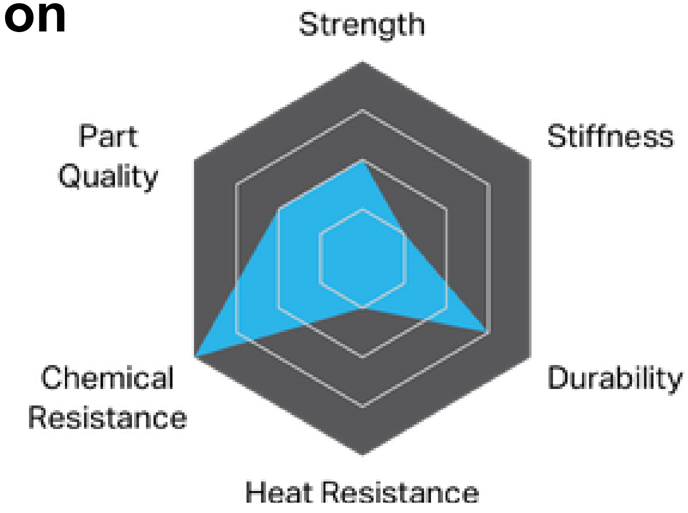
Conventional Nylon

- Moderately common AM printing plastic known for durability and chemical resistance
- Not stiff or heat resistant enough to be usable on a large scale
- Niche+ thermoplastic

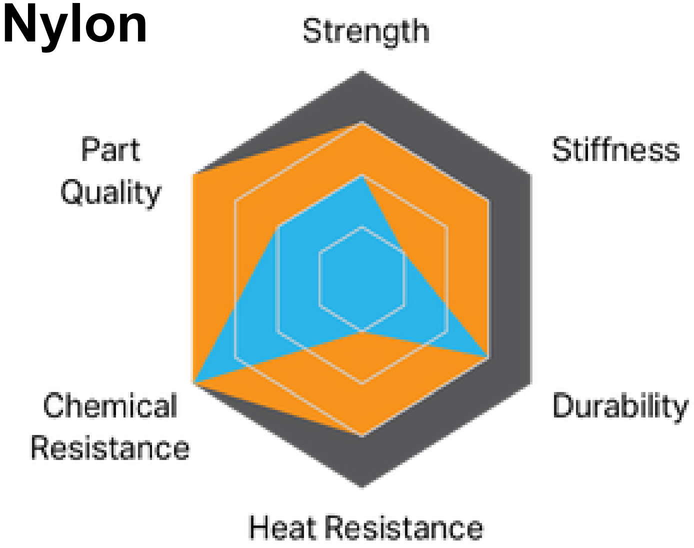
Carbon Fiber Filled Nylon

- Retains chemical resistance and durability
- Heat resistance increased
- Strength and Stiffness increased
- Part Quality Increased
- Becomes a superplastic

Nylon



CF Filled Nylon



Source: Markforged

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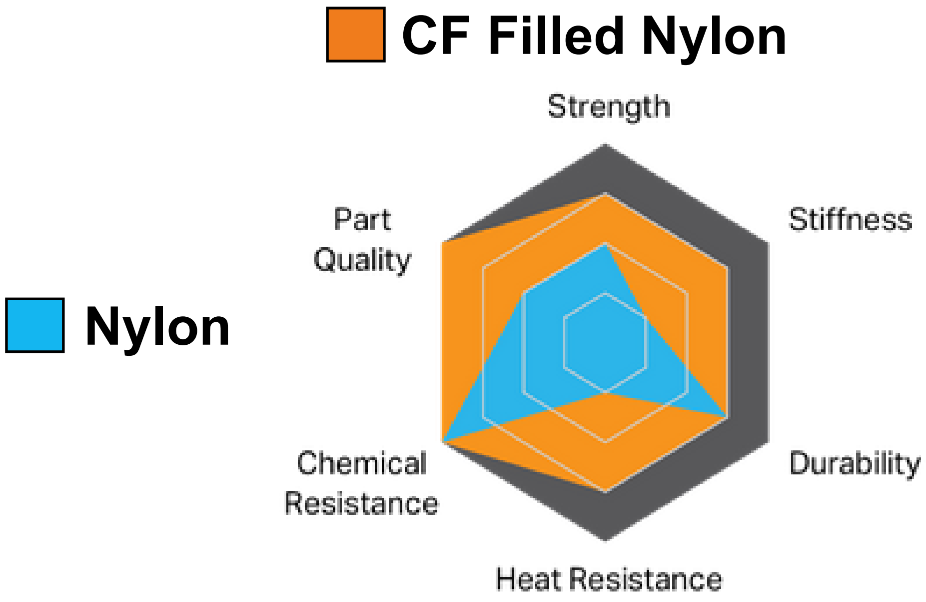
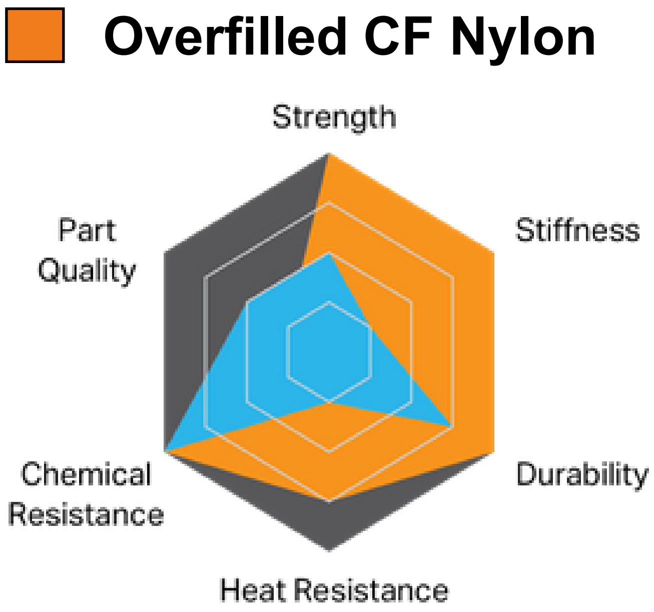
Increasing Fill Concentration (Overfilling)

- Overfilling nylon with carbon fiber yields a completely different material than filled CF Nylon
- Increasing carbon fiber concentration boosts strength and stiffness further, but at the cost of decreased print quality.

- When adding too much CF the print quality decreases
  - the binding thermoplastic cannot flow through the printing system properly => visible defects and rough surface texture
- End material is closer to niche+ plastic





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Most Common Fiber Materials

- **Fiberglass**
- **Carbon Fiber**
- **Kevlar**
- **High Strength High Temperature (HSHT) Fiberglass**

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Fiberglass

- all-purpose fiber/works in most scenarios
- most cost-effective fiber option
- bends until eventual fracture
- performs best under intermittent loading
- 3x stronger and 11x times stiffer than ABS

Applications

- works-like prototypes
- brackets
- drill jigs
- soft jaws

Fiberglass filled AM Printed Soft Jaws

Source: Markforged

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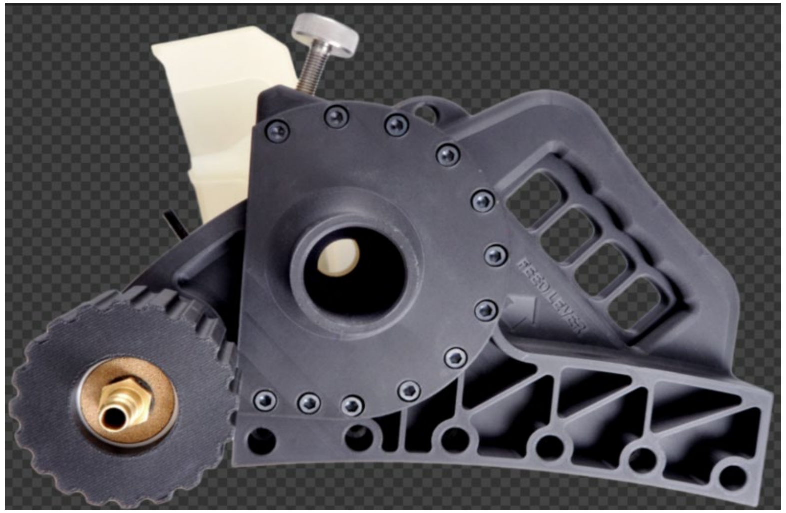
Carbon fiber

- strength-to-weight ratio 50% better than 6061 aluminum
- tensile modulus roughly equivalent to that of aluminum
- very stiff (stiffness 24x that of ABS)
- best for maximal strength under constant loading

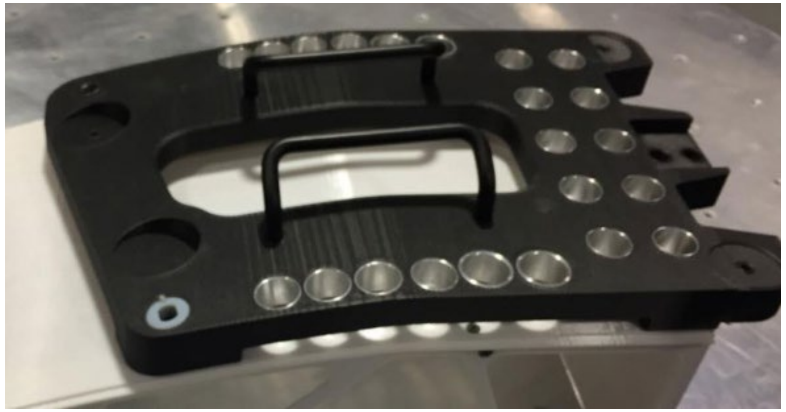
Applications

- inspection fixtures
- machining fixtures
- cantilevered members
- other end-use parts subject to constant loading



Circular Saw Frame

Source: Siemens Gas & Power



Drill Guide

Source: Airbus

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Kevlar

- extremely durable
- shock resistant
- elastically deforms prior to failure

Applications

- impact loading (clamping, stamping)
- parts where advance warning of failure is needed

Clamp for cast aluminum valves

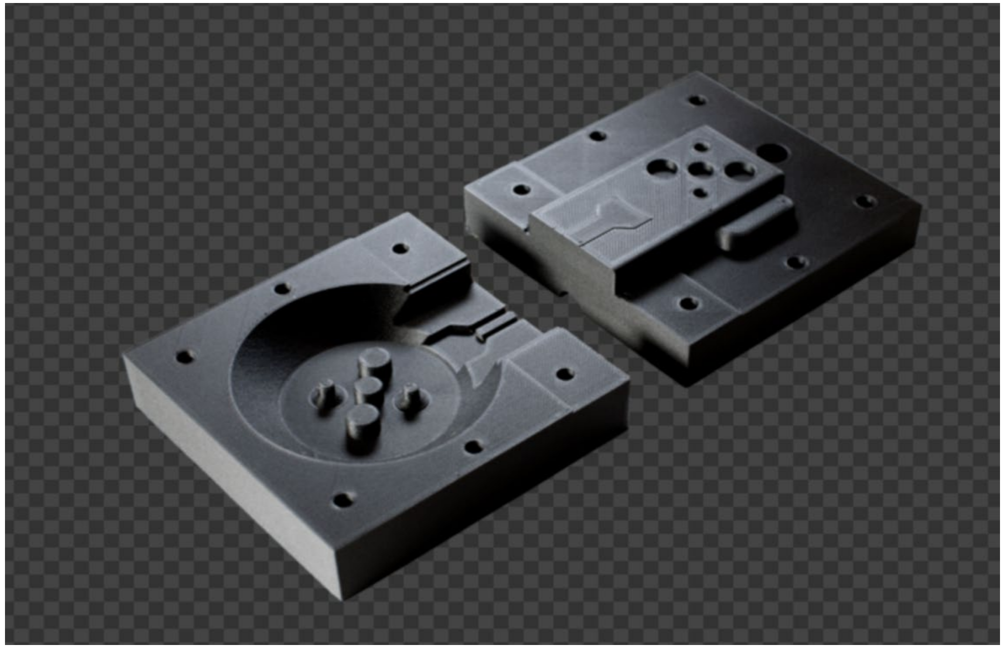
Source: Markforged

HSHT Fiberglass

- heat resistant (maintains properties up to 150°C+ vs 105°C for other fibers)
- suitable for both constant and intermittent loading

Applications

- weld fixtures
- thermoforms
- thermoset molds
- blow molds



Thermoset molds

Source: Humanetics

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Fibers Overview

	Carbon Fiber	Fiberglass	HSHT Fiberglass	Kevlar®
Properties	High strength-to-weight ratio, stiff	Sturdy, cost-effective	Sturdy, high heat deflection	Tough, impact-resistant
Ideal loading type	Constant loading	Intermittent loading	Constant loading at high temperatures	Impact loading
Failure behavior	Stiff until fracture	Bends until fracture	High energy absorption until fracture	Bends until deformation
Characteristics and advantages	Metal stiffness and strength, lightweight	Economical starting point, general-use fiber	Keeps strength at high temperatures	High deflection and impact resistance

Source: Markforged

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What if even greater mechanical properties and print quality are needed?

Combination of MEX printing and **Continuous Fiber Fabrication (CFF)** to lay down long strand fibers in conventionally printed thermoplastic parts

Continuous Fiber Fabrication (CFF) Method

- Requires 2 print nozzles
- Main nozzle prints the matrix material (polymer)
- Secondary nozzle lays down intact continuous fibers

Fibers do not melt—instead, they're captured by the thermoplastic matrix in a similar way that thermoset adhesives like epoxy capture fibers in traditional fiber fabrication methods.

Render of Continuous Fibers and Matrix

Source: Markforged

SAM: Continuous Fiber Fabrication (CFF)

Composites take advantage of the compressive strength of the plastic matrix and the tensile strength of embedded fibers.

Matrix (support structure compromising most of the part volume)

- Offers compressive strength
- Creates space so that the fiber has a lever arm to stabilize against the load
- Offers all the advantages of small-batch fabrication and rapid iterability
- Determines the **heat resistance, chemical resistance, and print quality**

Matrix Render

Source: Markforged

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Continuous Fibers (backbone of the part)

- Provides tensile strength though the embedded fibers
- Make the composite part mechanically stable and durable
- Can produce composite parts with directional strength of metal
- Elastic moduli between 16x- 46x greater than those of plastics
- Continuous fibers run uninterrupted through a part (3d geometrical distribution of load)
- Perform best in tension (critical to print them with loading conditions in mind)

Continuous Fibers Backbone

Source: Markforged

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Mutual Dependence:

- without fiber, the plastic part is only as strong as the adhesion within and between extruded plastic strands.
- Without the matrix, the fiber has no structure and therefore won't maintain its shape.

End Result

- composite with greater strength in both compression and tension than either can offer individually
- metal-strength properties at a fraction of the weight
- control the behavior and performance of parts
- optimization of a part's strength for its weight and material consumption

The engineer is not limited to a single set of material properties, but he can leverage the characteristics of both constituents

Brake Lever with 2 rings of co-ecentric continuous Kevlar Fiber

Source: Markforged

Co-funded by the Erasmus+ Programme of the European Union

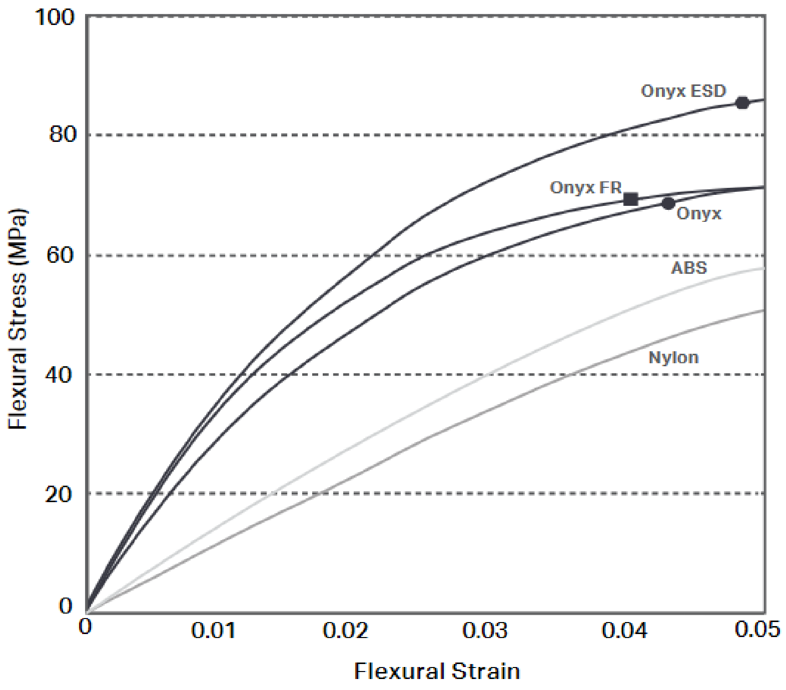
Continuous Fibers vs Filled vs Normal Thermoplastics Comparison

Source: Markforged

Thermoplastic Matrix vs Continuous Fiber Flexural Strength Comparison

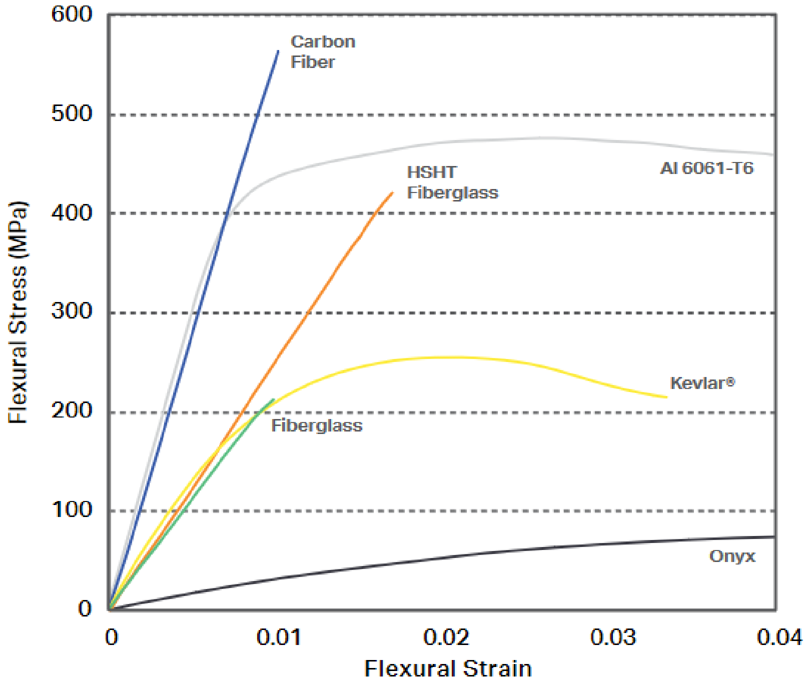
Composite Base

Markforged Composite Base materials print like conventional FFF thermoplastics. They can be printed by themselves, or reinforced with any of our continuous fibers, including Carbon Fiber, Kevlar, and Fiberglass.



Continuous Fiber

Continuous Fibers are laid down on the inside of parts through a second fiber nozzle. They cannot be printed by themselves — instead, they are used to reinforce parts printed out of a composite base material like Onyx.



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Agenda

- Introduction to Polymers/Thermoplastics
- Material Properties Overview
- Polymers in MEX Overview
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- **Material Selection**
- Biocompatibility
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How to choose a material

1. **Determine performance requirements via intent of use**
   - Prototyping and R&D?
   - Validation or pre-production?
   - End-use parts?
2. **Translate performance to material requirements**
   - Stiffness/hardness
   - Toughness/tear strength
   - Temperature and chemical resistance
   - Creep and durability
3. **Select material**
   - Design Space/Operation Environment
   - Durability
   - Longevity
   - Cost

Test print and iterate!!

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Example: Gaming Mouse Prototyping

source: 3D Hubs

What are the performance requirements for an early design prototype?

How are those performance requirements translated into material requirements?

What material would you use and why?

Example: Shield Boss

source: http://www.petefielding.com

What are the performance requirements if:

a) used as a decorative piece?

b) used in reenactment?

How do material requirements change when intent of use changes?

What material would you use in case a) and case b) and why?

Example: Brake Pedal Assembly

Source: Stratasys

What are the performance requirements?

How do the performance requirements translate into material requirements?

Which Material would you choose?

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Outline

- Introduction
- Biocompatible Applications
- Biocompatible Materials Overview
- Advantages/Limitations of MEX Process
- Overcoming Limitations of MEX
- Advances in Pharmaceutical Applications
- Conclusions

AM Printed Cheek and Forehead Implant

https://apiumtec.com/wp-content/uploads/2018/01/Skull_Cheek_Implant_NoBackground.png

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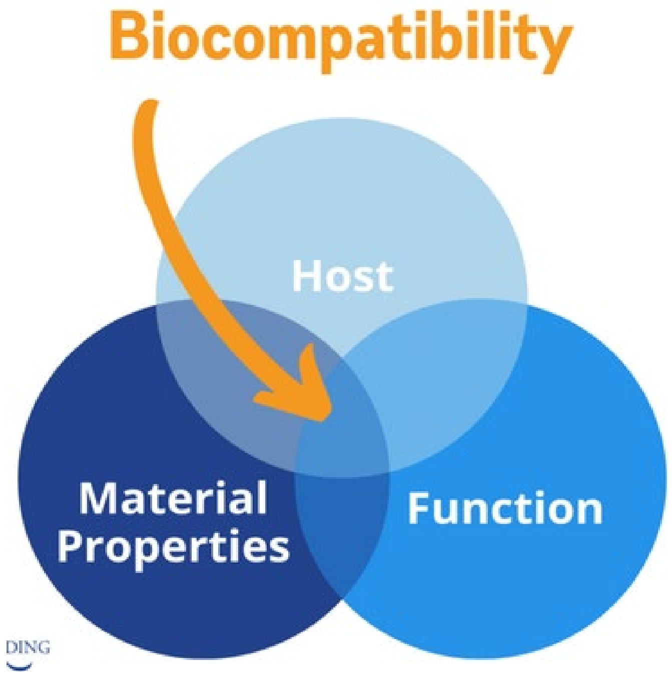
Biocompatibility: the ability of a biomaterial to sustain cellular activity including molecular signaling systems without provoking or arousing local or adverse effects to the host.

Biocompatible Material (Biomaterial): materials are biocompatible when they exert the expected beneficial tissue response and clinically relevant performance.

Components of Biocompatibility: cytotoxicity, genotoxicity, mutagenicity, carcinogenicity and immunogenicity.

Biocompatibility Standards

- United States Pharmacopoeia IV (USP Class IV) Biological Reactivity Test
- International Standards Organization 10993 (ISO 10993) Biological Evaluation of Medical Devices



https://www.cascobaymolding.com/biocompatibility

- Food Safe Parts (containers, tools)
- Medical (devices, prosthetics, implants, dentures)
- Pharmaceutical (individualised dosage pills, polypills)
- Training Tools (Medical Modeling/Surgical Planning)

Food Safe AM Printed cup and tools

https://www.sculpteo.com/en/3d-learning-hub/3d-printing-materials-guide/food-safe-3d-printing-materials/

Prosthetics

https://www.rapidmade.com/3d-printing-in-the-medical-industry

Polypill

https://www.crtonline.org/news-detail/polypill-prevents-cv-events-in-rural-iran

SAM SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING
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Biomedical Applications

Bone Implants

https://www.3dprintingprogress.com/articles/20405/3d-printed-implants-antibacterial-and-analgesic

Dentures

https://www.aegisdentalnetwork.com/idt/2013/08/three-dimensional-printing-of-dentures-using-fused-deposition-modeling

Dental implant

https://www.sculpteo.com/blog/2018/10/12/3d-printing-in-pediatrics-saving-lives-using-additive-manufacturing/

Hearing Aids

https://www.sonova.com/en/story/innovation/3d-printing-technology-improved-hearing

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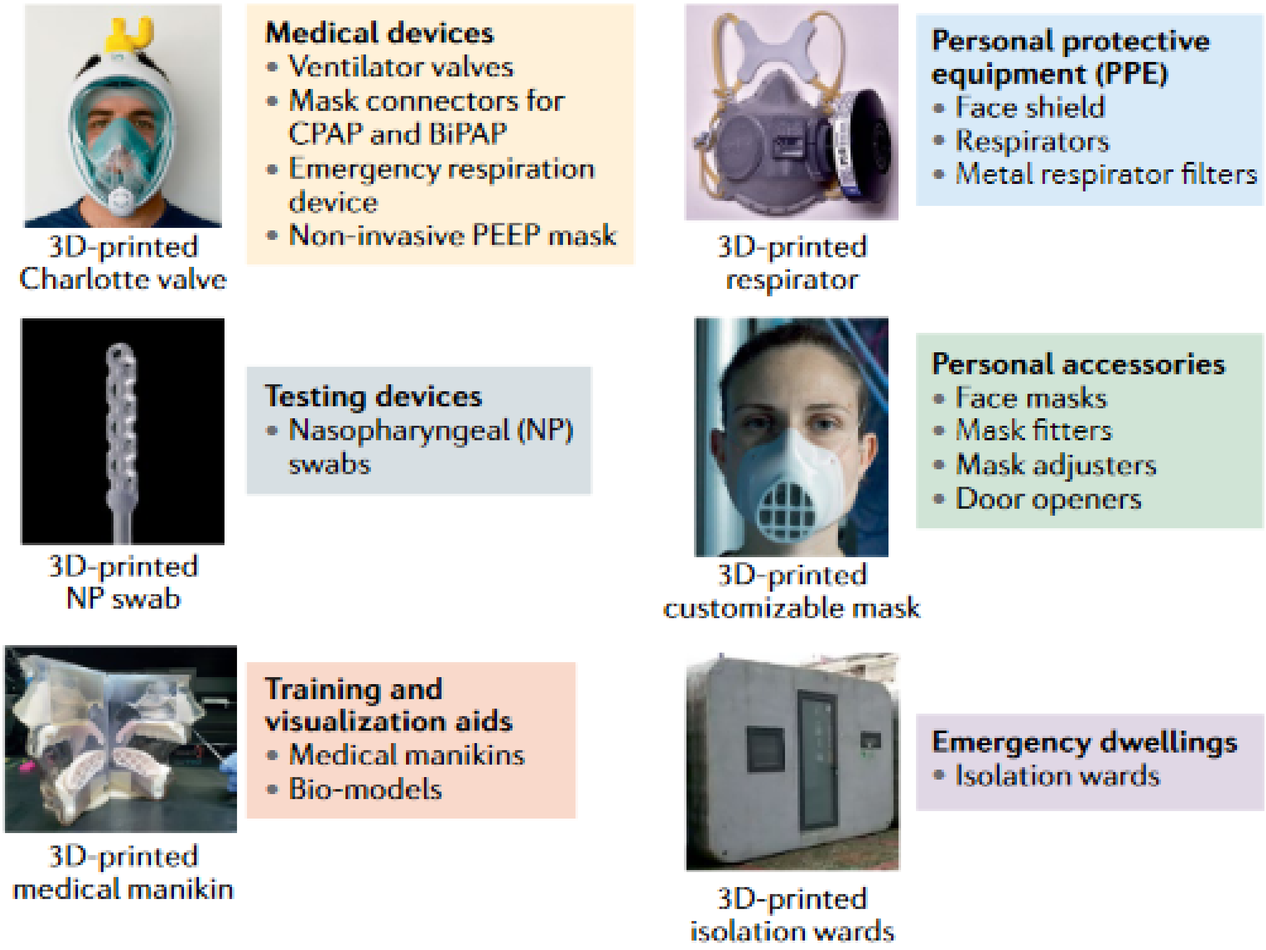
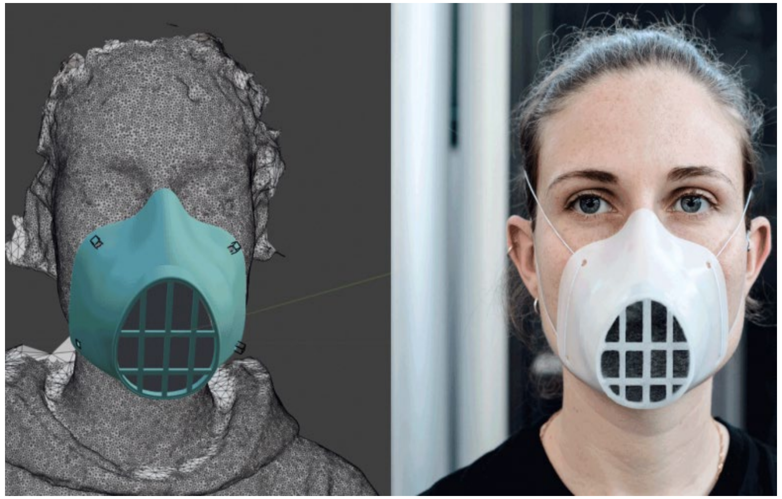
AM Printing Applications in the battle vs Covid-19



https://www.nature.com/articles/s41578-020-00234-3.pdf

Personal Protective Equipment (PPE)

Face masks



https://www.3dprintingmedia.network/personalized-ppe-mask/

Respirators

a b c

J.Alexander, N95 vs FFP3&FFP2masks – What’s the difference? https://fastlifehacks.com/n95-vs-ffp/

Face shields

https://www.eurologport.eu/3d-printed-face-shields-for-medics-and-professionals/

Co-funded by the Erasmus+ Programme of the European Union

Medical Devices and Parts

Ventilators

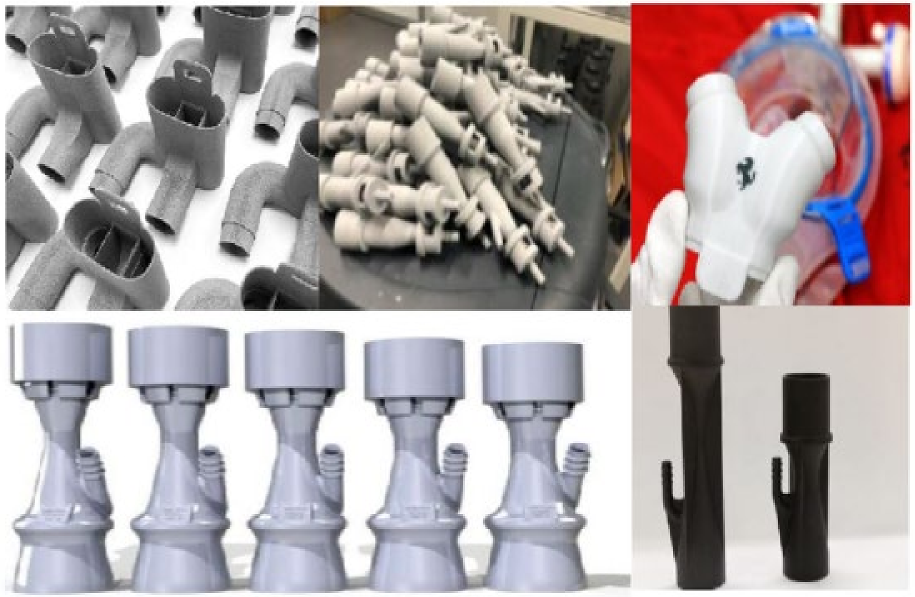
T. Boissonneault, These 3D printed nasal swabs self-adjust for comfort. 3D Print. Media Netw. (2020) https://www.3dprintingmedia.network/3d-printed-nasal-swabs-self-adjust/ , A. Faryami, C. Harris, Open source 3D printed ventilation device (2020).

Splitters

S. Ayyıldız, A. Dursun, V. Yıldırım, M. İnce, M. Gülçelik, C. Erdöl, 3D-printed splitter for use of a single ventilator on multiple patients during COVID-19. 3D Print. Addit. Manuf. 7, 181–185 (2020), A. Clarke, 3D printed circuit splitter and flow restriction devices for multiple patient lung ventilation using one anaesthesia workstation or ventilator. Anaesthesia 75, 819–820 (2020).

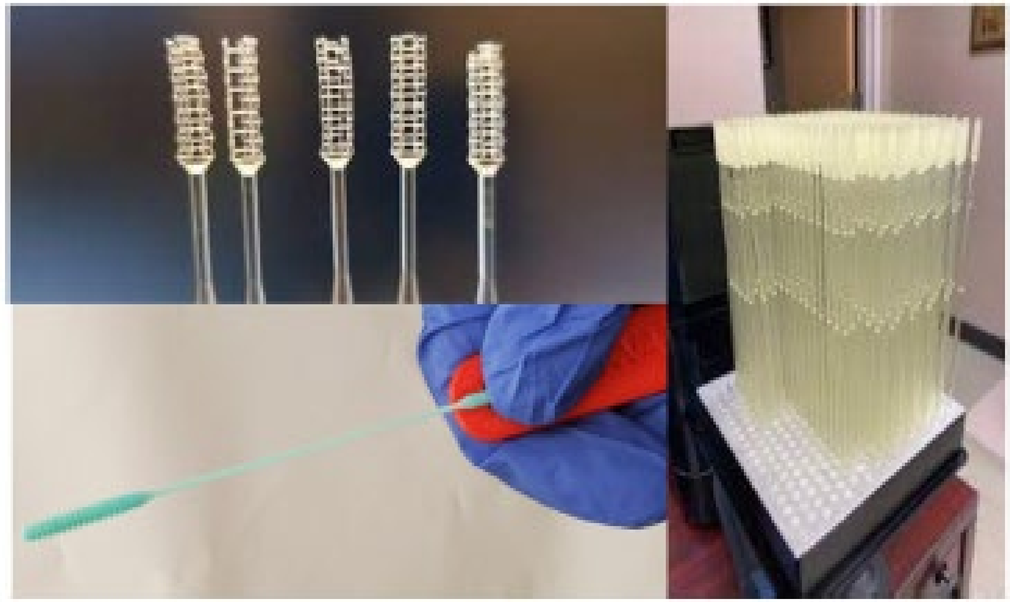
Medical Devices and Parts

Valves



source: https://link.springer.com/content/pdf/10.1007/s42247-021-00164-y.pdf

Diagnostic Tools - Swabs



Source: Aydin, A., Demirtas, Z., Ok, M. *et al.* 3D printing in the battle against COVID-19. *emergent mater.* **4,** 363–386 (2021)

Co-funded by the Erasmus+ Programme of the European Union

Materials and Methods used in the battle against Covid-19 Overview

Personal Protective Equipment (PPE)

Personal protective equipment (PPE)

Producer	Materials	Purposes	Method
Face mask			
Thomas et al.	PLA	Customized mask production	FDM
Kvatthro	PLA	Customized mask production	FDM/microwave
Lowell Makes	PLA/PETG	Flexible and adjustable strap	FDM
Erickson et al.	N/A	Converting Flyte helmets to PPE	FDM
Swennen et al.	PLA	To produce a perfect fit mask with 3D face scanning	FDM
Agarwal et al.	PLA	Comfortable breathing and preventing the formation of fog in glasses	FDM
Copper 3D mask	PLA/copper	To produce antibacterial copper nanoparticle masks	N/A
Face shields			
Tino et al.	PLA	Producing suitable face shields	FDM
Mueller et al.	PLA/PETG	Obtaining more durable face shields	FDM
Auxiliary accessories			
Manero and friends	PLA	To facilitate the use of masks	FDM

Ventilator Devices and Parts

Ventilator devices

Producer	Materials	Purposes	Method
Ventilators			
Faryami et al.	PLA	To create a device that can be produced quickly and easily to meet the need for ventilation devices	FDM
Leitat	N/A	To produce an emergency ventilator	FDM
California University	N/A	To produce a ventilator device that provides an eating setup for patients who need a ventilator	FDM
Northwell Health	N/A	To convert the V60 BiPAP machine to a ventilator	FDM
Materialise	N/A	To provide patients with high positive pressure outside of ventilator devices	FDM
Splitter			
Ayyildiz et al.	Acrylic resin	To create an intensive care ventilator to serve multiple patients in the emergency departments	PolyJet
Clarke	N/A	To create an intensive care ventilator to serve multiple patients in the emergency departments	FDM
Prisma Health, Johnson & Johnson	N/A	To create an intensive care ventilator to serve multiple patients in the emergency departments	FDM
Valves			
Fraccasi et al.	N/A	To produce the required valves by the 3D printing method	FDM
Photocentric	Photoresin (RG35)	To produce large quantities of valves quickly	SLA
CRP Technology	Wildform P1	To produce Charlotte valves that are fast, cheap and in abundant to create ventilators	HSS
Ferrari/Mares	Nylon 12	To produce large quantities of valves quickly	FDM

Aydin, A., Demirtas, Z., Ok, M. *et al.* 3D printing in the battle against COVID-19. *emergent mater.* **4,** 363–386 (2021).

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AM Printed parts used in the fight against Covid-19 overview:

Item	AM technologies
Face shields	FFF, SLA, SLS
Safety goggles	FFF, SLA, SLS
N95 respirators similar	FFF
Half-face masks	FFF, MJF, SLS
Antimicrobial mask	FFF
PAPR parts	FFF
Ear Savers	FFF
Mask fitters	FFF
Isolation chambers	FFF
Isolation wards	Not specified
Valves for CPAP	FFF
Splitter valves	Not specified
Valves for NIV helmets	Not specified
Venturi valves	FFF, SLA, SLS
Field Respirators parts	Not specified
Nasopharyngeal swabs	DLP, FFF, MJF, SLS, SLA
Hands-free door openers	MJF, FFF, SLS
Hands-free tools	FFF
Manikin for swab testing training	Not specified
Educational models	SLS, PolyJet
Mounts to point webcams downward	FFF
Bias tape makers	FFF
Mask pleaters	FFF
Copper filters	Binder jetting
Surgery mask	FFF

MEX Printing was the most commonly used method

Longhitano, G.A., Nunes, G.B., Candido, G. *et al.* The role of 3D printing during COVID-19 pandemic: a review. *Prog Addit Manuf* **6,** 19–37 (2021). https://doi.org/10.1007/s40964-020-00159-x

SAM: Biocompatible Materials Overview

Most commonly-used biocompatible materials (or biomaterials) are **polymers**

- inherent flexibility
- tunable mechanical properties
- resorbable (ability to be absorbed into the circulatory systems of cells or tissue)
- degradation of by-products safe for psychological conditions

Most common biocompatible polymers:

- medical grade acrylonitrile-butadiene-styrene (**ABS**)
- polylactide (**PLA**)
- polyetheretherketone (**PEEK**)
- polycarbonate (**PC**)

Other biocompatible polymers:

- cyclic olefin copolymer (COC)
- polyetherimide (PEI)
- medical grade polyvinylchloride (PVC)
- polyethersulforone (PES)
- polyethylene (PE)
- polypropylene (PP)

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PLA

+ biodegradable/resorbable + made from renewable sources (such as corn starch or sugarcane) + aesthetics/finish + fair to good sterilization properties	- can very easily lose its structural integrity (particularly if under load, as it approaches 60 °C)

ABS

+ good mechanical properties (higher flexural strength, better elongation, heat resistance) + thermal stability + ductility + machinability + recyclable	- medical grade quality should be used for bio-applications - not biodegradable - potentially toxic at high temperatures - low to medium sterilization properties

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PEEK:

+ advanced biomaterial with extremely good cell biocompatibility + good sterilization properties + resistant to organic and aqueous environments + high performance polymer • high melting temperature • high tensile strength • elastic modulus being comparable to that of cortical bone => great for reduced stress shielding for implant use • machinable • thermostable, good electric and thermal insulation	- higher price - not biodegradable - not recyclable - challenging to process with MEX

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PC:

+ highly transparent (light transmission comparable to glass ~90%) + high impact strength + high medical retention + can withstand repeated steam sterilization + high performance polymer • very high melting temperature • high tensile strength • thermostable, good electric and thermal insulation • flame retardant	- easily attacked by hydrocarbons - drying is required before processing - low fatigue endurance - yellowing tendency post exposure to UV - not biodegradable - challenging to process with MEX

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Comparison of Most Common Biocompatible Thermoplastics: ABS, PLA, PEEK

Properties	Medical Grade ABS	PLA	PEEK	PC
Tensile Strength (MPa)	27	37	90-100	55-75
Elongation	3.5-5	6	1.5	1.5
Flexural Modulus (GPa)	2.1-7.6	4	3.6	2.2-2.5
Density (g/cm^3)	1.0-1.4	1.3	1.32	1.15-1.2
Melting Point (^{o}C)	N/A (amorphous)	173	343	100-110
Glass Transition Temperature (^{o}C)	105	60	143	147
Biodegradable	No	Yes (under conditions)	No	No
Recyclable	Yes	Yes	No	Yes
Sterilization (autoclave, dry heat, EtO, Gamma irradiation, electron beam)	Poor-Good	Fair-Good	Good	Fair-Good

Advantages of MEX in Bioprinting

- Cost effective (compared to traditional manufacturing methods)
- Availability and ease of use
- Printing speed (in comparison to SLA, SLS, and PBP)
- Material versatility (variety of available pharmaceutical grade polymers)
- Freedom of design (easily customized parts)
- Not requiring toxic or organic solvents

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Limitations of MEX Bioprinting

- High temperature required => potential thermal degradation of pharmaceutical excipients and active drugs
- Dimensional inaccuracy (compared to other AM techniques)
- Relatively poor to medium thermoplasticity and mechanical properties of the FDA-approved pharmaceutical grade polymers => balanced by adding plasticizer/filler or blending with other thermoplastic polymers, special attention must be given to the changes in the release behavior of the drug
- Physical state of APIs in printed dosage form is difficult to control => balance between print ability and drug release might reduce the design flexibility for the formulation optimization
- Restrictions with regard to the material properties of the feedstock filament material necessary to feed it through the rollers and nozzle => changes in the properties of the material require considerable effort to recalibrate the feeding parameters

Overcoming Limitations in MEX Bioprinting

a) Semisolid Extrusion (EXT) Printing
b) Hot Melt Extrusion (HME) Printing

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Semisolid Extrusion (EXT) Printing

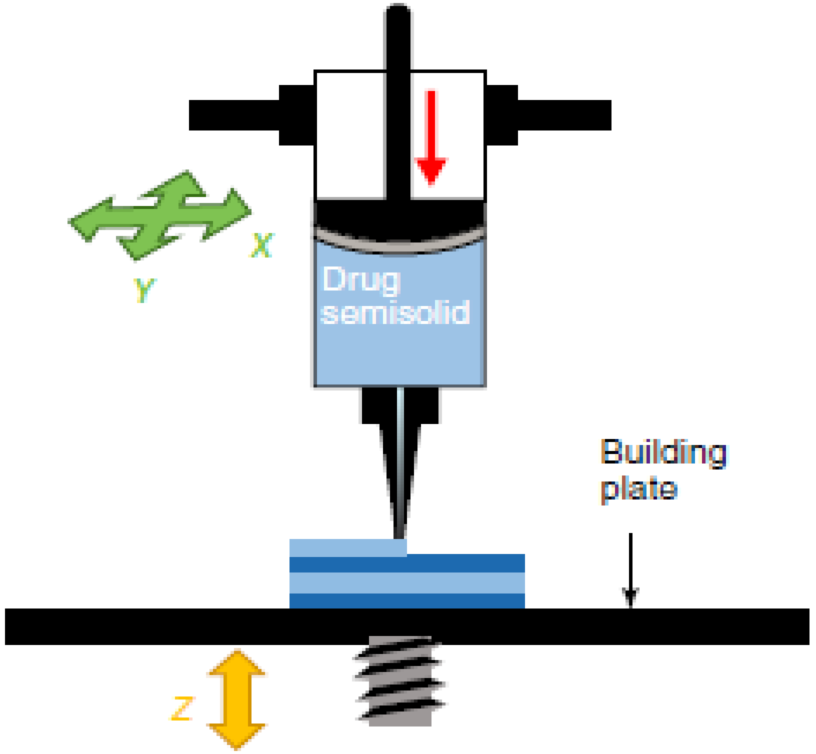
Process

- Use of semisolids as the starting material
- Semisolid material is extruded through a syringe-based toolhead
- Semisolids are usually in the form of gels and pastes
- Viscosity of the semisolids can be controlled by varying amount of polymers and solvents mixed together

Pros and Cons

+ Does not require high temperatures (like MEX) => preferred technology for bio-printing

- Printing material needs to be in the form of gel/paste
- Low printing resolution
- Possibility of collapse
- Possibility to shrink or deform



Semisolid Extrusion Process

Alhnan, M.A., Okwuosa, T.C., Sadia, M. et al. (2016). Emergence of 3D printed dosage forms: opportunities and challenges (in eng). *Pharmaceutical Research* 33 (8): 1817–1832.

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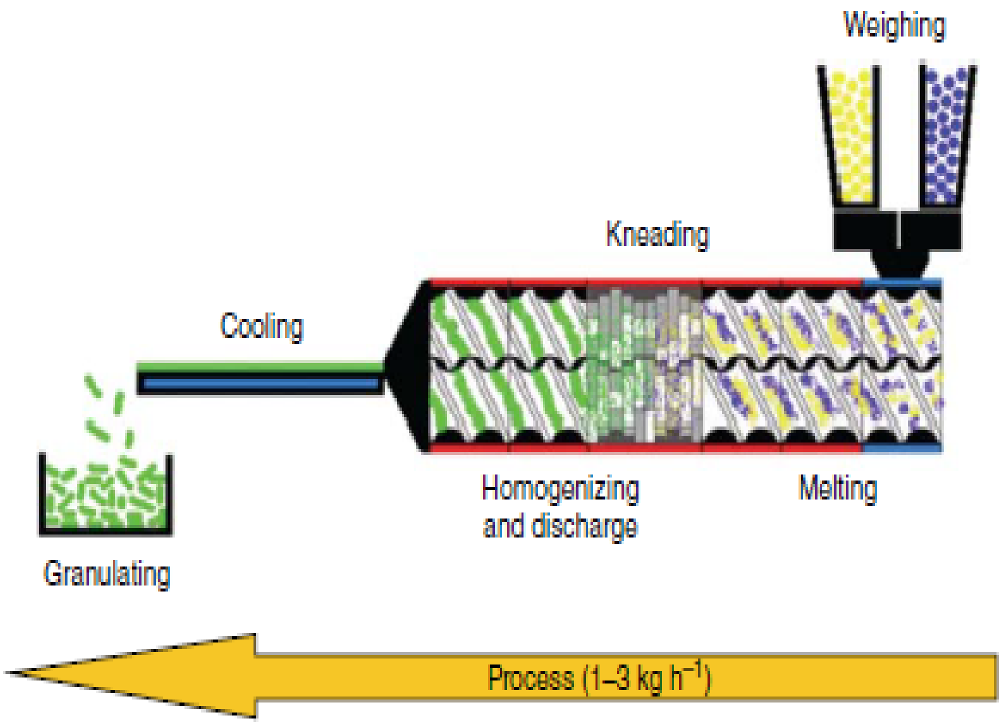
Hot Melt Extrusion (HME) Printing

Process

- Feeding of the raw materials (usually polymers)
- Melting and mixing of materials
- Extrusion of the mixed material through a die
- Cooling/Cutting/Collecting

Main Component: Extruder

- barrel containing one or two rotating screws
- screws transport the material down the barrel



Hot Melt Extrusion Process

Maniruzzaman, M., Boateng, J.S., Snowden, M.J., and Douroumis, D. (2012). A review of hot-melt extrusion: process technology to pharmaceutical products. *ISRN Pharmaceutics* 2012: 1–9. 436763.

Hot Melt Extrusion (HME) Printing

+ good homogenous mixing of multiple materials
+ enhances bioavailability and solubility of APIs (active pharmaceutical ingredients)
+ enables printing of drug-loaded and polymer mixed filaments
- Not suitable for thermally labile drugs
- Limited availability of materials

AM printed theophylline-loaded tablets

Mohammed Maniruzzaman (2019), 3D and 4D Printing in Biomedical Applications: Process Engineering and Additive Manufacturing, Wiley-VCH Verlag

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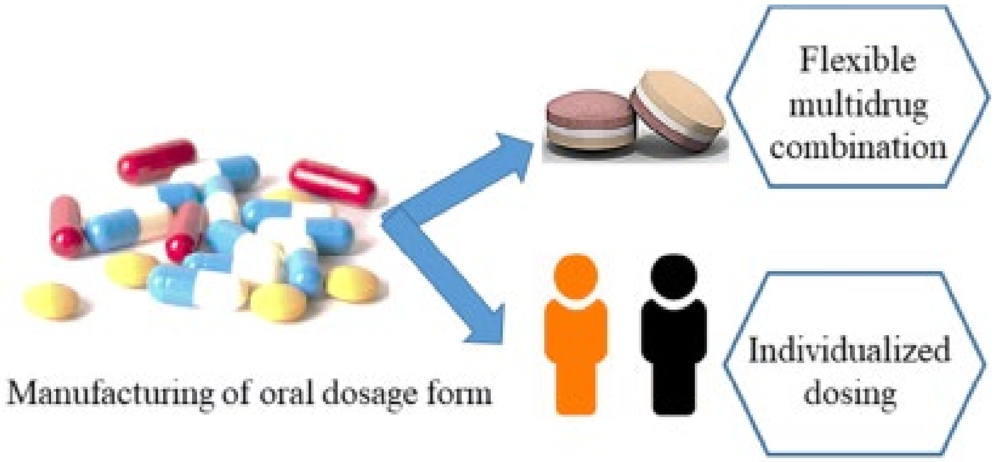
A new paradigm in Health Care - Individualised solutions for treatment

Production of medicinal products in smaller batches, on demand, personalized, and tailored for specific diseases.

Applications

- Drug Delivery Carriers
- Individualized - Single Dosing Pill Fabrication
- Polypill – Multidrug Manufacturing



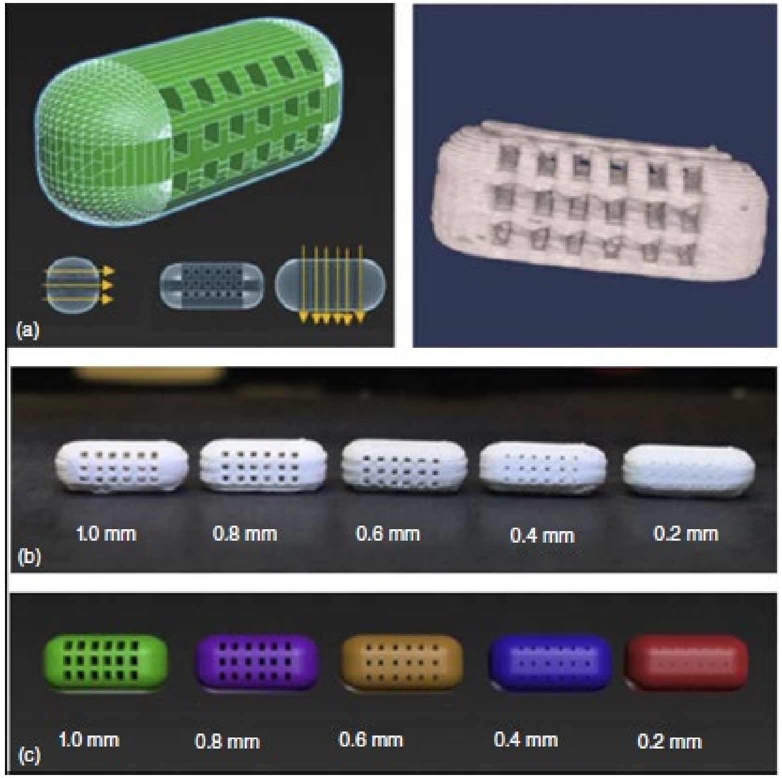
Pandey, M., Choudhury, H., Fern, J.L.C. *et al.* 3D printing for oral drug delivery: a new tool to customize drug delivery. *Drug Deliv. and Transl. Res.* **10,** 986–1001 (2020)

Drug Delivery Carrier Improvement

- Manufacturing of channeled caplets exhibiting accelerated release of the incorporated drug
- Accelerated release depends on size of the perforating channels

Single Dosage Pill Fabrication

- Flexible manufacturing of on demand, personalized pills with right amount of APIs



Sadia, M., Arafat, B., Ahmed, W. et al. (2018). Channelled tablets: an innovative approach to accelerating drug release from 3D printed tablets. *Journal of Controlled Release* 239: 355–363

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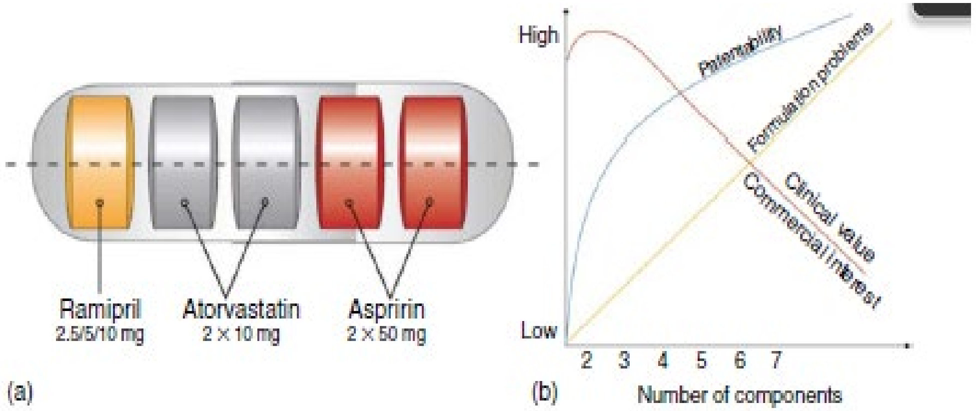
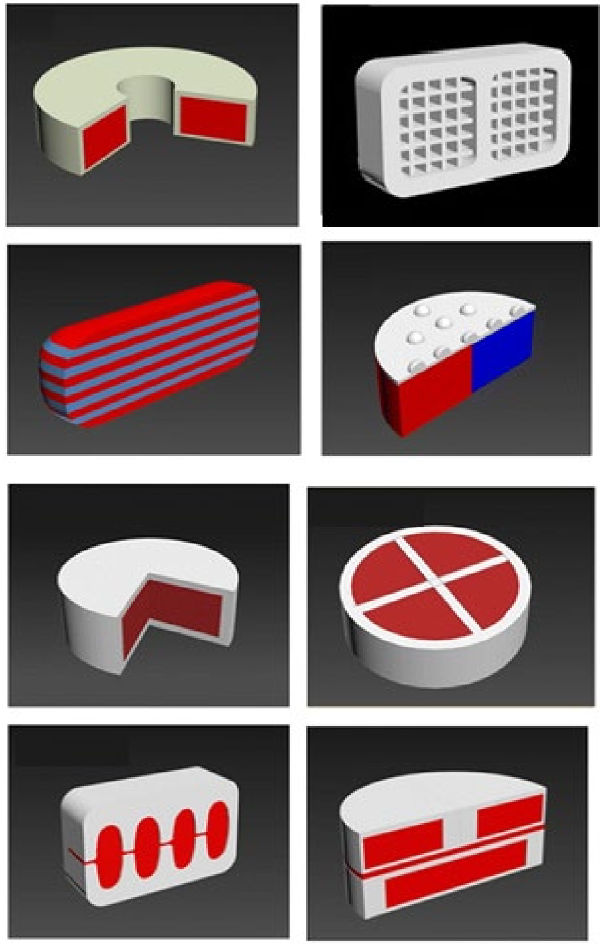
Polypills

- incorporate multiple drugs all with different release times.
- different release profiles depending on design of
  - exposed surface area
  - geometry of the dosage form
  - using more than one kind of carrier material with different drug release characteristics

An AM printed polypill that contains three different drugs has already been developed for patients with diabetes and hypertension



Tamargo, J., Castellano, J.M., and Fuster, V. (2015). The Fuster-CNIC-Ferrer cardiovascular polypill: a polypill for secondary cardiovascular prevention. *International Journal of Cardiology* 201: S15–S23.



A Alhnan, Mohamed & Okwuosa, Tochukwu & Sadia, Muzna & Wan, Ka-Wai & Ahmed, Waqar & Arafat, Basel. (2016). Emergence of 3D Printed Dosage Forms: Opportunities and Challenges. Pharmaceutical Research. 33

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Agenda

- Introduction
- Material Properties Overview
- Polymers in MEX Overview
- Metal Filled, Fiber Filled Polymers and Continuous Fiber Fabrication
- Material Selection
- Biocompatibility
- Summary

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Common Mechanical and Thermal Properties

- Tensile Strength
- Young's Modulus
- Elongation
- Flexural Strength
- Fatigue Strength
- Flexural Modulus
- Impact Strength
- Indentation Hardness (Shore)
- Compression Set
- Water Absorption
- Heat Deflection Temperature
- Vicat Softening Point
- Thermal Expansion

Other Useful Material Properties

- Chemical Resistance
- Electrical Properties
- Machinability
- Ease of Printing
- Layer Adhesion
- Optical Properties
- Recyclability/Biodegradability
- Biocompatibility

Overview of MEX compatible Materials

Standard Materials	Specialty Materials
a. ABS/ASA b. PLA c. Polycarbonate d. ABS/Polycarbonate Blends e. Nylon f. PPSF/PPSU g. ULTEM 9085, 1010 h. Metal filled polymer filaments (bronze, steel, stainless steel, copper, Inconel etc.)	i. Clay/Brick/Wood filled polymer ii. Metal filled polymer iii. Concrete iv. Chocolate v. Polyurethane foam vi. Silicone vii. Epoxy viii. Biomaterials ix. HPA/PCL x. Fiber filled polymer filaments

Overview of Polymer Materials in MEX

PLA - Hobbyist material
ABS - Low grade industrial material
PETG - Low grade industrial material

→ **Basic thermoplastics**

Nylon - Tough, flexible niche material
TPE - Flexible niche material
Polycarbonate - Medium Grade industrial material

→ **Niche thermoplastics**

PEEK/ULTEM - Superplastics, ideal for industrial uses

→ **Engineering Grade Polymers (Superplastics)**

Chopped Fiber Reinforced Plastics - Superplastics, ideal for industrial uses
Continuous Fibers - Composite materials, ideal for industrial uses

→ **Specialty Industrial Grade "Composite" Materials**

SAM: Summary - Polymers in MEX Overview

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Properties	PLA	ABS	PET/PETG	Nylon	TPU/TPE	PC	PEEK
Tensile Strength (MPa)	37	27	55-75	40-50	26	55-75	90-100
Elongation	6	3.5-5	1.5	0.6-1.1	5.5-5.8	1.5	1.5
Flexural Modulus (GPa)	4	2.1-7.6	2.8-3.1	2.1	0.78	2.2-2.5	3.6
Density (g/cm^3)	1.3	1.0-1.4	1.38-1.45	1.06-1.14	1.21	1.15-1.2	1.32
Melting Point (^oC)	173	N/A (amorphous)	250	268	220	100-110	343
Glass Transition Temperature (^oC)	60	105	81	70	-24	147	143
Biodegradable	Yes (under conditions)	No	No	No	Yes	No	No
Recyclable	Yes	Yes	Yes	Yes	Yes	Yes	No
Price (per kg)	15-30	15-45	20-60	50-100	90-100	40-90	200-400
Printability (1-10 scale)	9	8	9	8	3	4	4
Other Notable Properties	Biocompatible, Good for support structures, Resorbable	Impact Resistant	Chemically Resistant, Fatigue Resistant, Water Resistant	Flexible, Impact Resistant, Heat Resistant, Fatigue Resistant	Flexible	Impact Resistant, Heat Resistant, Fatigue Resistant	Biocompatible, Heat Resistant, Chemically Resistant, Machinable

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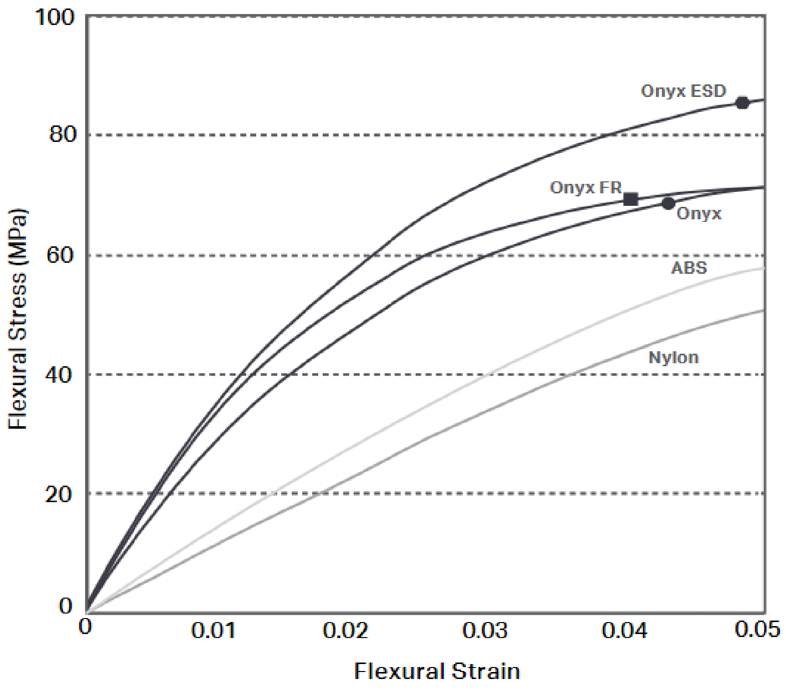
Thermoplastic Matrix vs Continuous Fiber Flexural Strength Comparison

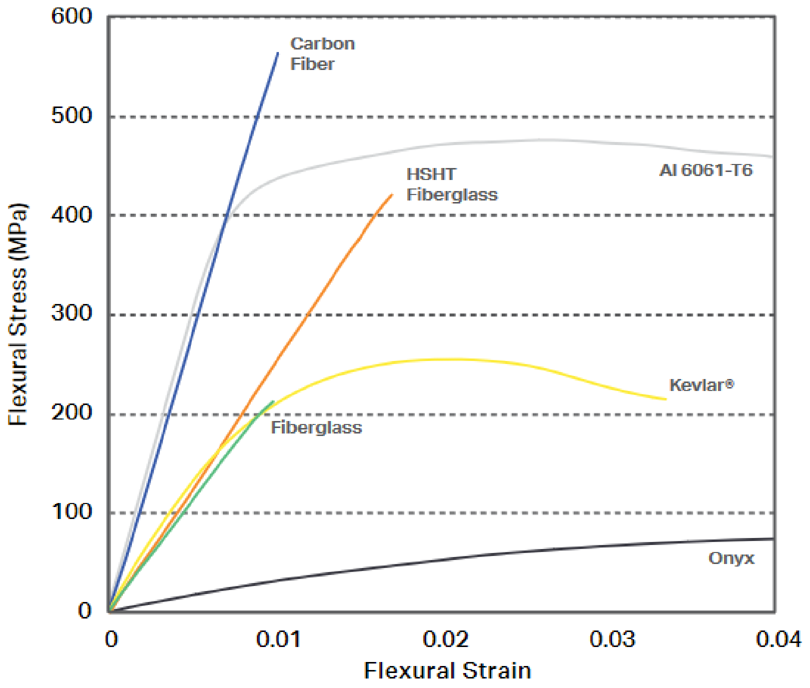
Composite Base

Markforged Composite Base materials print like conventional FFF thermoplastics. They can be printed by themselves, or reinforced with any of our continuous fibers, including Carbon Fiber, Kevlar, and Fiberglass.



Continuous Fiber

Continuous Fibers are laid down on the inside of parts through a second fiber nozzle. They cannot be printed by themselves — instead, they are used to reinforce parts printed out of a composite base material like Onyx.



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Material Selection Thought Process

1. **Determine performance requirements via intent of use**
   - Prototyping and R&D?
   - Validation or pre-production?
   - End-use parts?
2. **Translate performance to material requirements**
   - Stiffness/hardness
   - Toughness/tear strength
   - Temperature and chemical resistance
   - Creep and durability
3. **Select material**
   - Design Space/Operation Environment
   - Durability
   - Longevity
   - Cost

Test print and iterate!!

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Comparison of Most Common Biocompatible Thermoplastics: ABS, PLA, PEEK

Properties	Medical Grade ABS	PLA	PEEK	PC
Tensile Strength (MPa)	27	37	90-100	55-75
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Density (g/cm³)	1.0-1.4	1.3	1.32	1.15-1.2
Melting Point (ºC)	N/A (amorphous)	173	343	100-110
Glass Transition Temperature (ºC)	105	60	143	147
Biodegradable	No	Yes (under conditions)	No	No
Recyclable	Yes	Yes	No	Yes
Sterilization (autoclave, dry heat, EtO, Gamma irradiation, electron beam)	Poor-Good	Fair-Good	Good	Fair-Good

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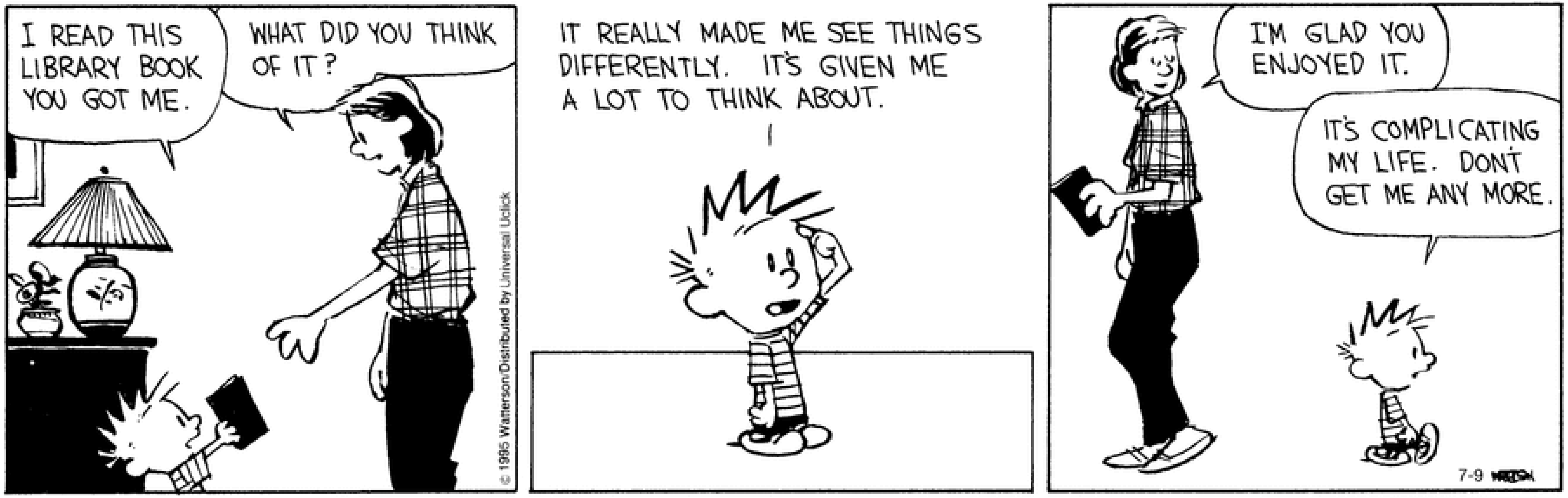
Questions?



Watterson, Bill. The Essential **Calvin and Hobbes**: A **Calvin and Hobbes** Treasury. , 1988. MLA (7th ed.)

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

skills4am.eu

Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Design for Material Extrusion

SESSION 03: Specific Design Considerations

22 JUNE 2021

Harry BIKAS – LMS

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Agenda

- Introduction to DfAM
- Design aspects for MEx
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

Introduction to DfAM

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- Design for AM (DfAM) refers to **design optimization** following certain **rules and guidelines**, aiming to improve **AM manufacturability**
  - *Manufacturability* is not a duality nature of can-or-cannot be manufactured
  - *Manufacturability* is used to describe the ease to implement a manufacturing technology to realize a part design
  - *Manufacturability* for AM requires identification of the Design Aspects of the part and their comparison with AM capabilities

- Current design optimization methods (Topology Optimization/Generative Design) generate highly complex parts that are appealing for AM.

- Most complex geometries with structural purposes display low AM manufacturability due to the poor dimensional accuracy and surface quality of AM final products.

- Modifications are required on a second stage to address problematic aspects of the design (post-processing)

Introduction to DfAM

- When designing a part to be built using AM, the process characteristics must be considered.

- Design for Additive Manufacturing (DfAM or D4AM) is defined as “the practice of designing and optimizing a product together with its production system to reduce development time and cost, and increase performance, quality, and profitability.” [2]

➢ The layer-by-layer nature of AM introduces some design limitations that are present in every AM process

➢ Some design limitations are presented on the following slides

[1] “Design Guidelines – FDM” https://www.materialise.com/en/manufacturing/materials/abs/design-guidelines
[2] “Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., and Martina, F., 2016, “Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints,” CIRP Ann. Manuf. Technol., 65(2), pp. 737–760

Introduction to DfAM: Workflow

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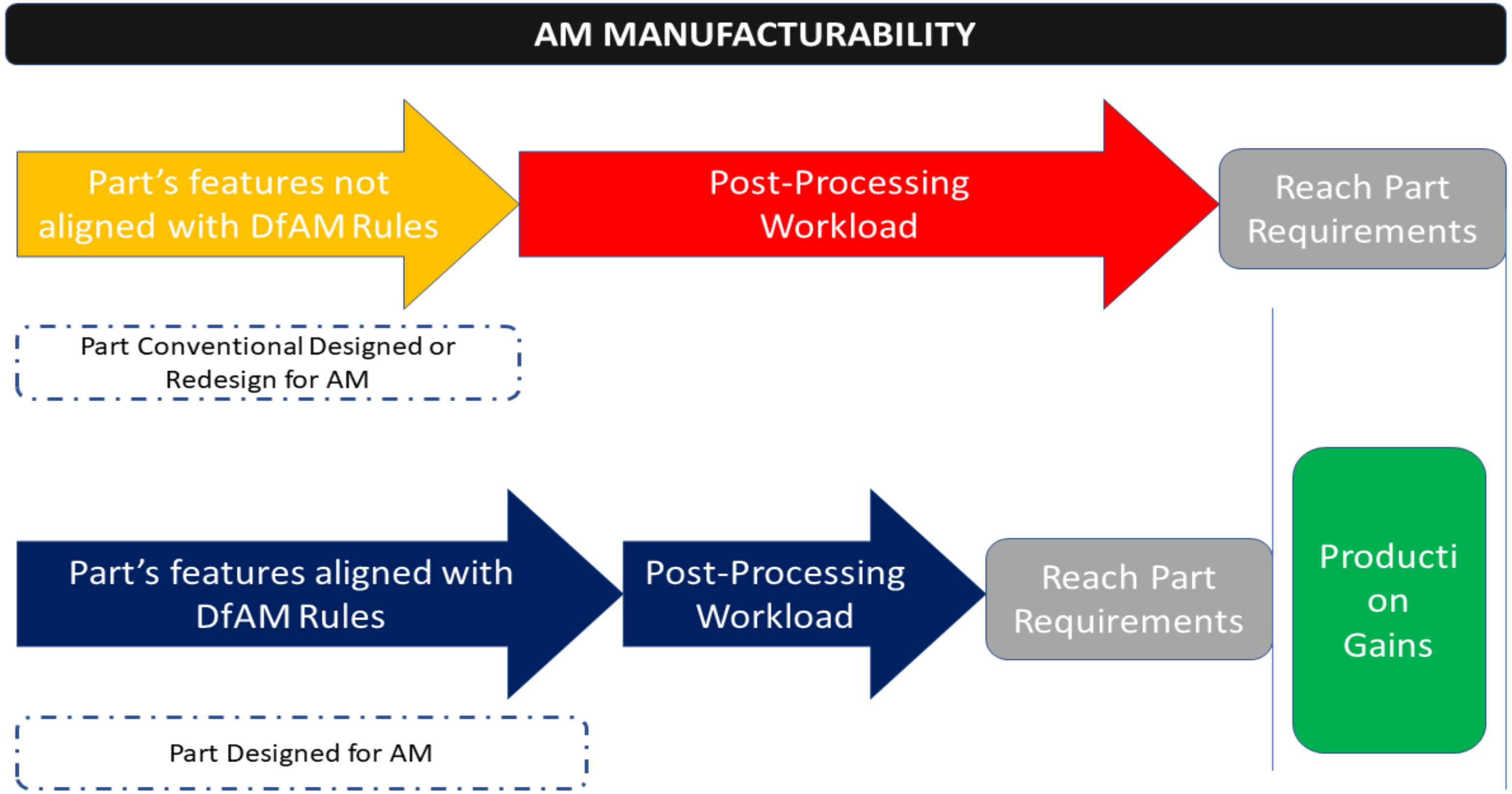
Determining AM part’s Manufacturability		
#Step	Indicator	
1. Part’s geometric features recognition	[from CAD/.STL file]	
2. Crosschecking Design features with the AM process capabilities	[Limit of Overhangs, etc.]	0 1
3. Crosschecking Design Considerations with Part Specifications	[Surface roughness, porosity]	0 1
4. Magnitude of feature alternation to achieve manufacturable features	[Feasible-Impractical-Add Supports]	
5. Determine the actions for excess material removal	[Few-Numerous Supports]	
6. Post-processing to reach parts requirements (post-treatment)	[Minimal-Major]	

Introduction to DfAM: Benefits



Introduction to DfAM: Aspects & considerations

DfAM considerations

Design aspect: feature which can be quantified at the design phase.

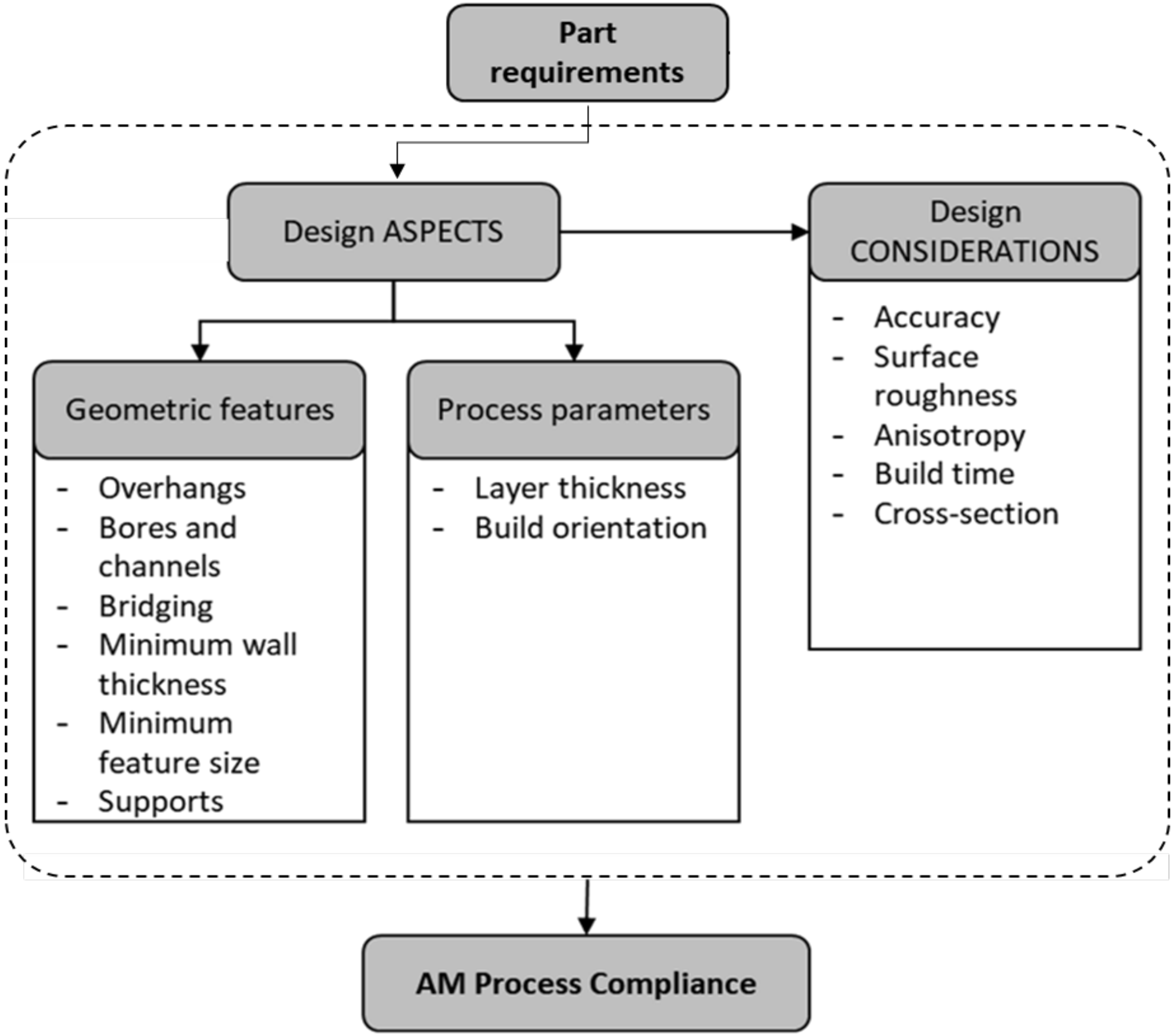
- The design aspects are divided into
  - Geometric features (overhangs, bores, channels, etc.)
  - Process variables/parameters (layer thickness, orientation, etc.)

Design consideration: the result on the part

- The result is measured in terms of dimensional accuracy, surface roughness, built time etc.

Overall

- Need to map aspects (causes) to considerations (outcomes), in order to define design rules
- Design aspect effects and thresholds are dependent on the process mechanism and material



Agenda

- Introduction to DfAM
- Design aspects for MEx
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

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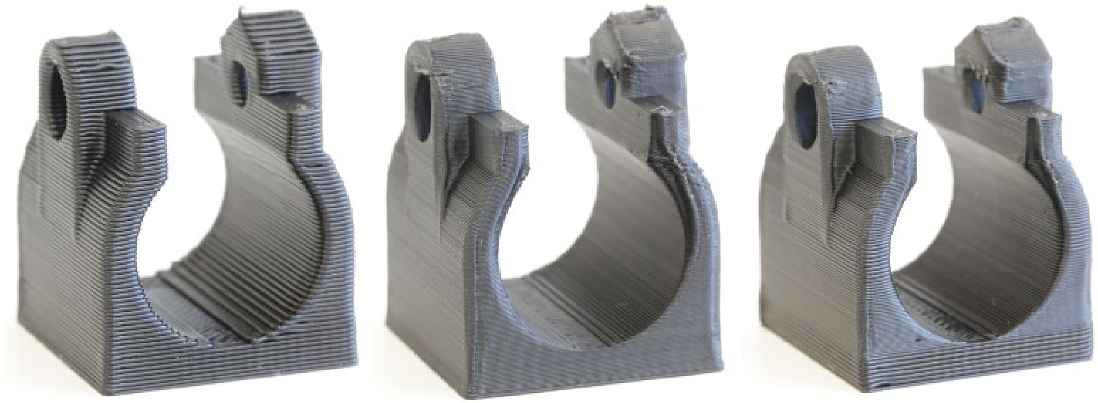
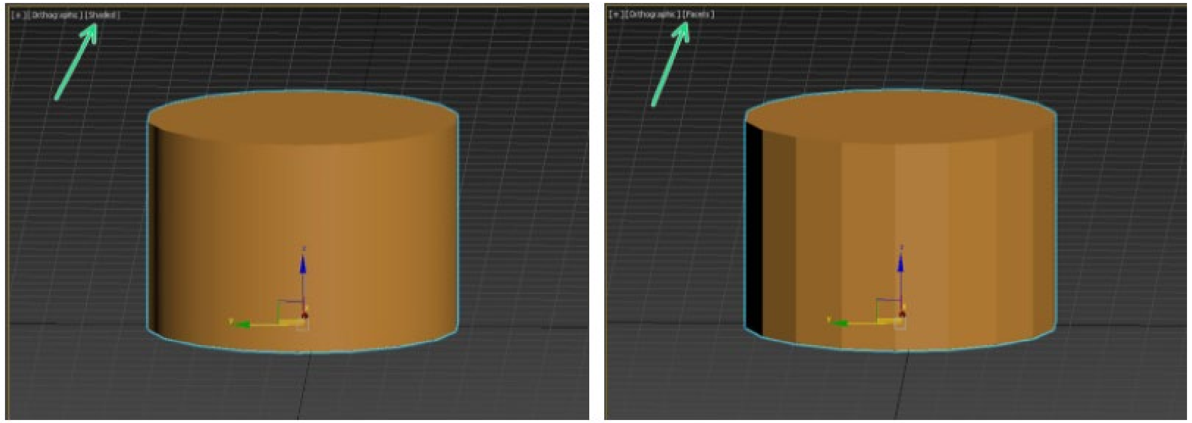
- **Finishes and precision**
- At the initial steps of the process selection the required precision (dimensional or surface) is determined
- It is known that an MEx printer can achieve medium to low quality of surface finish and precision.
- Optimized process parameters can improve significantly the dimensional accuracy and appearance.
- The decision criteria are:
  - What is the desired precision based on the application
  - What is the provided accuracy based on the selected process/equipment



Source: https://manual.slic3r.org/expert-mode/variable-layer-height



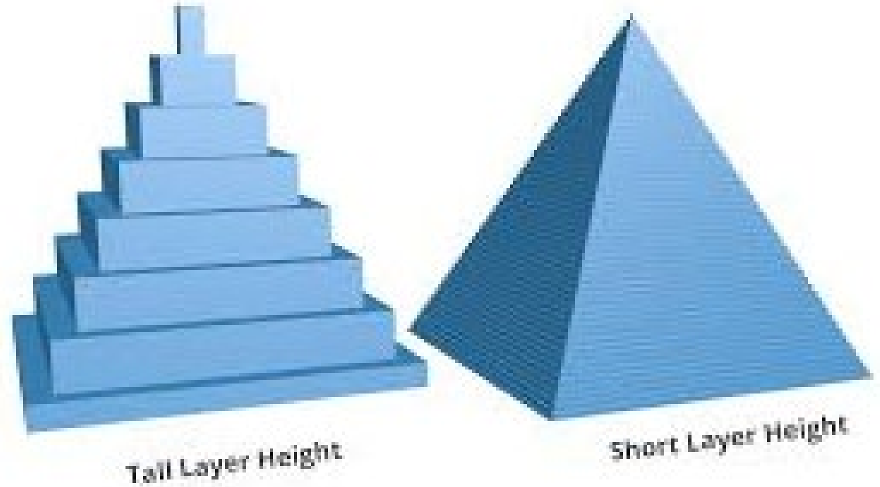
https://help.prusa3d.com/en/article/modeling-with-3d-printing-in-mind_164135/

Overall Considerations

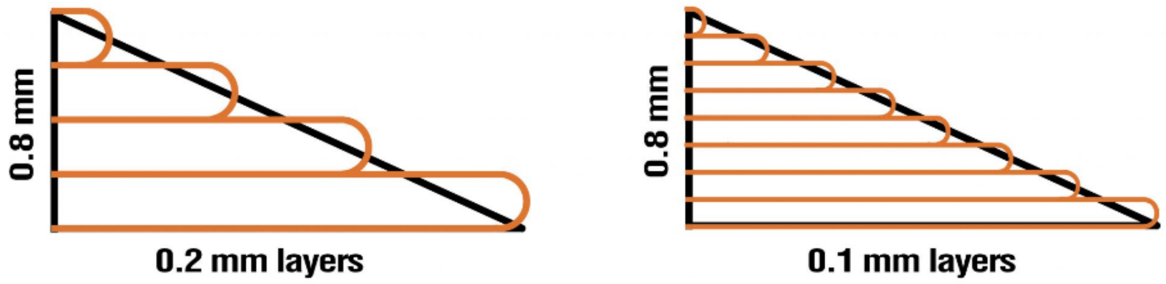
- ✓ Usually, small layer height and low deposition speed increase the quality of the final part.
- ✓ Post processing methods (paint, sandpaper) are proposed to improve the surface quality.

Design aspects for MEx: Layer thickness

- The best-known value associated with a 3D printer's resolution is the minimum Z layer height.
- 3D printers construct objects layer-by-layer, and this value describes the thickness of one of these layers.
- A large layer height has less resolution but prints faster while a smaller layer height can create more fine features but is slower.
- The dimensional accuracy as well as the surface quality of the part are affected significantly with the choice of layer height.
- Very detailed features ask for the minimum layer height.
- Model height must be an integer multiple of the selected layer height.



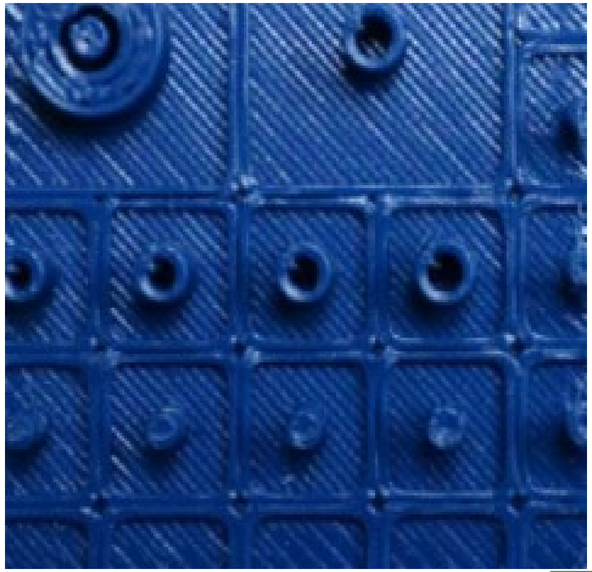
Source: https://3space.com/blog/what-does-resolution-mean-in-3d-printing/3d-printing-resolution-layer-height/

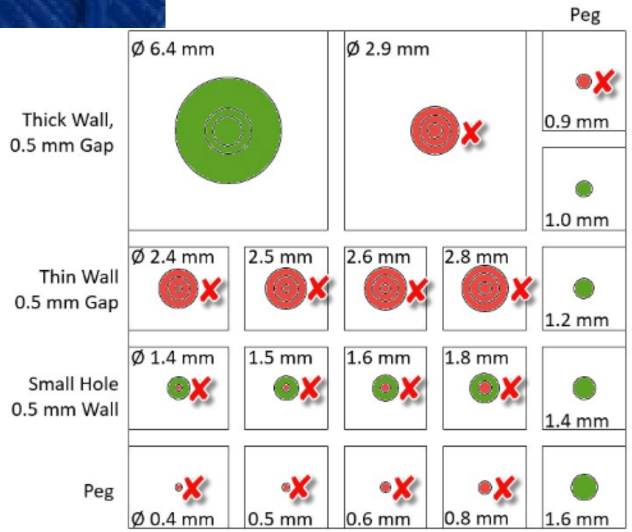


Source: https://blog.prusaprinters.org/everything-about-nozzles-with-a-different-diameter_8344/

Design aspects for MEx: Minimum feature size

- Most MEx printers use 0.4mm nozzle which means that geometrical features with area less than the area of the cylindrical nozzle cannot be created.
- Many printers allow their nozzles to be swapped out and 3rd party upgrades can be purchased with diameters as narrow as 0.15mm
- This concept applies to features that stand on their own such as towers and spikes and isn't applicable to components like text embossed onto the side of an object.
- Due to the cylindrical shape of the extruded material the minimum feature can be a cylinder.
- Regarding the minimum feature across the height of the part, that is determined from the lowest layer height.

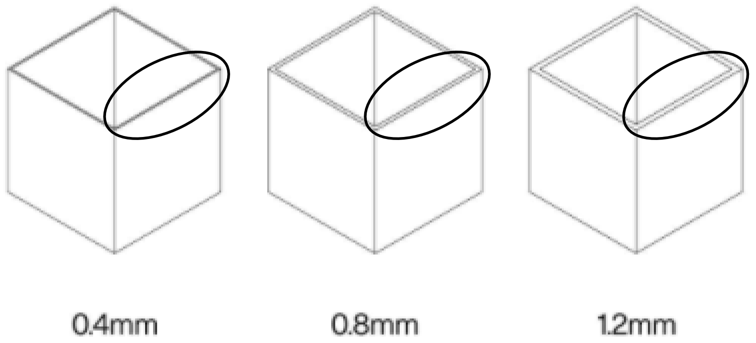


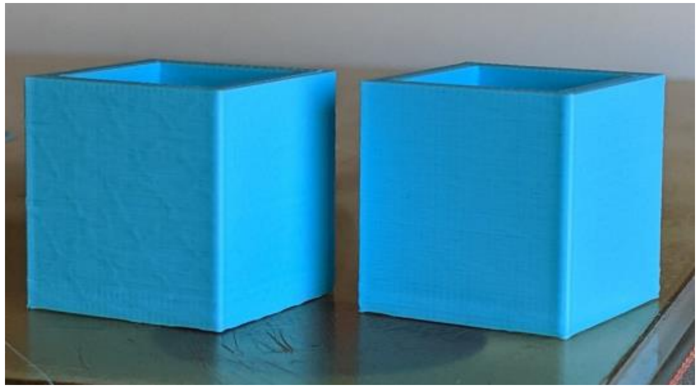


Source: https://support.xometry.com/hc/en-us/articles/217723698-What-is-the-smallest-feature-that-you-can-print-

Design aspects for MEx: Wall thickness

- A wall gives the outer shape of the part.
- The wall thickness is highly related to the nozzle diameter.
- Typically wall thickness is 2-3 times the size of the nozzle aiming to to have a stiff structure.
- The infill lines are attached to the wall across the height of the part.
- Depending on the slicing software that it is used, thinner walls may be ignored and not printed.
- Single walls can be printed, however they usually dictate that the model is hollow (“vase mode”).

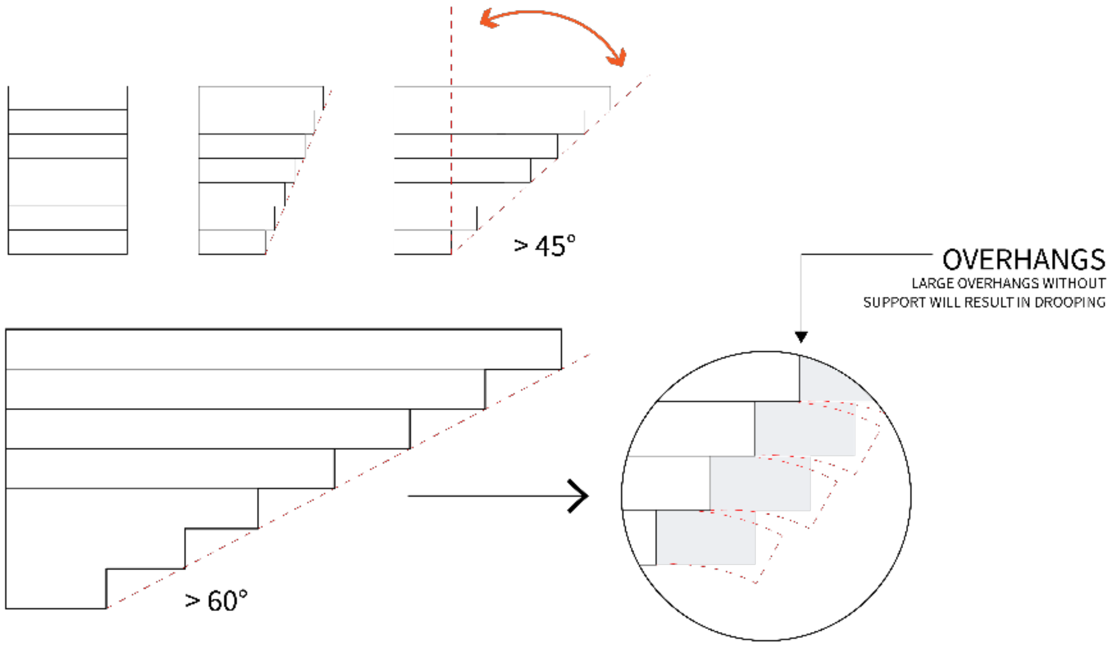




Source: https://www.hubs.com/knowledge-base/selecting-optimal-shell-and-infill-parameters-fdm-3d-printing/#infill

Design aspects for MEx: Overhangs

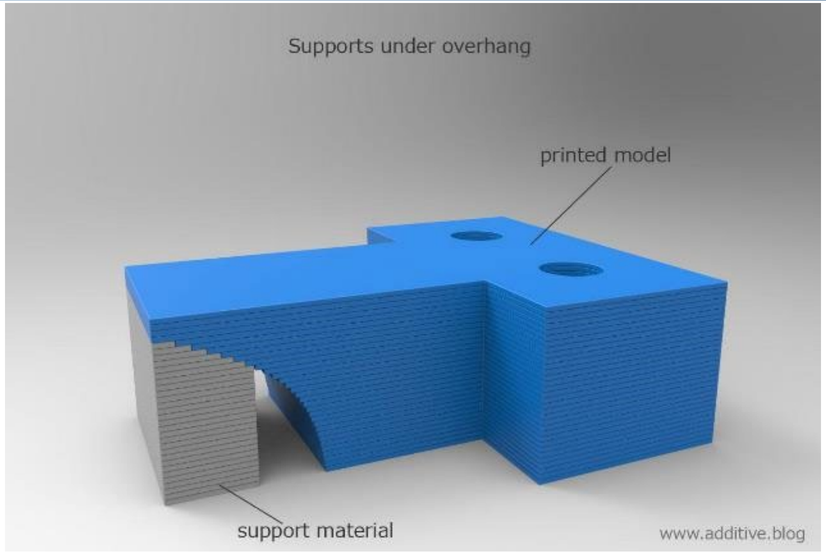
- **Overhangs** are shapes that extend outwards beyond the previous layer (cantilevers).
- We know that MEx is a process where each layer is deposited over the previous layer below.
- Therefore, at certain overhanging angles, there may be insufficient material from the previous layer for the next layer to print on.
- This will affect any layers beyond this as it will droop.



Source: https://msd-makerspaces.gitbook.io/next-lab/3d-printing/ultimate-guide/design-guidelines

Design aspects for MEx: Overhangs

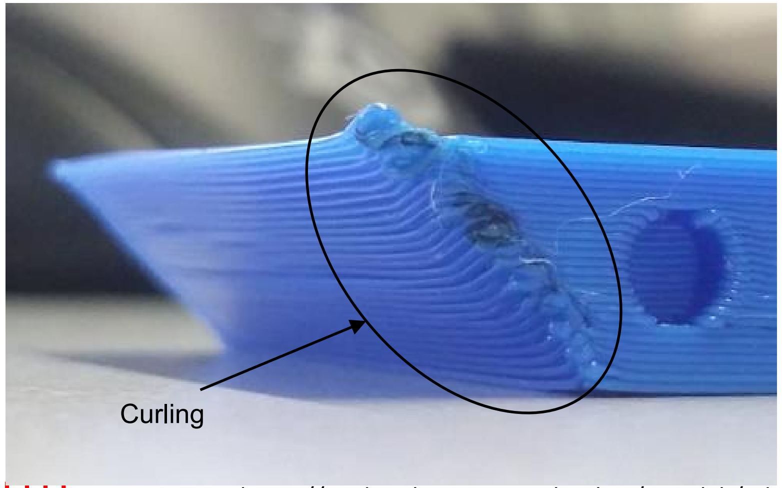
- **Overhangs**
- Overhangs occur when the printed layer of material is only partially supported by the layer below.
- The newly printed layer becomes increasingly thinner at the edge of the overhang, resulting in differential cooling causing it to deform upward→ known also as curling



Source: https://www.simplify3d.com/support/print-quality-troubleshooting/poor-bridging/

<u>Overall considerations</u>

- ✓ Below the 45 degrees, an overhang can usually be printed with no loss of quality up to depending on the material, the offset of the head from the print table and the 3D printer characteristics.
- ✓ At 45 degrees, the newly printed layer is supported by 50% of the previous layer. This allows sufficient support and adhesion to build upon.
- ✓ Above 45 degrees, support is required to ensure that the newly printed layer does not bulge down and away from the nozzle.



Source: https://msd-makerspaces.gitbook.io/next-lab/3d-printing/troubleshooting

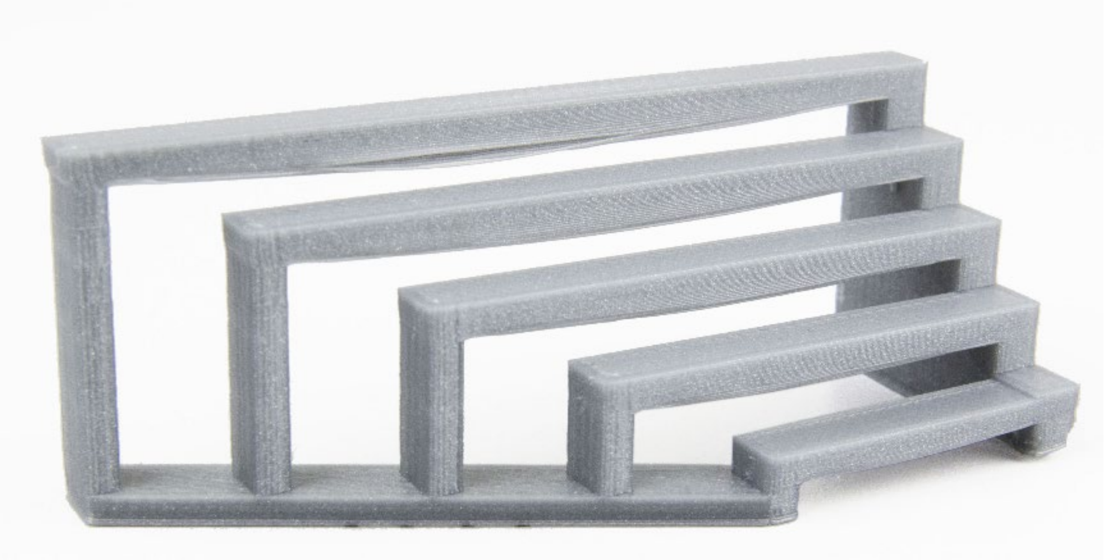
Design aspects for MEx: Bridging

- **Bridging** in 3D printing is the horizontal extrusions supported by structures on either sides.

- Unlike overhangs, bridges can be created without supports.

- This is heavily influenced by two main factors:
  - bridging distance
  - amount of cooling.

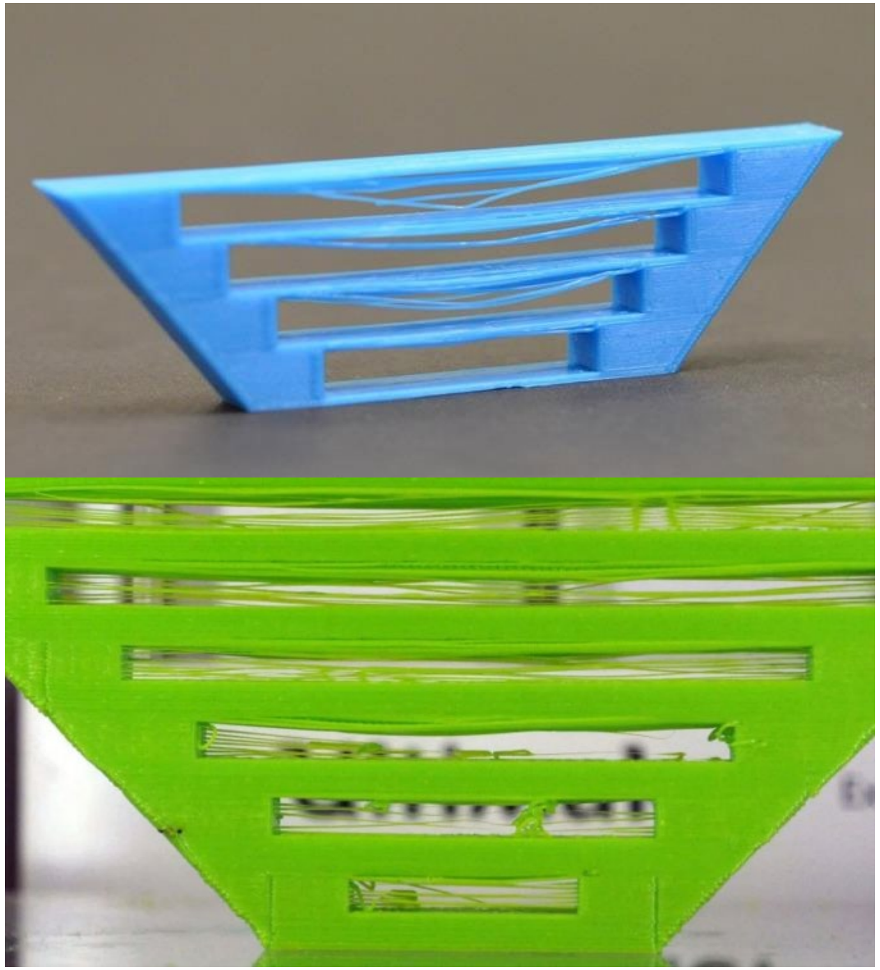
- Bridges can not be dimensionally accurate
  - there will inevitably be some sagging underneath the bridge as the filament is being extruded over thin air.



Source: https://msd-makerspaces.gitbook.io/next-lab/3d-printing/ultimate-guide/design-guidelines

Design aspects for MEx: Bridging

- **Bridging**
- Bridging in MEx occurs when the printer is required to print between two vertical geometries that are not connected with material at the same height or anchor points.
- Bridges are found most often in horizontal axis holes found in the walls of objects or in the top layer (or roof) of hollow parts.
- The absence of support below the build layer can result in poor layer adhesion, bulging or curling.



Source: https://www.simplify3d.com/support/print-quality-troubleshooting/poor-bridging/

Source: https://msd-makerspaces.gitbook.io/next-lab/3d-printing/troubleshooting

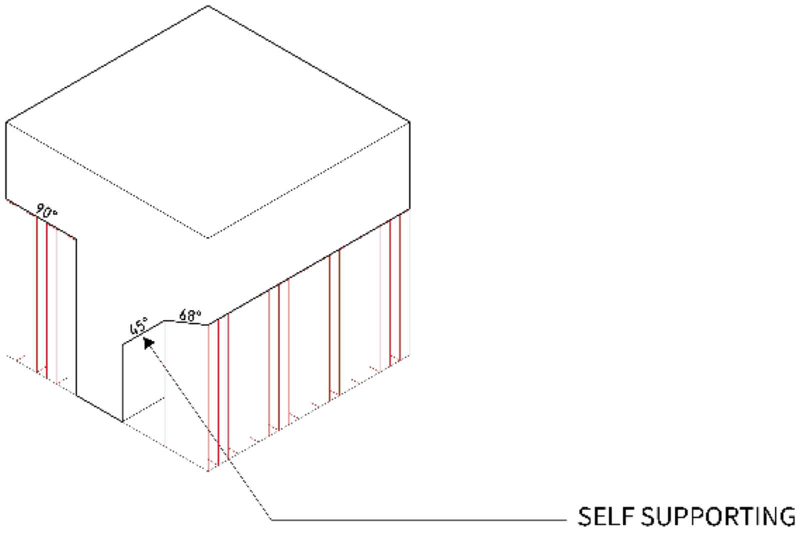
<u>Overall considerations</u>

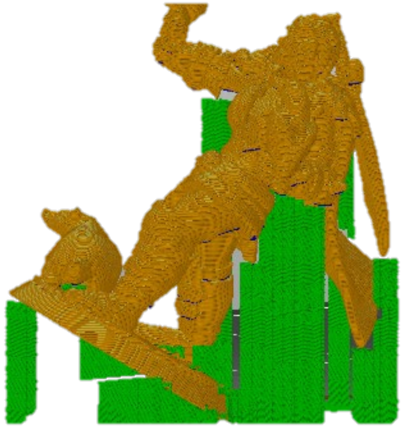
In order to reduce the impact of bridging, some solutions could be to:

- ✓ Reduce the distance of the bridge
- ✓ Include support structures
- ✓ Increase the print speed
- ✓ Increase cooling

Design aspects for MEx: Supports

- Supports are sacrificial layers, generated to counter the effects of gravity on filament during printing.
- Essential part of 3D printing is understanding support angles, overhangs and bridges.
- In situations where an overhang is necessary, and the inclusion of supports will hinder a successful outcome It is recommended to either incorporate artificial bridges (to be eliminated during post processing), or design the model undersides with an acceptable angle.
- The amount of support structures determine the sustainability of the process as well as the printability of the part.
- Soluble supports are an option in the case of intricate hollow geometries with internal cavities, where support cannot be mechanically removed
- Soluble support for MEx is usually PVA and requires a 2nd nozzle to be deposited





Source: https://help.prusa3d.com/en/article/support-material_1698

Design aspects for MEx: Vertical bosses/pins

- **Vertical bosses**

Vertical bosses are often printed in MEx when assembly of parts or alignment is required.

- Large bosses (greater than 5mm diameter) are printed with a perimeter and infill, affording a strong connection to the rest of the print.
- Smaller diameter bosses (less than 5mm diameter) can be made up of only perimeter prints with no infill.

Source: https://www.hubs.com/knowledge-base/how-design-parts-fdm-3d-printing/#vertical-axis-holes

<u>Overall considerations:</u>

- ✓ Correct printer calibration (optimal layer height, print speed, nozzle temperature etc.) can reduce the likelihood of small bosses failing.
- ✓ The addition of a radius at the base of the pin will eliminate that point as a stress concentration and add strength.
- ✓ For critical bosses smaller than 5mm diameter, an off the shelf pin inserted into a printed hole may be prefferable

Design aspects for MEx: Holes

➢ **Horizontal axis holes**

- MEx will often print horizontal axis holes undersized.

- The general process for printing a hole diameter and the reason the reduction in diameter occurs is:

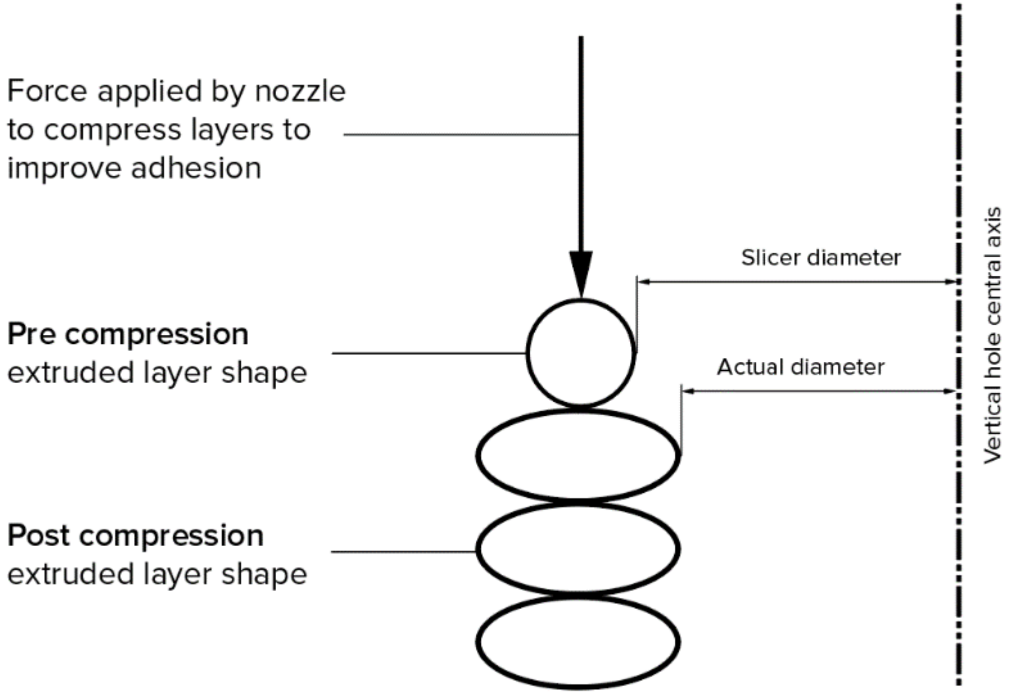
✓ As the nozzle prints the perimeter of a vertical axis hole, it compresses the newly printed layer down onto the existing build layers to help improve adhesion.

✓ The compressing force from the nozzle deforms the extruded round layer shape from a circle into a wider and flatter shape

✓ This increases the area of contact with the previously printed layer (improving adhesion), but also increases the width of the extruded segment.

✓ The result of this is a decrease in the diameter of the hole that is being printed.

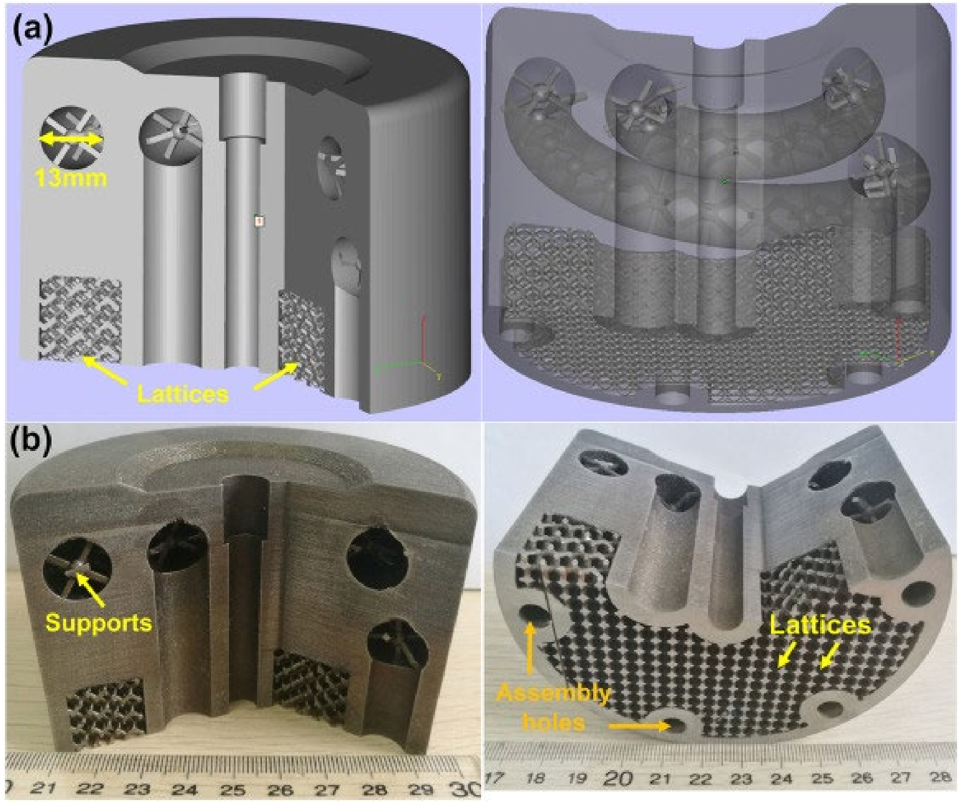
✓ Post-processing (drilling) may be required; need to keep in mind when sizing wall thickness around hole



Source: https://www.hubs.com/knowledge-base/how-design-parts-fdm-3d-printing/#vertical-axis-holes

Design aspects for MEx: Bores & channels

- Bores and channels are internal structures that are not visible from outside most of the times.
- The correct orientation of the part during the development ensure the successful creation of these structures.
- Channels are internal routes which can be used either in case of cooling fluids or for weight reduction
- Bores can be used to fit a bolt or a blind thread etc.
- It is difficult to manufacture these geometries with any other manufacturing process.
- Support dissolving/removal should be taken into account.



Source: https://www.sciencedirect.com/science/article/pii/S0264127520306821

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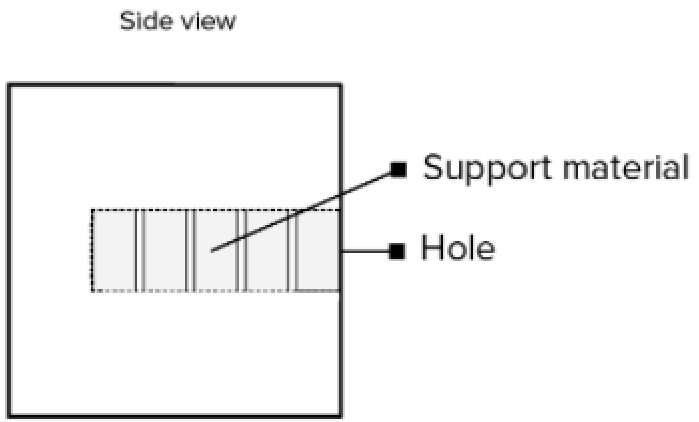
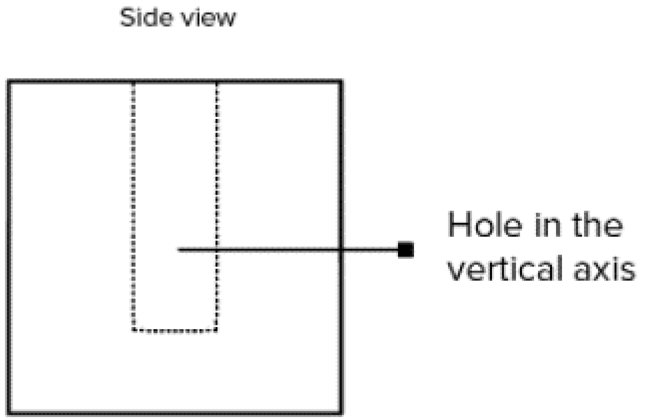
Design aspects for MEx: Build orientation

- Ideal orientation minimizes support material and achieves the best surface finish.
- Less material used means a more sustainable and efficient process considering also reduced build time
- As an example, support for holes is best avoided by changing the print orientation.
- Removal of support in horizontal axis holes can often be difficult, but by rotating the build direction 90 degrees, the need for support is eliminated.
- For components with multiple holes in different directions, prioritize blind holes, then holes with the smallest to largest diameter, then criticality of hole size.

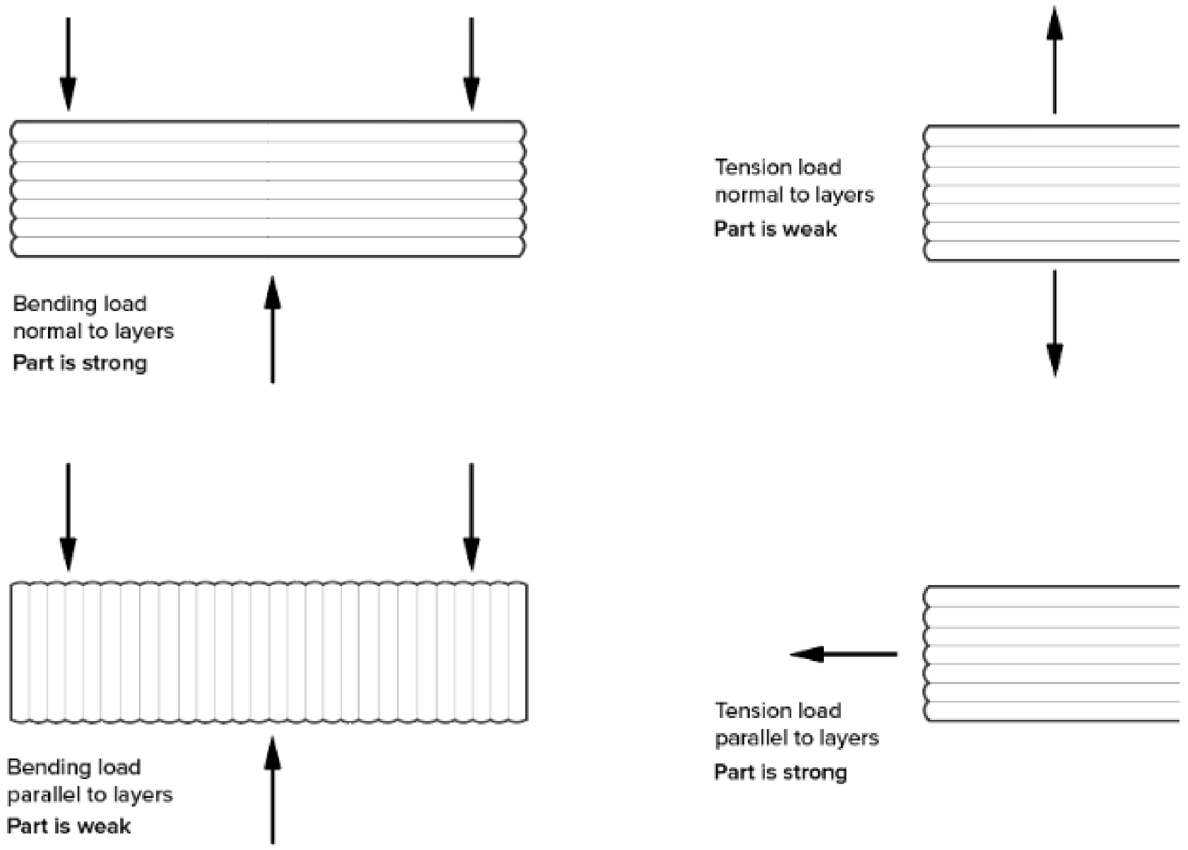




Source: https://wikifactory.com/+wikifactory/stories/ultimate-guide-how-to-design-for-3d-printing

Design aspects for MEx: Build orientation

- Upward facing surfaces tend to have a better surface finish.
- Since curved and angled surfaces are often prone to stair-stepping effect (rough surface texture), they can be oriented parallel to the build platform to minimize this effect.
- Long surfaces should be oriented in the x-y plane (large contact area with the bed).
- Loading of the part should be considered.
- Tabs should be oriented in x-y direction.



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SAM: Standard benchmarking objects

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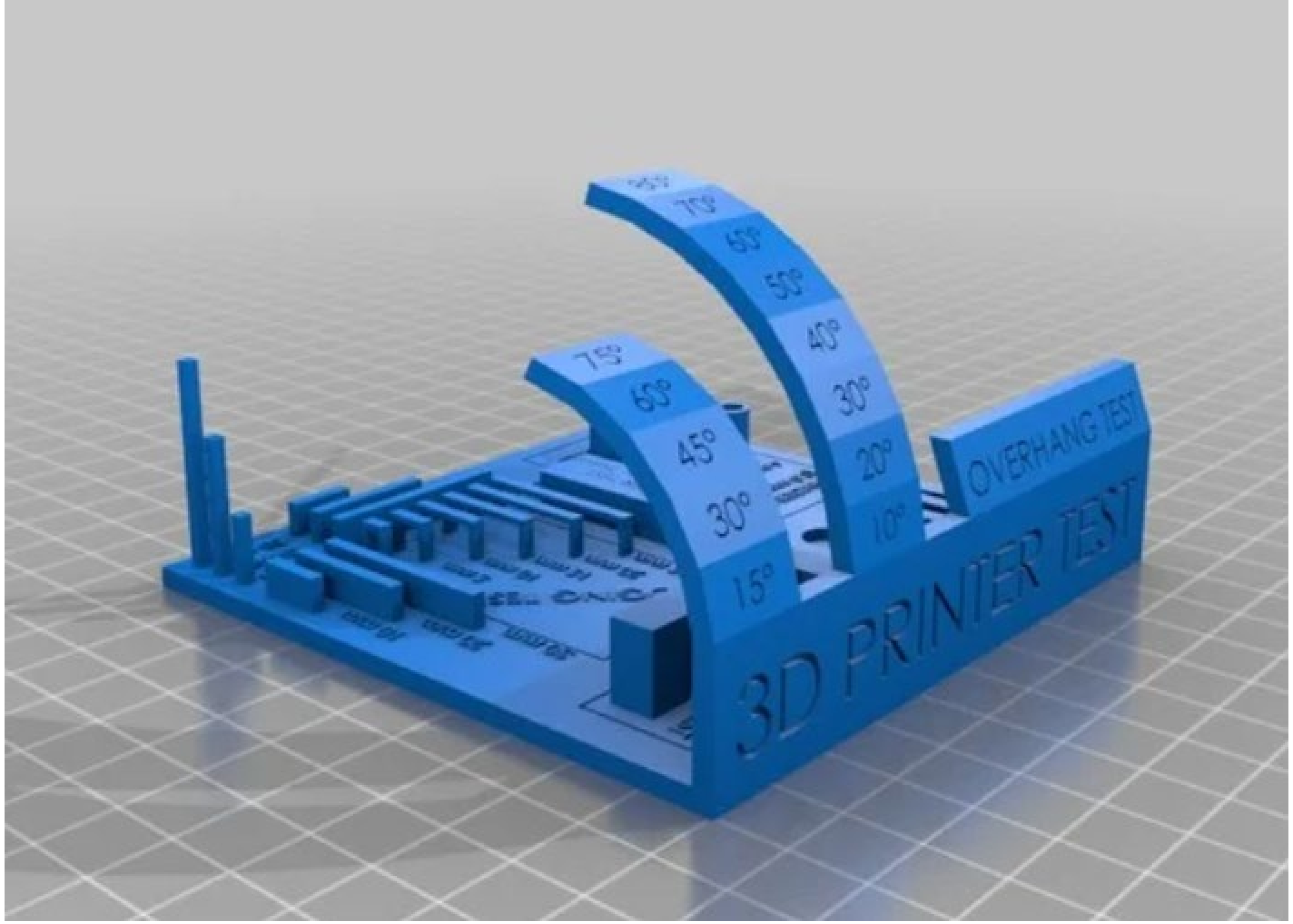
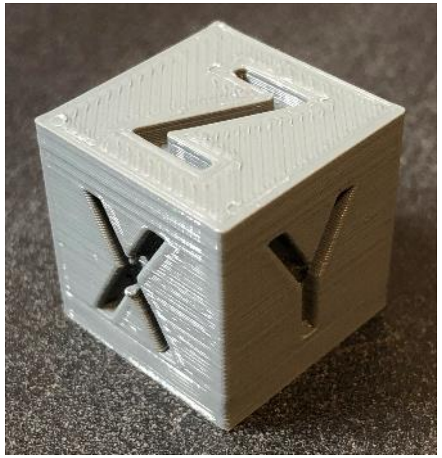
- Used to test machine/material limits
- Used to optimize process parameters
- Multitude of objects available
- Easier to start one-at-a-time
- Individual aspects can be "tuned" by modifying process parameters and/or machine settings (e.g. extrusion multiplier)
- All-in-one as final confirmation



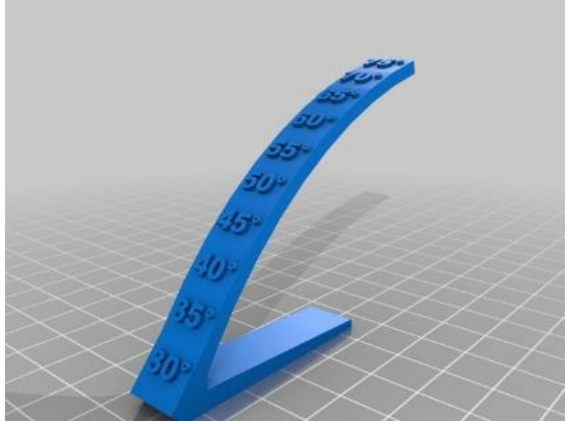
SAM: Standard benchmarking objects



Scale/tolerance test

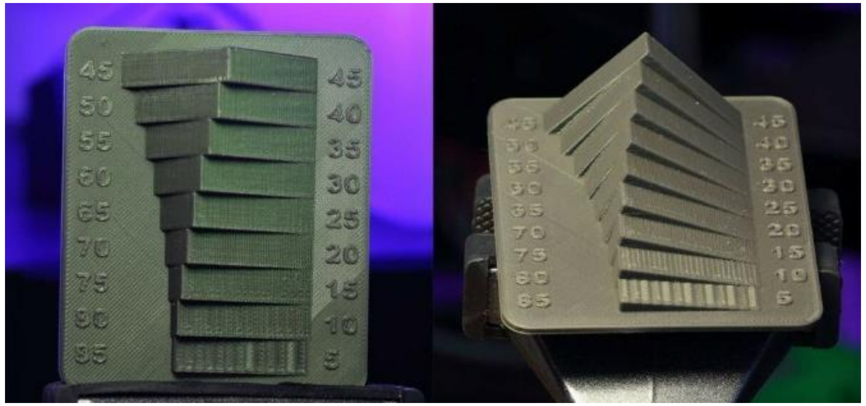
Minimum feature size test

Holes & bosses (horizontal/vertical) test



Overhang test

Bridge test



Slope test (roughness/surface finish)

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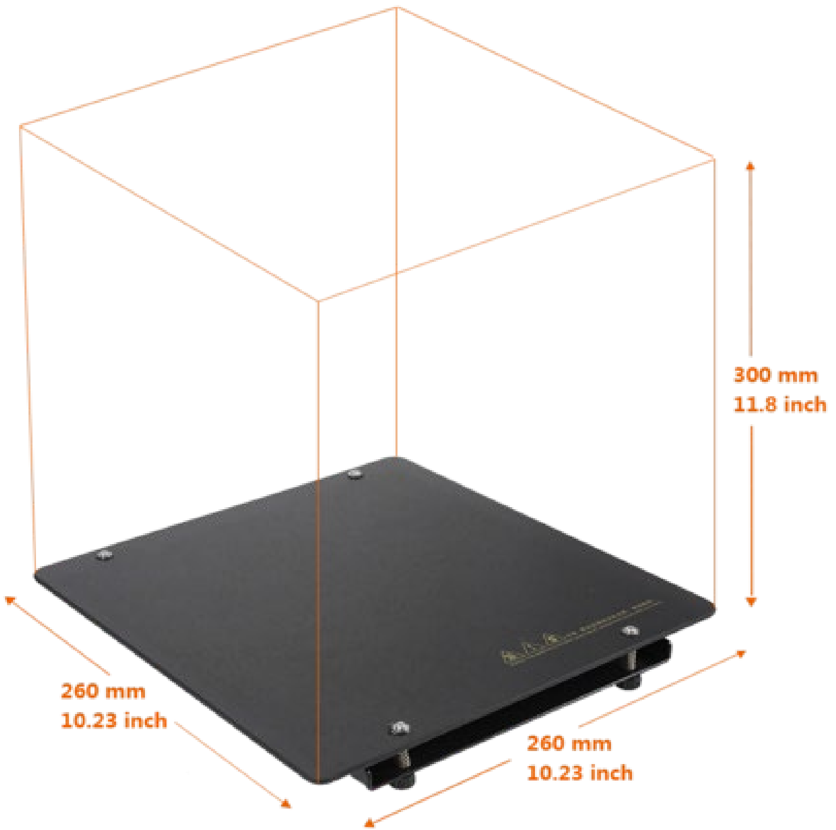
MEx design guidelines: Part dimensions

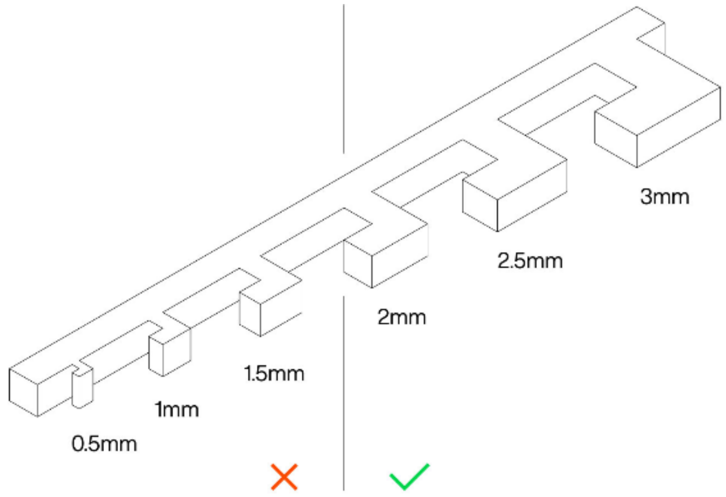
- The maximum dimensions of a part are somewhat overlooked while designing and the result is that the designed part will not fit the build volume of the available printer.
- In order to avoid that problem, the maximum dimensions of the build volume have to be considered while designing so the part will comfortably fit the printer or to be designed in split parts that will later be merged.
- However, during merging is significant to consider that if assembly bosses are used and the dimensions are equal in both sides the join will be considerably difficult.
- The dimensional accuracy of an MEx printer vary between certain limits.
- It is difficult to know a priori the exact accuracy so tight fit geometries are not suggested.



MEx design guidelines: Part dimensions

➢ **Minimum geometrical features (**Minimum feature size, Minimum wall thickness**)**

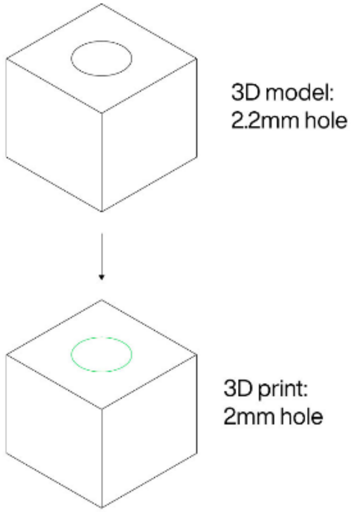
- The minimum feature size corresponds to the nozzle size. So, geometries that are smaller than the nozzle size can not be achieved.
- Most stepper motors are capable of moving that platform by as little as 10 microns, but MEx extruders cannot control the flow of filament precisely enough to produce clean results.
- For this reason, 10 micron prints on MEx machines often end up looking worse than 100 micron prints even though the individual layers may be finer
- It's important to keep in mind that smaller features are more easily deformed by heat in MEx printing.
- Tall and thin towers often fail because the heat of the molten plastic and nozzle cause the structures to soften.



[REF] "Design Guidelines – FDM" https://www.materialise.com/en/manufacturing/materials/abs/design-guidelines
[REF] https://grabcad.com/tutorials/fused-deposition-modeling-fdm-design-guidelines

MEx design guidelines: Part dimensions

- **Precision (Dimensional accuracy, surface quality)**



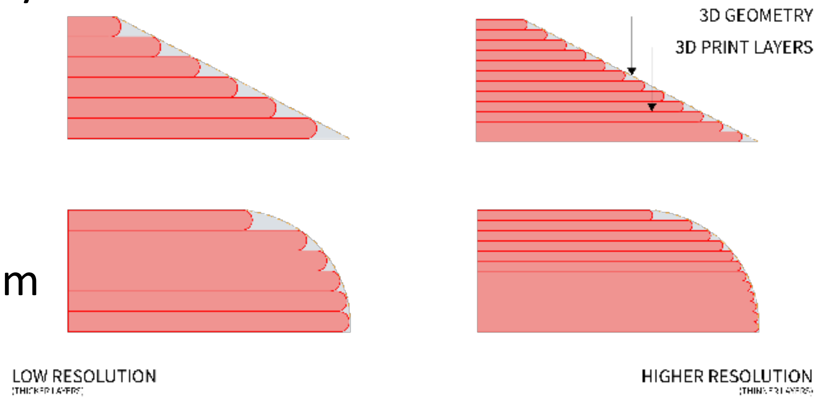
- The quality of the final product can be quantified in terms of dimensional accuracy as well as the surface roughness

- Before proceeding to the creation of the desired part with specified specifications it is important to examine the accuracy of the machine as well as the consistency of providing the same output.

- This step may lead to design modifications in order to receive the desired output.

- Complex geometries with lot of geometrical features may need detailed slicing (very small layer height) in order to be achieved.

- The achievable surface roughness is found between 10-20μm.



- 97.7% of the dimensions are found in ±0.50 mm tolerance range and most of them were positive indicating a larger fabricated features than in the input CAD model.
- Engineers can expect a vertical tolerance of +/- 0.2mm.
- This tolerance is usually at the top of the tolerance band when attempting to print thin sections less than 0.8mm.

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[REF] “Design Guidelines – FDM” https://www.materialise.com/en/manufacturing/materials/abs/design-guidelines
[REF] https://grabcad.com/tutorials/fused-deposition-modeling-fdm-design-guidelines

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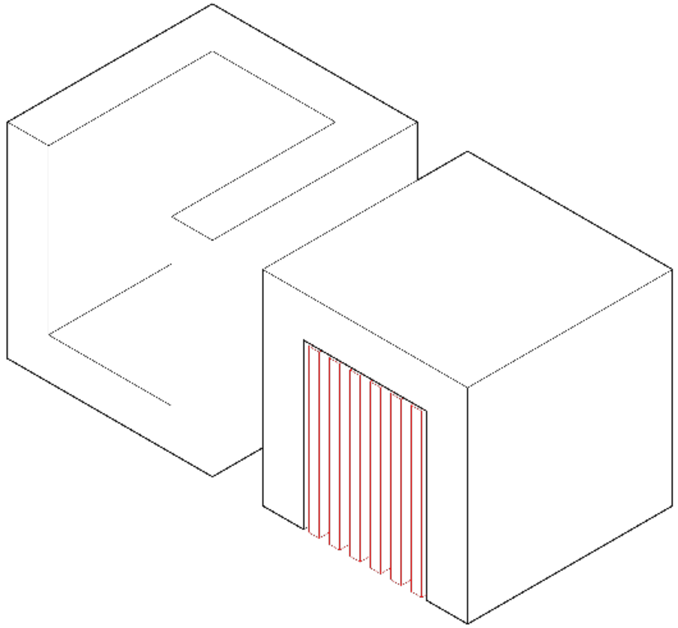
MEx design guidelines: Build orientation

➢ **Building orientation (Anisotropy, accuracy)**

❖ Build orientation dictates the directional behaviour of design requirements, like mechanical properties but also aesthetics & surface finish.

❖ Apart from the aesthetic effects of wrong orientation the material waste that arises due to the required support structures, drops the printability of the part.



❖ The ideal time for choosing build orientation is after the concept design is completed but before detailed design requirements are implemented, in order to avoid features experiencing the staircase effect because of height layer height and overhang combination.

❖ The anisotropy of structural properties that arise of the building orientation is considered when the part is oriented for structural applications.

[REF] "Design Guidelines – FDM" https://www.materialise.com/en/manufacturing/materials/abs/design-guidelines
[REF] https://grabcad.com/tutorials/fused-deposition-modeling-fdm-design-guidelines

MEx design guidelines: Build orientation

➢ **Anisotropy**

❖ Due to the anisotropic nature of MEx printing, understanding the application of a component and how it is built are critical to the success of a design.

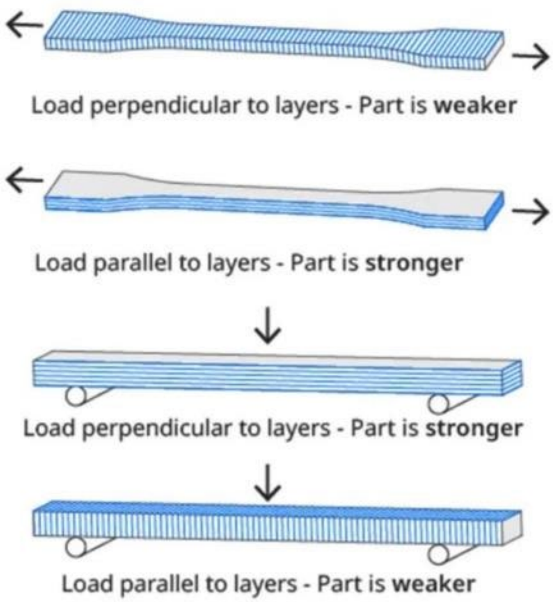
❖ The lack of continuous material paths and the stress concentration created by each layer joint contribute to this weakness.

❖ Since the layers are printed as a round-ended rectangle, the joints between each layer are small valleys.

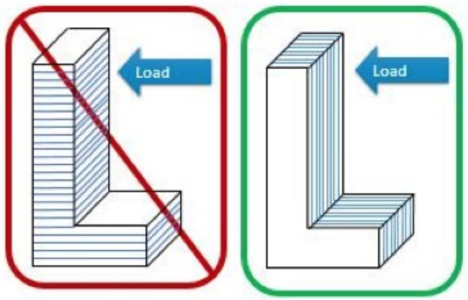
❖ This creates a stress concentration where a crack will want to form.

❖ With MEx, parts have their strongest strength at the tensile mode along the X-Y plane and the lowest strength in the Z-direction because of the technology's build style of one layer cooling and solidifying while the other is laid on

❖ Annealing can mitigate most anisotropic behavior



Source: https://ultimaker.com/learn/design-for-fff-3d-printing



Source: https://www.3dprintacademy.co.uk/fdm-3d-printing-tips-for-designers-tip-3-part-orientation/

MEx design guidelines: Geometric features

➢ **Geometry (e.g., corners, fillets and chamfers etc.)**

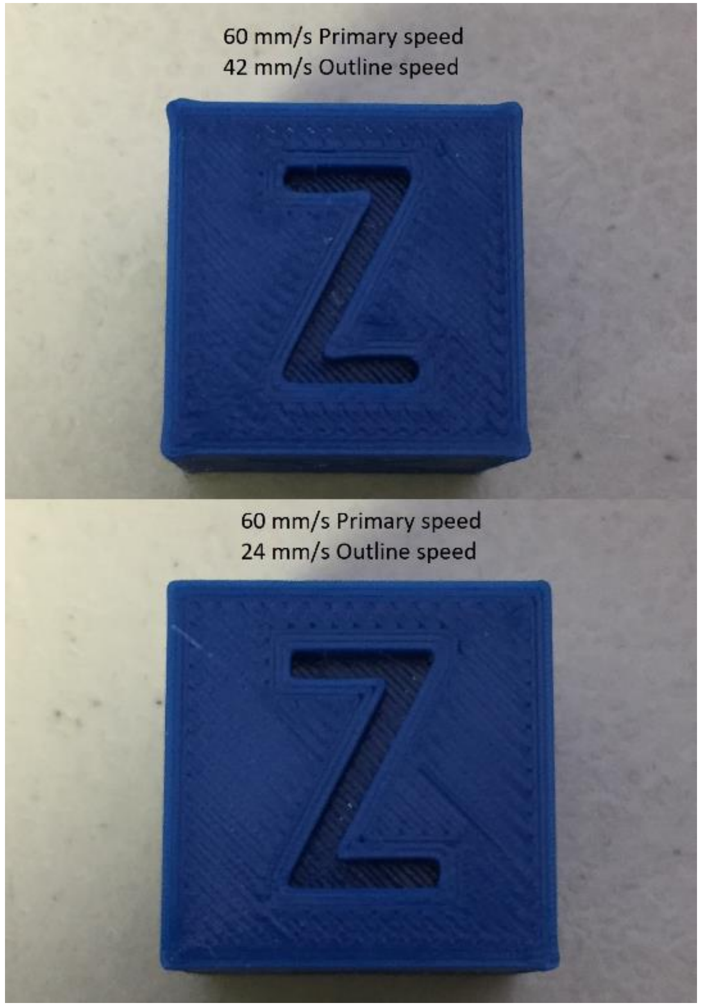
❖ Some features (corners and edges) will never be perfectly square due to the circular printing nozzle that creates radius equal to the size of the nozzle.

❖ As the printer approaches a corner, it needs to stop moving on one axis, and start moving on another. This means that the nozzle is stationary, adding to print time.

❖ Pressure inside the nozzle leads to material keep being extruded, resulting in over-deposition.

❖ This can be solved by adding small fillet radiuses in the corners, smoothing the print head movement

❖ Process parameters tuning can also reduce the issue (acceleration, jerk, linear/pressure advance)



Source: https://forum.prusaprinters.org/forum/original-prusa-i3-mk2-s-others-archive/bulging-round-corners/

MEx design guidelines: Geometric features

- **Geometry (e.g., corners, fillets and chamfers etc.)**

- As the nozzle prints each layer, it compresses the print material down to improve adhesion.

- For the initial print layer, this creates a flare(“elephant's foot”) which can impact the ability to assemble MEx parts as this flare protrudes outside the specified dimensions and often it needs post processing to be removed.

- The addition of a chamfer or radius along the edges of the part that are in contact with the build plate will reduce the impact of these problems by distributing more evenly the thermal stresses.

- This will also assist in removal of the component from the build plate once the print has been completed

Source: https://msd-makerspaces.gitbook.io/next-lab/3d-printing/troubleshooting

Source: https://support.3dverkstan.se/article/38-designing-for-3d-printing

➢ **Shrinkage & Warping**

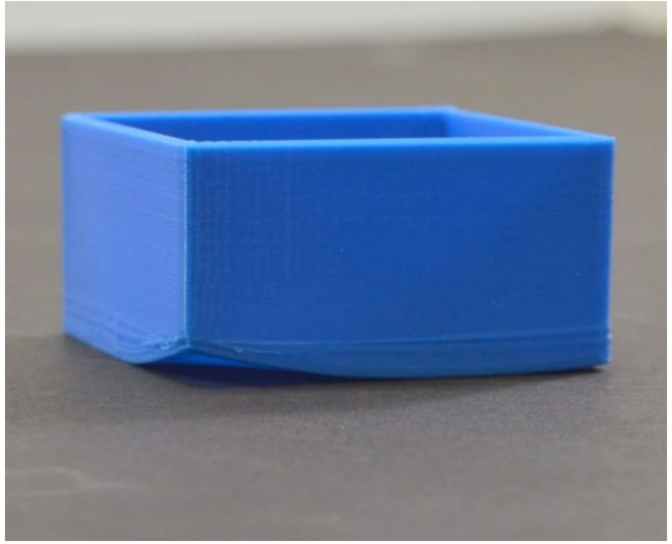
❖ Another issue that is often present relating to the first print layer of an MEx print is warping.

❖ The base layer is the first layer to be printed and cools as the other hot layers are printed on top.

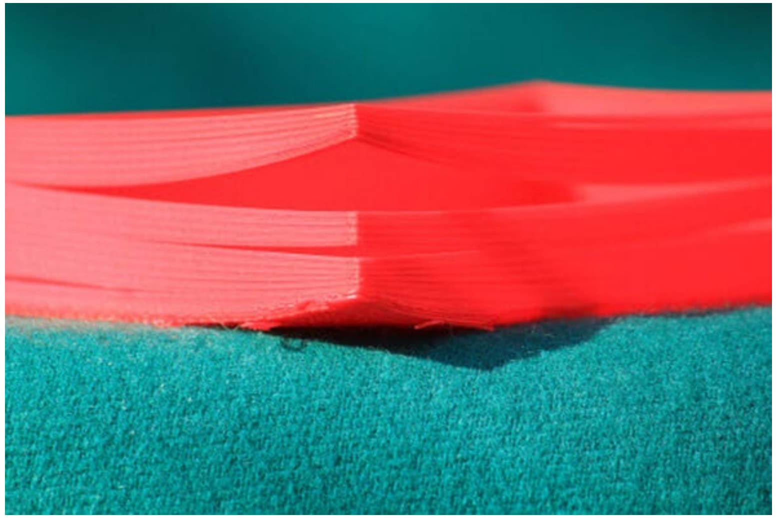
❖ This causes differential cooling and can result in the base layer curling up and away from the build plate as it shrinks and contracts.

❖ ABS is more vulnerable to warping due to its high printing temperature when compared to PLA.

❖ The user has to be aware as it regards the properties of the printed material and to modify parameters such as the temperature of the build platform as well as to maintain the chamber heated during the building.



Source: https://www.makerbot.com/stories/engineering/abs-3d-printing/



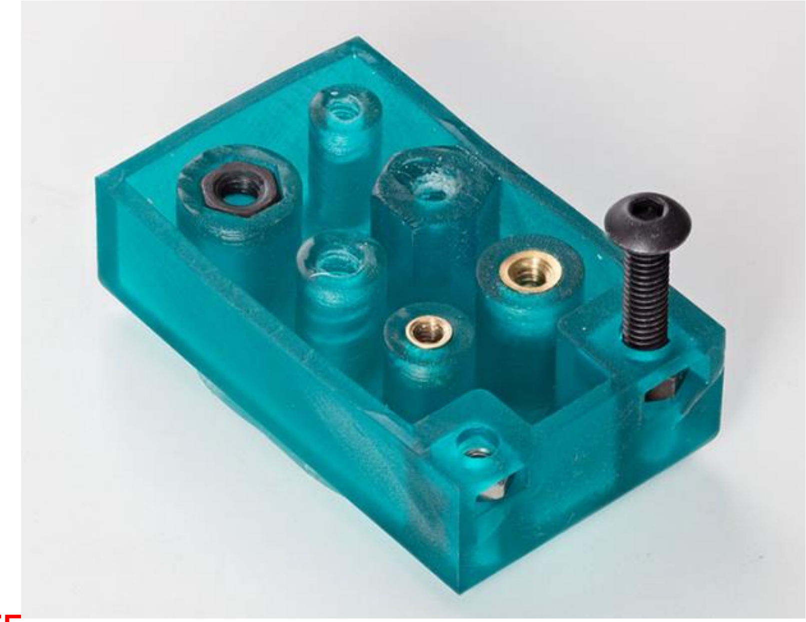
MEx design guidelines: Threaded holes

Threaded holes

- Should be limited only to blind holes, as bolt through hole and nut on the opposite side are generally stronger
- A flush insert (or pocketed nut) can be used in through holes where there is no space for a nut
- Bending along the axis parallel to printing should be generally avoided
- Double check your CAD model before adding fastening features

5 options for MEx processes

- Print-in-place threads
- Cutting threads (tapping)
- Self-tapping screws
- Inserts
- Embedded nuts



How to select?

- Will you need to disassemble and reassemble the components?
- What are your strength requirements or holding forces?
- What are the geometric or spatial constraints inherent in the design of your parts?

MEx design guidelines: Threaded holes

➢ **Print-in-place threads**

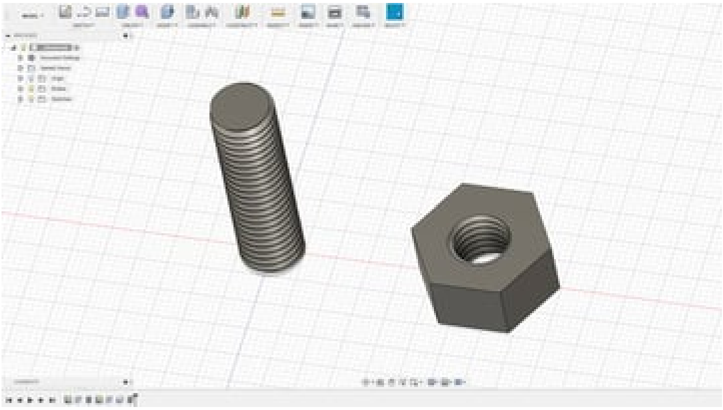
❖ Not suited for small threads and requires high printer detail/resolution to print accurately

❖ Limited to vertical holes only, as required support for horizontal holes messes up the required tolerances

❖ Thread usually requires clean-up with a tap after printing and before using

❖ Make sure the tolerance between internal and external threads is 0.15-0.2 mm

❖ Avoid sharp edges and 90-degree angles (stress concentrators) and include a radius on the root.



MEx design guidelines: Threaded holes

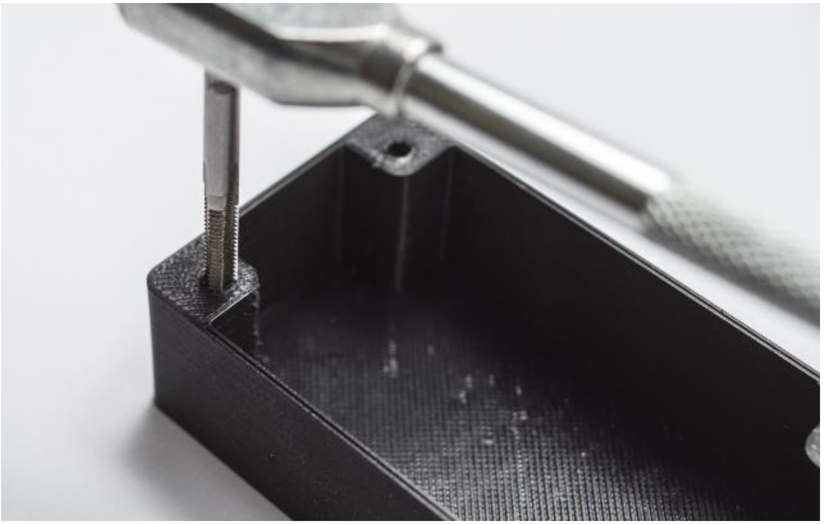
- **Cutting threads/tapping**

- Similar method to the one used for metallic parts

- Holes should be slightly undersized and drilled before tapping to the correct size (https://littlemachineshop.com/images/gallery/PDF/TapDrillSizes.pdf)

- Operation should not be forced, as the part could split between layers

- Minimum wall thickness around a thread should match the diameter of the fastener (e.g. an M5 fastener requires a minimum of 5mm wall thickness around the threaded hole).

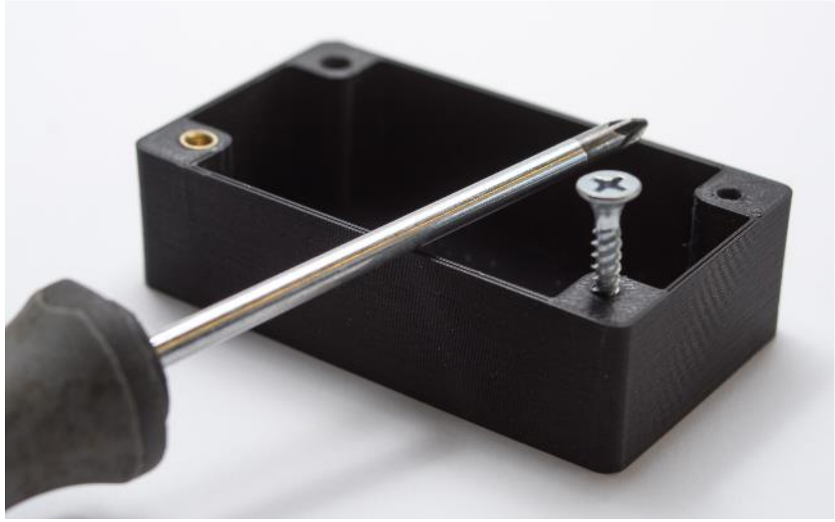


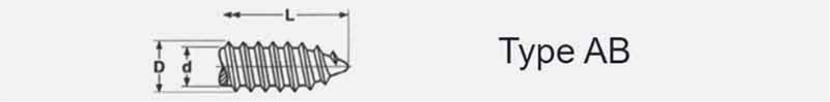
Metric Tap & Clearance Drill Sizes		Tap Drill			
		75% Thread for Aluminum, Brass, & Plastics		50% Thread for Steel, Stainless, & Iron	
Screw Size (mm)	Thread Pitch (mm)	Drill Size (mm)	Closest American Drill	Drill Size (mm)	Closest American Drill
M1.5	0.35	1.15	56	1.25	55
M1.6	0.35	1.25	55	1.35	54
M 1.8	0.35	1.45	53	1.55	1/16
M 2	0.45	1.55	1/16	1.70	51
	0.40	1.60	52	1.75	50
M 2.2	0.45	1.75	50	1.90	48
M 2.5	0.45	2.05	46	2.20	44
M 3	0.60	2.40	41	2.60	37
	0.50	2.50	39	2.70	36
M 3.5	0.60	2.90	32	3.10	31

MEx design guidelines: Threaded holes

- **Self-tapping screws**

- Commonly used in IM parts
- Screw cuts its' own threads while tightening
- A pilot hole size that provides 75% to 80% thread engagement is a good starting point; screw manufacturers usually list specifications
- Operation should not be forced, as the part could split between layers
- Special self tapping screws for plastic that limit the radial stress should be used whenever possible
- Minimum wall thickness around a thread should match the diameter of the fastener (e.g. an M5 fastener requires a minimum of 5mm wall thickness around the threaded hole)
- Suitable only for applications where parts will not be assembled/disassembled regularly





Nominal Size or Basic Screw Diameter		Threads per Inch	D Major Diameter Max.	D Major Diameter Min.	d Minor Diameter Max.	d Minor Diameter Min.	L These Lengths or Shorter Have AB Threads 90° Heads	L These Lengths or Shorter Have AB Threads Csk Heads
4	0.1120	24	0.114	0.110	0.086	0.082	3/16	7/32
6	0.1380	20	0.139	0.135	0.104	0.099	7/32	17/64
8	0.1640	18	0.188	0.161	0.122	0.116	9/32	21/64
10	0.1900	16	0.189	0.183	0.141	0.135	21/64	3/8
12	0.2160	14	0.215	0.209	0.164	0.157	3/8	13/32
1/4	0.2500	14	0.246	0.240	0.192	0.185	13/32	15/32
5/16	0.3125	12	0.315	0.306	0.244	0.236	5/8	3/4
3/8	0.3750	12	0.380	0.371	0.309	0.299	3/8	29/32

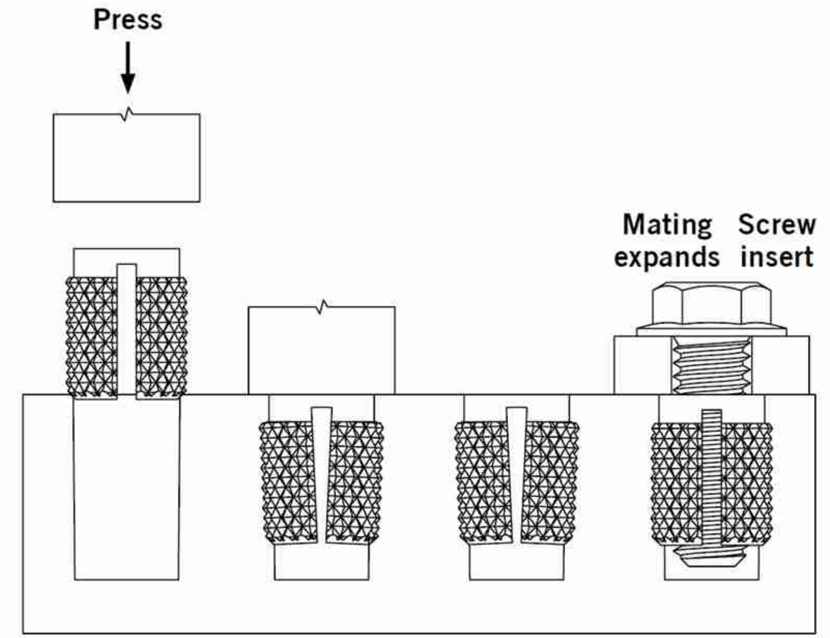
- **Press-fit inserts**

- Ideal for applications where parts will be assembled/disassembled frequently

- Expansion-type: When a mating screw is installed, the sides of these inserts are expanded and force the fins or knurls into the sides of the holes

- Hole size for the insert is provided by the manufacturer

- Minimum wall thickness around a thread should be at least half the insert diameter



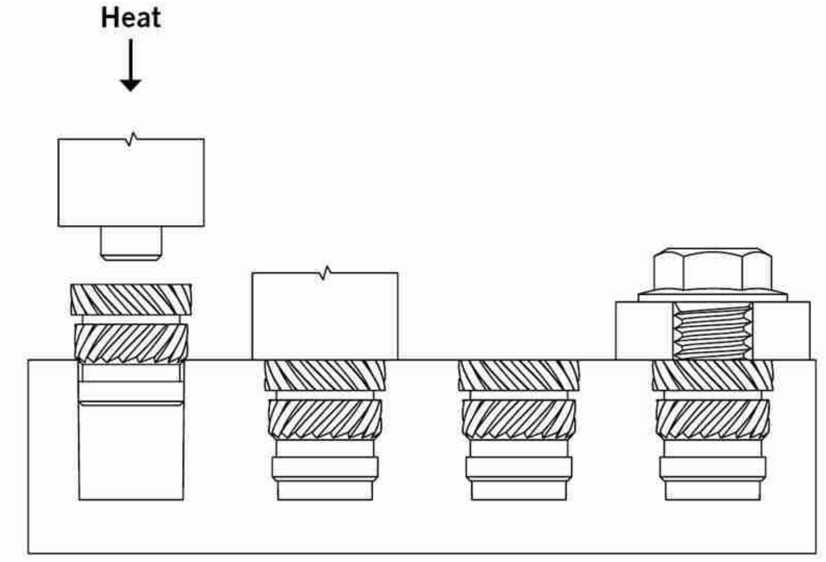
PRESS INSERT 240 SERIES — FLUSH BRASS

Part Number	Thread Size	L (in.)	A (in.)	B (in.)	Hole Size* (in.)	Minimum Depth (in.)
240-000-BR	0-80	.125	.094	.104	.094	.130
240-002-BR	2-56	.156	.125	.135	.125	.173
240-004-BR	4-40	.188	.156	.166	.156	.215
240-006-BR	6-32	.250	.187	.199	.188	.259
240-008-BR	8-32	.313	.218	.230	.219	.302
240-008-BR.250	8-32	.250	.218	.230	.219	.302
240-3-BR	10-24	.375	.250	.262	.250	.345
240-332-BR	10-32	.375	.250	.262	.250	.345
240-332-BR.250	10-32	.250	.250	.262	.250	.345
240-4-BR	1/4-20	.500	.312	.326	.313	.432
240-5-BR	5/16-18	.563	.375	.389	.375	.518

MEx design guidelines: Threaded holes

- **Heat-set inserts**

- Ideal for applications where parts will be assembled/disassembled frequently
- Hole size for the insert is provided by the manufacturer
- The thread insert is heated via thermal conduction and pressed into the hole once the plastic reaches the proper melting temperature
- After the heated press tip is retracted, the plastic will become cool and solid, locking the thread insert into place
- Pressing against a cool flat surface until the plastic solidifies is encouraged to avoid plastic budging
- Minimum wall thickness around a thread should be at least half the insert diameter



TAPERED SINGLE VANE

Part Number.	Internal Thread	Overall Length (L)	Insert Diameter (W)	Pilot Diameter (N)	Rec. Hole Size* (D)	Rec. Hole Size* (S)	Minimum Wall Thickness
TH-002-SV	2-56	.115	.136	.122	.123	.118	.080
TH-004-SV	4-40	.135	.172	.157	.159	.153	.093
TH-006-SV	6-32	.150	.220	.203	.206	.199	.116
TH-008-SV	8-32	.185	.250	.230	.234	.226	.133
TH-124-SV	10-24	.225	.296	.272	.277	.267	.159
TH-132-SV	10-32	.225	.296	.272	.277	.267	.159
TH-420-SV	1/4-20	.300	.375	.354	.363	.349	.194
TH-428-SV	1/4-28	.300	.375	.354	.363	.349	.194
TH-518-SV	5/16-18	.335	.469	.439	.448	.431	.245
TH-316-SV	3/8-16	.375	.563	.530	.540	.523	.293
TH-324-SV	3/8-24	.375	.563	.530	.540	.523	.293
TH-M25-SV	M2.5-0.45	.135	.172	.157	.159	.153	.093
TH-M30-SV	M3-0.5	.150	.220	.203	.206	.199	.116
TH-M40-SV	M4-0.7	.185	.250	.230	.234	.226	.133
TH-M50-SV	M5-0.8	.265	.328	.308	.315	.303	.171
TH-M60-SV	M6-1.0	.300	.375	.354	.363	.349	.194

MEx design guidelines: Threaded holes

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➢ **Embedded nuts**

❖ Ideal for applications where parts will be assembled/disassembled frequently

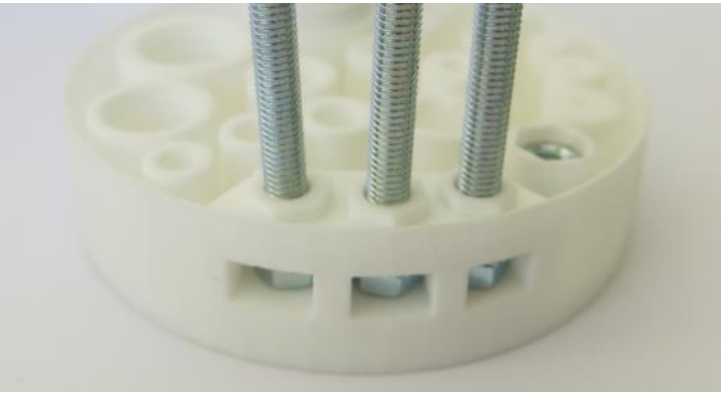
❖ A socket needs to be designed on the part, to allow for a cavity for the nut. You can have this enclosed (nut completely encapsulated), or open on the side.

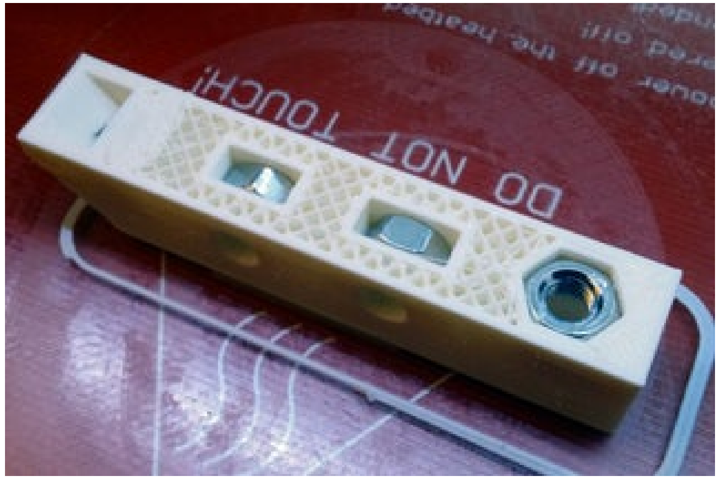
❖ Print needs to be paused at a specific height (the top-most face of the nut), to insert the nut(s). Allow 1 additional layer due to tolerances.

❖ Remember to disable support in the socket area, so that space is left for the nut

❖ Tolerances need to be tight (0.1mm typically works well). Superglue can also be used to secure the nut in place

❖ Minimum wall thickness around the nut should be at least half the distance across flats

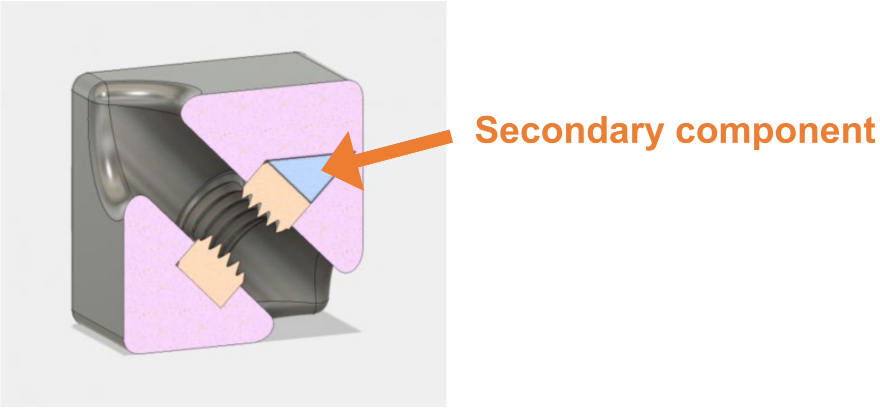


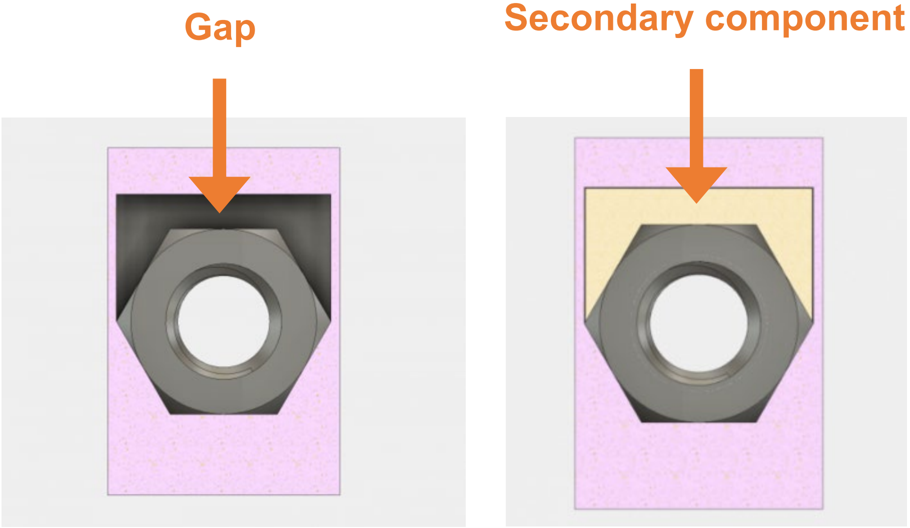


MEx design guidelines: Threaded holes

- **Embedded nuts**

- Other insertion directions can also be used
- In case of horizontal holes, secondary components should be used to allow resuming printing
- Secondary components need to be pre-printed
- Square nuts can also be used in such cases if available
- Similar approach can be used for other angles as well





Source: https://markforged.com/resources/blog/embedding-nuts-3d-printing

MEx design guidelines: Threaded holes

➢ **Summary**

Type	Pros	Cons
Print-in-place	• Can design custom threads • Good when inserts aren't available (ie. M50 thread) • Works well with brittle materials	• Threads will wear down over time • Difficult to model accurately • Requires high resolution prints
Tapping	• Better assembly/disassembly than self threading screws	• Low strength • Plastic threads wear down over time • Time intensive
Self-tapping	• Easy installation • Minimal design requirements • Cheap	• Brittle material may break • Limited assembly/disassembly • Low strength
Inserts	• Fast, easy and clean • Unlimited assembly/disassembly • Production quality	• More expensive • Requires increased wall thickness
Embedded nuts	• Low cost solution • Good holding force • Easy install	• Pause print function • Tolerances

MEx design guidelines: Part splitting & DFA

➢ **Design for Assembly**

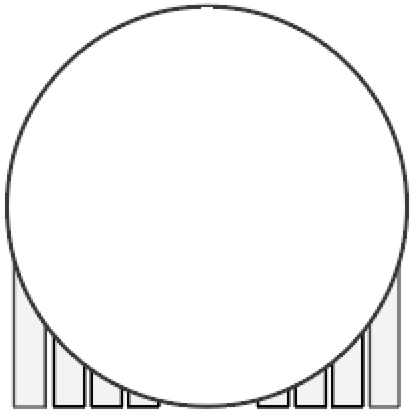
Key design aspects to consider when printing with MEx are:

- How to reduce the amount of support required
- How to achieve optimal strength
- Direction the part is built on the build platform

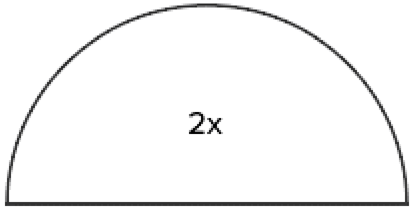
Overhangs that require a large amount of support may be removed by simply splitting a complex shape into sections that are printed individually. If desired, the sections can be glued together once the print has been completed.

This results in:

✓ Reduction of the amount of supports
✓ Simplification of the post-processing
✓ Faster printing process
✓ Less material consumed



Printing as one object
Support is needed



Slicing in two parts
No support is needed

Source: https://www.hubs.com/knowledge-base/how-design-parts-fdm-3d-printing/#vertical-axis-holes

MEx design guidelines: Part splitting & DFA

➢ **Design for Assembly considerations**

❖ What is the minimum number of parts that can be used?

❖ What would be the loads transferred between the parts?

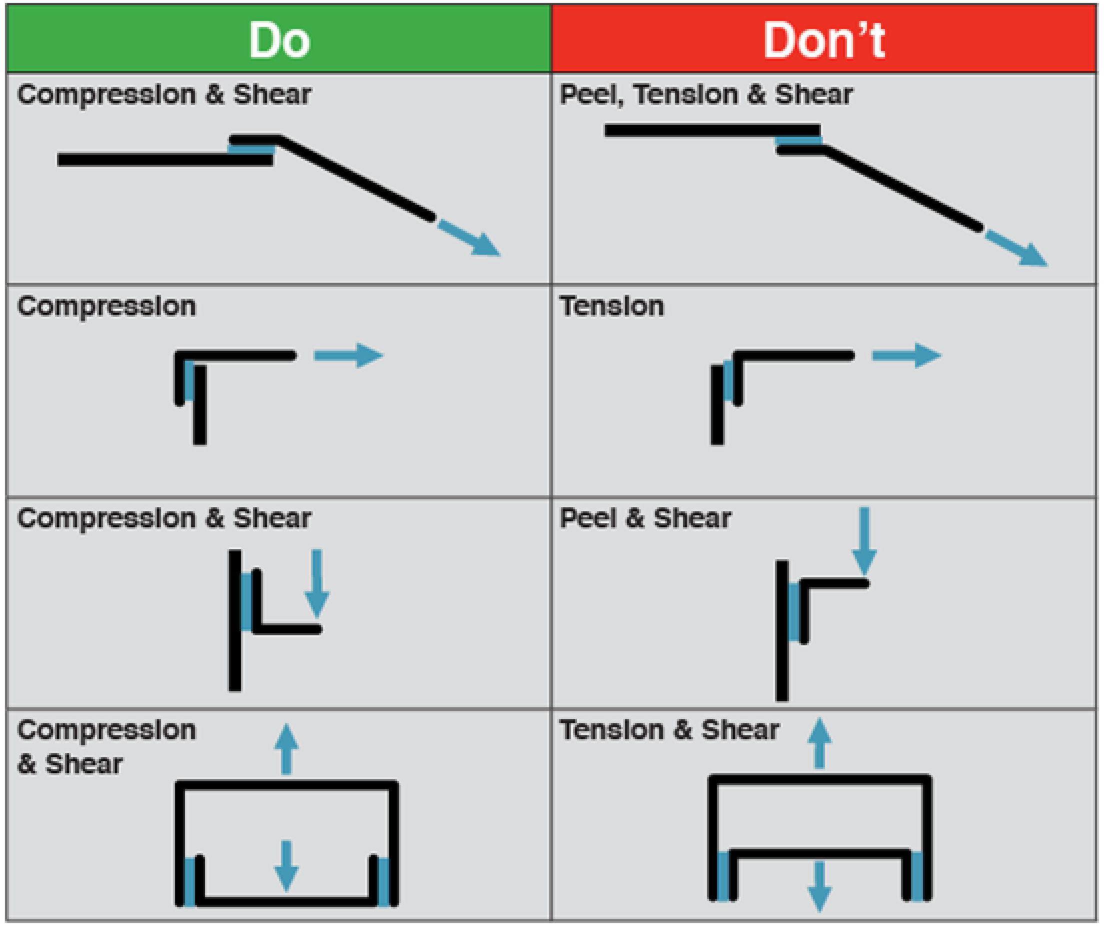
❖ How will the individual components be joined together?

- Clip together
- Screws
- Adhesive

❖ Adhesive is the most common way, however the joint should be designed properly to transfer forces effectively (shear)

❖ Locating features

- Parts can be designed to be self-locating/self-jigging
- Locating features can offer additional strength



Source: https://www.chemical-concepts.com/blog/2018/09/structural-adhesive-joint-design-guide/

MEx design guidelines: Print-in-place mechanisms

➢ **Interlocking Parts, Hinges & Clearances**

- If a 3D model that has multiple parts or pieces that will be assembled later will be created with MEx process, it is advised to ensure that there is enough space to join the pieces together.

- If it is planned to create a part in one piece without having to assemble afterwards, it is advised to check that there is enough clearance between any moving parts such as ball joints, hinges, gears, cogs or chain links.

- If minimum clearances are not met, the 3D model could possibly fuse together during the 3D printing process and making the 3D printed model solid instead of movable.

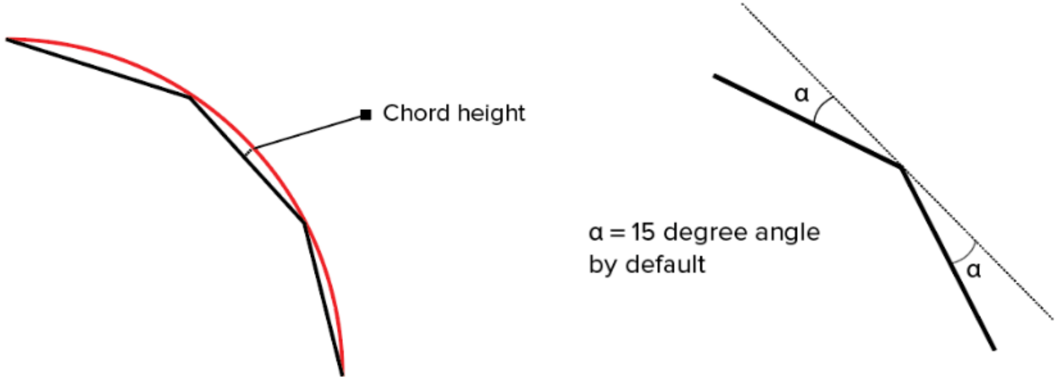
- Also consider that some materials allow to create complex assemblies of objects that 3D printing alone could not accomplish (flexible material etc.)

Source: https://www.leolane.com/blog/tessas-weekly-picks-3d-printed-gifts-2/

MEx design guidelines: STL files

❖ Polygon/model resolution when converting to STL is important for the final quality of the part

- Mainly defined by chord height & chord angle
- The chord height is the maximum distance that the software will allow between the surface of the original 3D model and the surface of the STL file
- The recommended value for the chord height is 1/20th of the 3D printing layer thickness and never below 0.001 mm
- Chord angle is the maximum allowable angle between the normals of adjacent triangles of the STL file



Source: https://www.hubs.com/knowledge-base/3d-printing-stl-files-step-step-guide/

❖ Many repair tool for watertight shapes and STL check exist and for each tool there are several examples on how to deal with common issues. Some of the tools are:

- Microsoft STL repair (Netfabb),
- Meshmixer, Meshlab,
- 3D Builder

Source: https://www.matterhackers.com/articles/improve-your-prints-with-open-source-3d-printer-research

➢ **Watertightness**

❖ Watertight part: It means that there are no holes on the surface of the 3D model.

❖ In order to manufacture a part with MEx process, it is obligatory to watertight

❖ Having a watertight design can affect the printability of a part — non-watertight models cannot be 3D printed — which is why it is vital to check the design before sending it to print.

❖ Some slicer automation software can easily check for watertight issues so it can be controlled before the actual print.

Source: https://www.myminifactory.com/object/3d-print-spin-vase-3-41523

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- **Non-Manifold Edges & Singular Points**

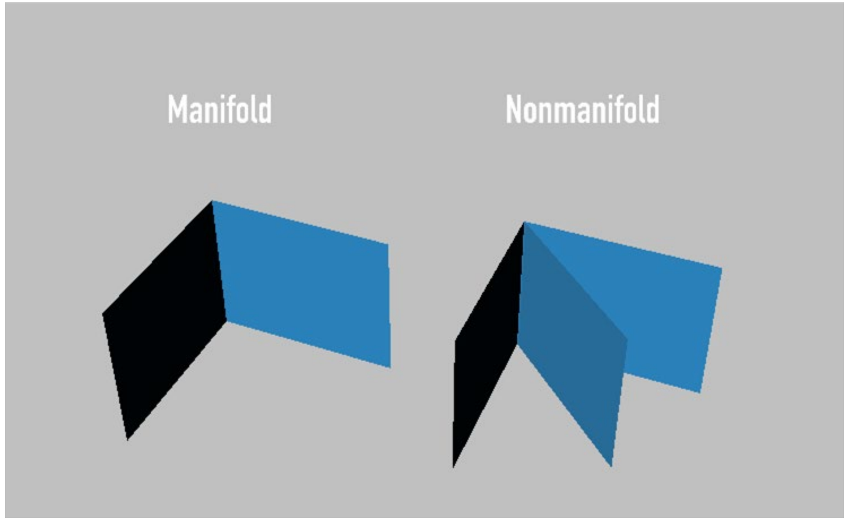
- During the conception of the 3D file, certain operations may create unattached, ambiguous surfaces which do not connect.

- Other operations may separate surfaces, creating singular point of connection.

- To define a clear volume, each side must be connecting two and only two adjacent faces.

- Similarly, singular points must arrive at the collection of multiple faces. If two faces share only one point (figure), the model is considered "non-manifold" and will not be able to be printed.

- These singularities can be eliminated by either disconnecting the non-manifold surface and giving it volume, or by deleting it completely.



Source: https://discourse.mcneel.com/t/manifold-vs-non-manifold-geometries/45265

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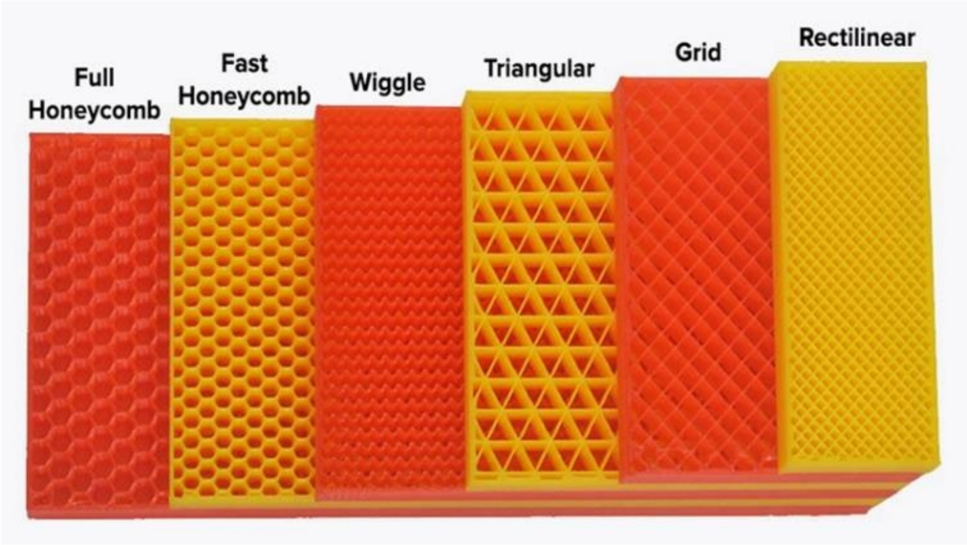
- **Hollowing**
- If a model is large or a decrease of the amount of material used for weight or cost savings is desired, then hollowing a model is the way to go.
- If want some parts of the object to be hollow, a hole in the model can be created so as to save significant portion of the material.
- Afterwards, an infill pattern and infill percentage can be selected on the slicer software in order to strengthen the internal structure of the part.



Source: https://www.tianseoffice.com/blog/how-to-use-infill-percentage-and-pattern-enhance-strength-save-material/

https://www.hubs.com/knowledge-base/selecting-optimal-shell-and-infill-parameters-fdm-3d-printing/#infill

Agenda

- Introduction to DfAM
- Design aspects for MEx
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

SAM: MEx Design Optimization methods

- Design from scratch provides the freedom to tailor material placement into the part to a high level of detail

- Conformance on both performance metrics (structural) and AM manufacturability

- **Design optimization techniques**
  - Several design optimization techniques with respect to different targets (structural, thermal, fluid dynamics) exist such as (Topology Optimization, Generative design, etc.)
  - However, these methods do not take into account manufacturability constrain
  - Although AM is the enabler of design freedom, it is not guaranteed that all designs can be built **effectively**

- AM manufacturability should be checked

- Addition of design elements to ensure AM manufacturability

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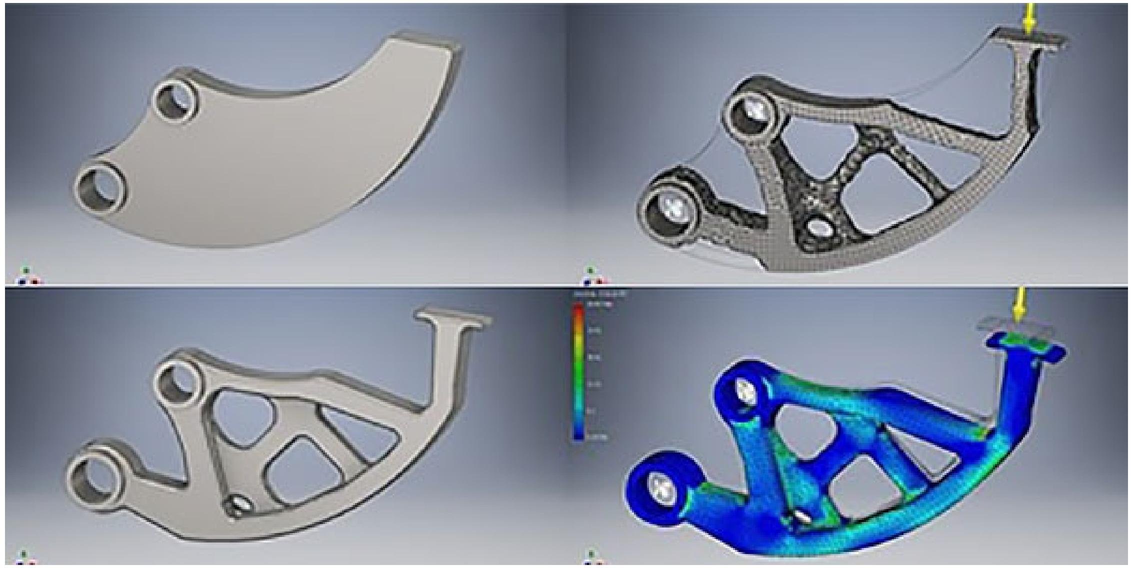
Topology: Area of mathematics concerned with properties that are preserved under continuous deformation of objects

Optimization: Selection of the best option from a set of available alternatives

Topology optimization: A mathematical approach that optimizes material distribution within a given design space (topology), for a given set of loads and boundary conditions, such as the result meets a prescribed set of performance (optimization) targets.

- An objective function needs to be defined, that needs to be maximized/minimized.
- A number of alternatives is produced, and the best one selected



MEx Design Optimization methods: Topology Optimization

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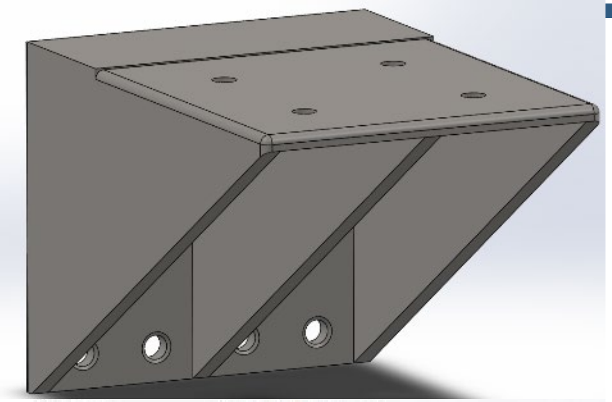
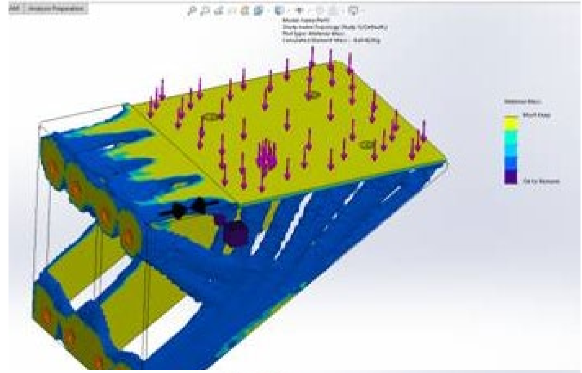
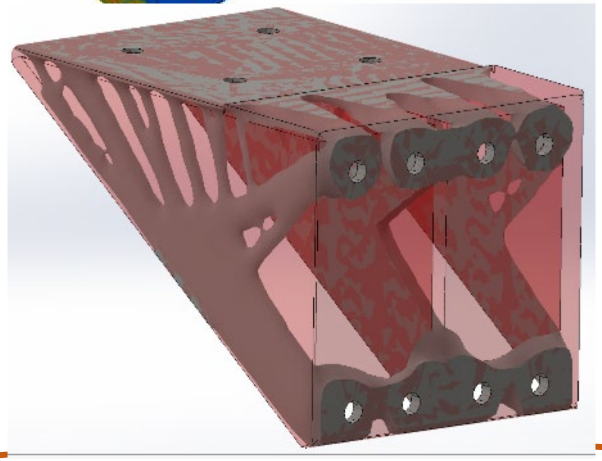
- **Preparation:** The input to the topology optimization software would the 3D cad of the part
- **Defining the simulation parameters:** The applied loads and locations as well as the fixtures and the designed constraints are determined.
- **Goals and Constraints:** Selection of the optimization goal and constraints such as a) Best stiffness to weight ratio, b) Minimize maximum displacement and c) Minimize mass with displacement constraints.
- **Manufacturing Controls:** Add constraints that assist with the manufacturability of the part and can be used to keep regions of material that you don't want removed by the optimization process
- **Mesh and run:** At this step the Mesh Density is controlled. A finer mesh will create a more accurate study but will take longer to mesh.
- **Results and analysis:** Identify which conditions provide the more optimized results. Iterations until the desired output come.







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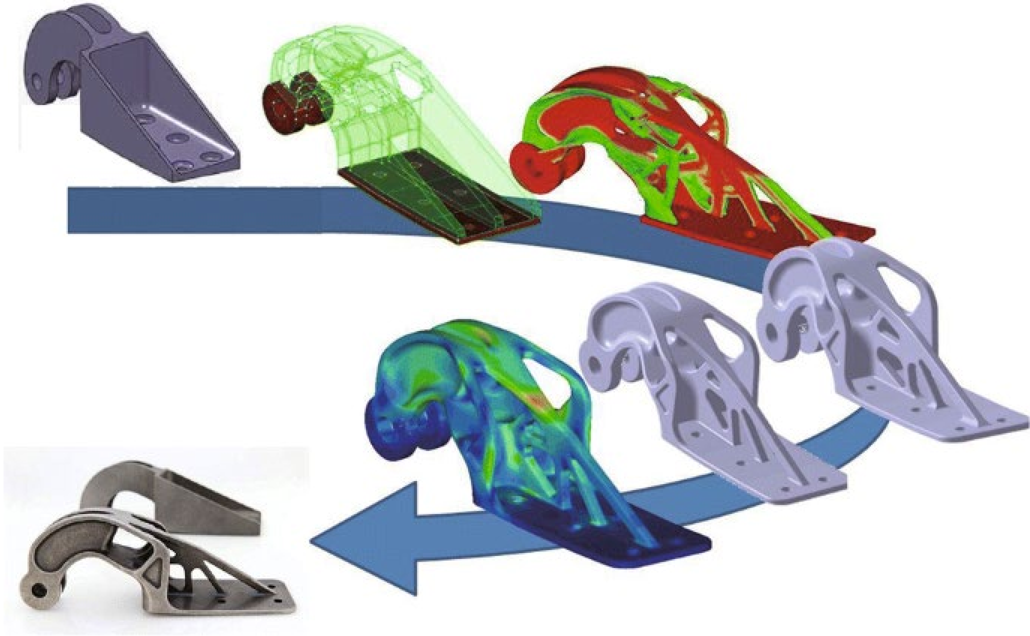
- **Dedicated software tools:**
  - Altair OptiStruct
  - Altair Inspire
  - Ansys
  - Dassault Systèmes
  - Autodesk
  - nTopology
  - Tosca

- **Try for yourselves!**
  http://www.topopt.dtu.dk/



- **CAD-embedded solutions:**
  - Solidworks
  - Creo
  - Fusion 360

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- The typical design process, requires the knowledge and expertise of the designer to craft products that meet the needs of the end user.

- Combine this with the next generation of products that are emerging, which require ultra-high-performance characteristics and are too demanding for the traditional design process, and this is where generative design will help create the optimized designs of the future.

- Designers or engineers input design goals into the generative design software, along with parameters such as performance or spatial requirements, materials, manufacturing methods, and cost constraints.

- With the emergence of technologies such as artificial intelligence algorithms and infinite computing, which are much more accessible that any time in the past, designers and engineers can co-create designs using parameter driven optimization.

- The software explores all the possible permutations of a solution, quickly generating design alternatives.

Source: https://www.autodesk.com/solutions/generative-design

Source: https://knepublishing.com/index.php/KnE-Engineering/article/view/612/1903

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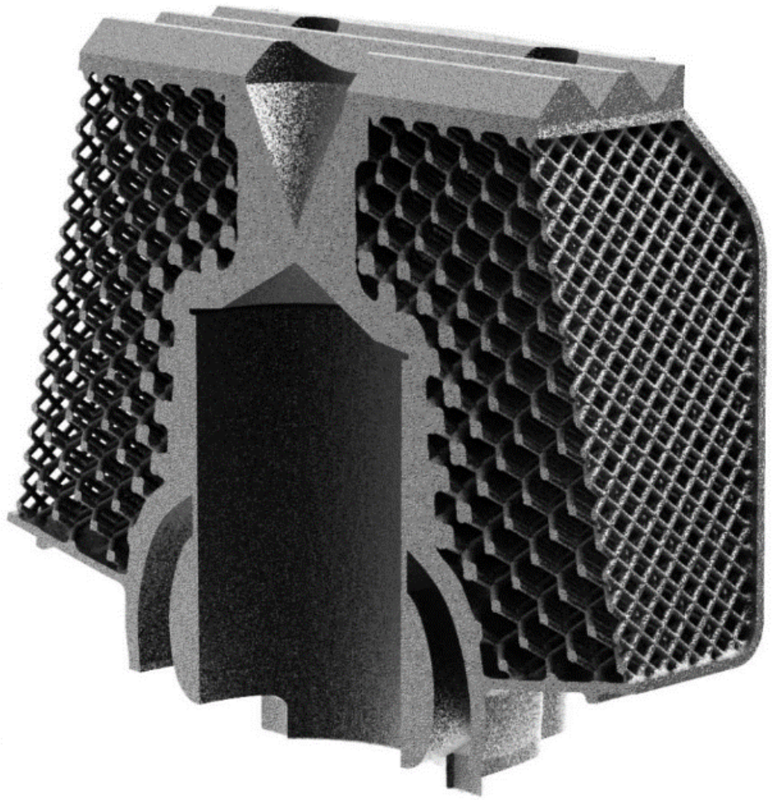
❖ **Dedicated software tools:**
- Ntopology
- MSC software
- CIDEON
- Ansys
- Dassault Systèmes
- Autodesk
- Tosca
- Altair Inspire

Try for yourselves!

https://www.layopt.com/truss/



❖ **CAD-embedded solutions:**
- Siemens NX
- FUSION 360
- Solidworks

MEx Design Optimization methods: Topology vs Generative

- For the topology optimization, the software generates a single optimized mesh-model concept ready for an engineer's evaluation.
- In other words, topology optimization requires a human-designed model from the outset to function, limiting the process, its outcomes, and its scale.
- In a way, topology optimization serves as the foundation for generative design.
- Generative design takes the process a step further and eliminates the need for the initial human-designed model, taking on the role of the designer based on the predefined set of constraints.

Source: https://formlabs.com/blog/generative-design/

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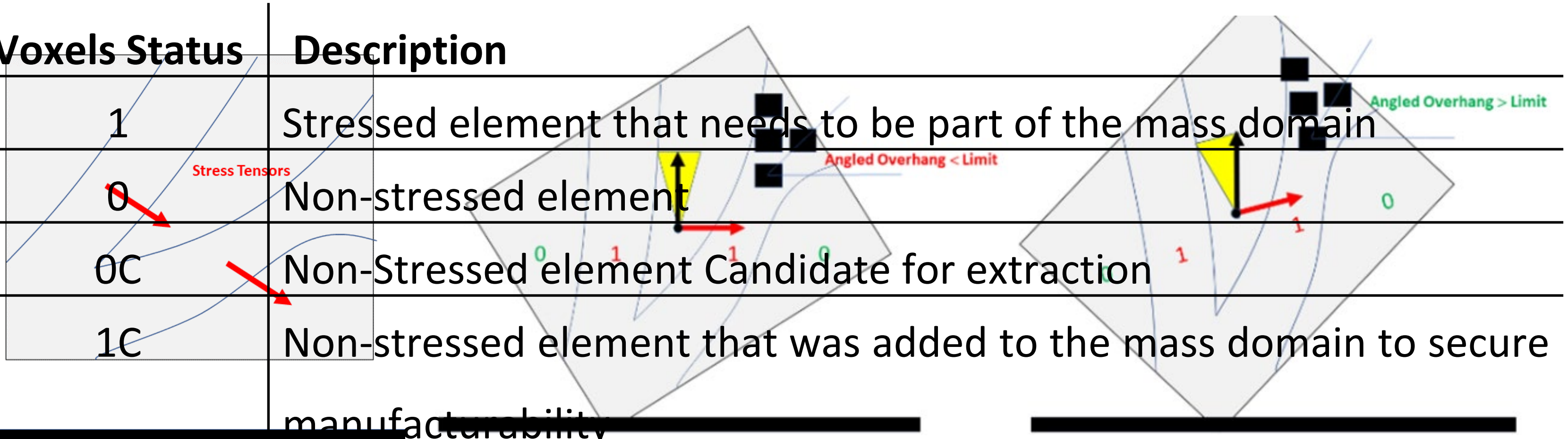
- A top-down layer creation direction is defined
- A number of voxel stages is defined
- A voxel is candidate for removal when both following criteria are valid:
  - ✓ Load is below the allowable stress threshold
  - ✓ The resulting geometry conforms to 3 main DfAM rules

Voxels Status	Description
1	Stressed element that needs to be part of the mass domain
0	Non-stressed element
0C	Non-Stressed element Candidate for extraction
1C	Non-stressed element that was added to the mass domain to secure manufacturability



FE analysis of the build envelope → Build orientation determination → Top-down geometric optimization → AM manufacturable optimized part

[A. K. Lianos, H. Bikas, P. Stavropoulos, "A Shape Optimization Method for Part Design Derived from the Buildability Restrictions of the Directed Energy Deposition Additive Manufacturing Process", (2020)]

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3. Top-Down geometric optimization

Rule 1: HB Ratio

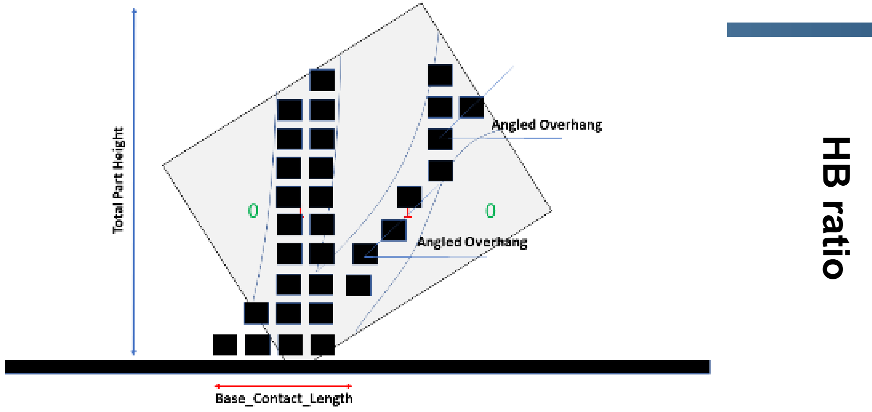
- Ratio of total base area to total part height
- Used as a mechanical connection to the build plate
- Used as a heatsink to the build plate
- Threshold to be experimentally determined for each process/material

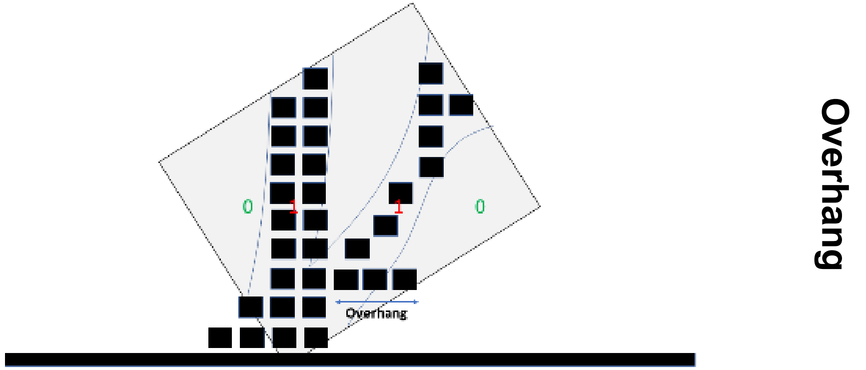
Rule 2: Overhang length

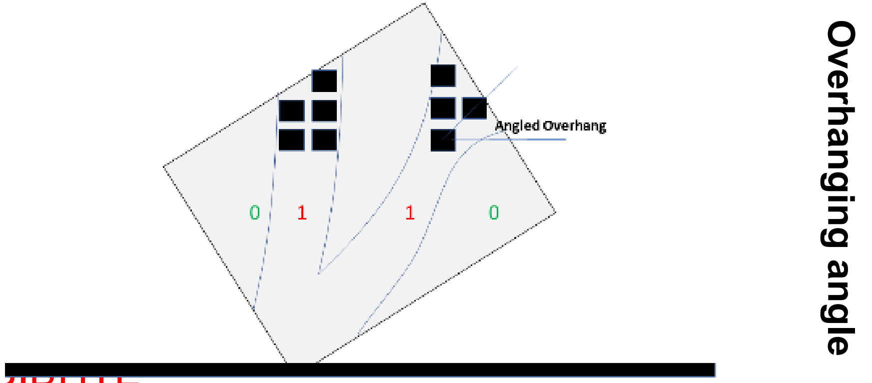
- Maximum length of a unsupported structure
- Threshold to be experimentally determined for each process/material

Rule 3: Overhang angle

- Maximum angle of a unsupported structure
- Threshold to be experimentally determined for each process/material







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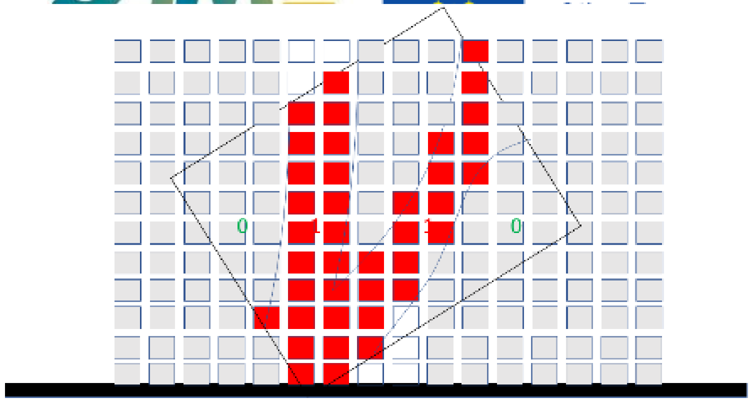
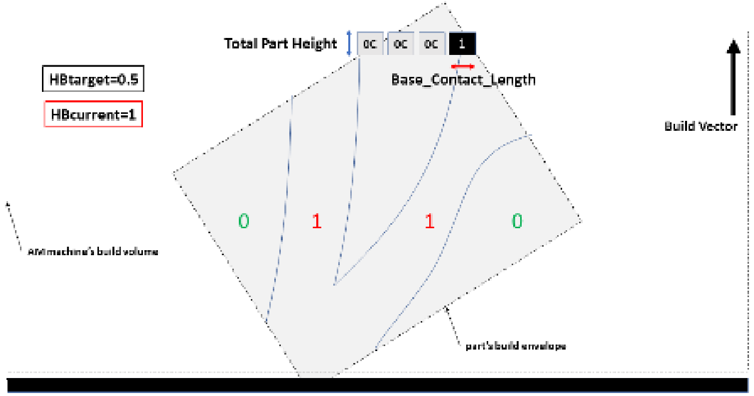
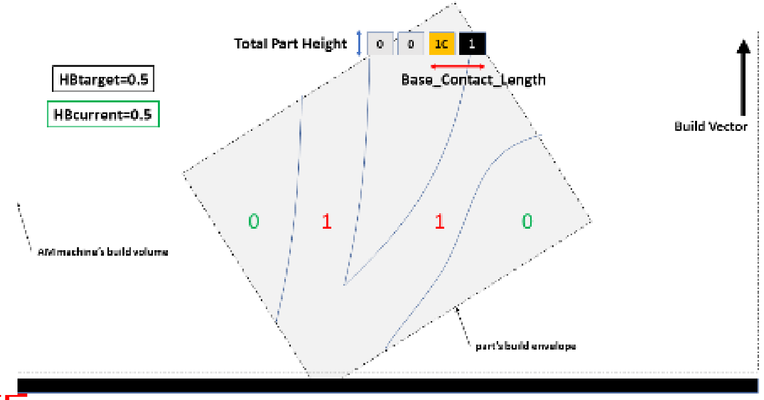
3. Top-Down geometric optimization

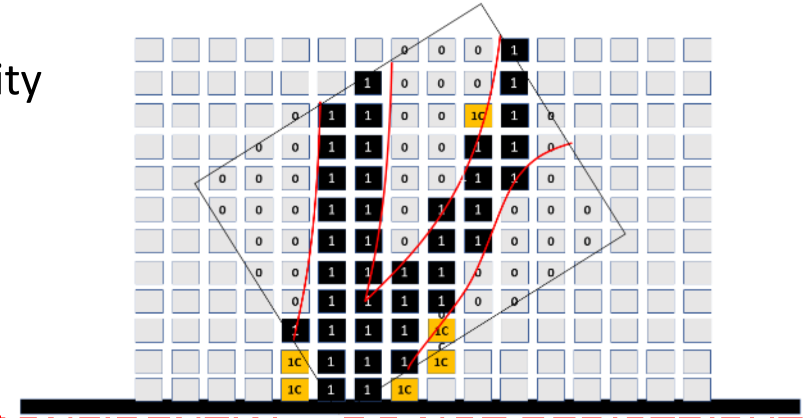
- The only factors morphing the part are the target HB ratio and the elements that are loaded
- The loaded element gets a value of 1
- The rest get a value of 0C
- DfAM rules are checked
- Candidate elements needed for manufacturability change their status from 0C to 1C
- Newly calculated domain now consists of
  - 0, 0C (material is subtracted)
  - 1,1C (material remains)

- 1C elements increase manufacturability









MEx Design Optimization methods: AM optimiser

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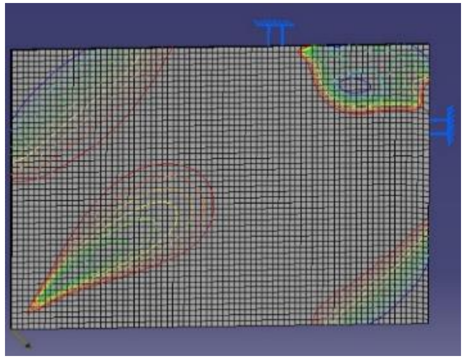
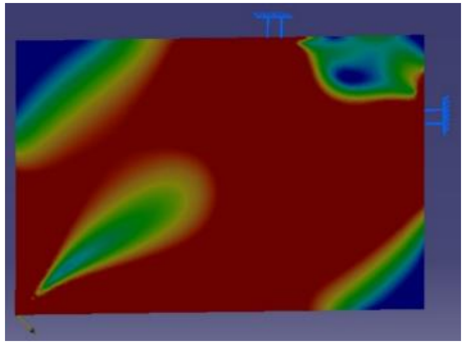
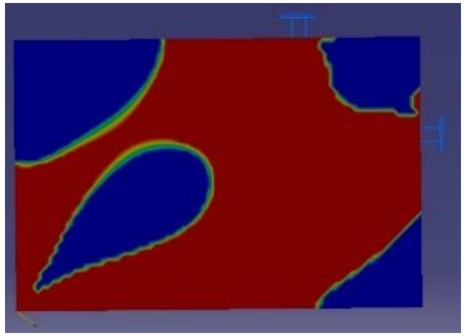
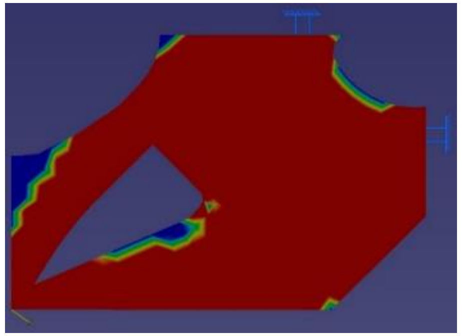
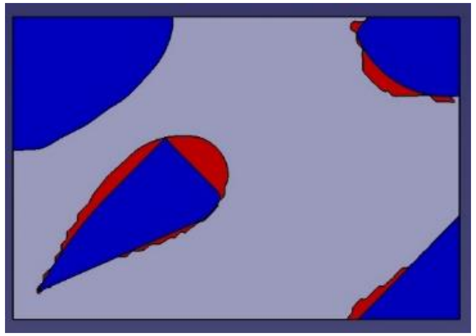


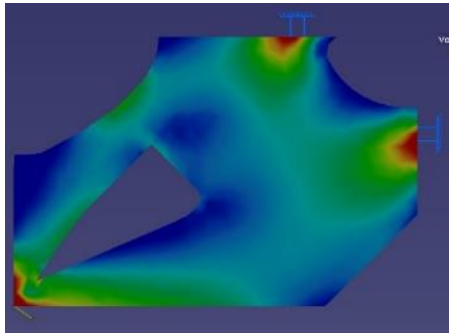


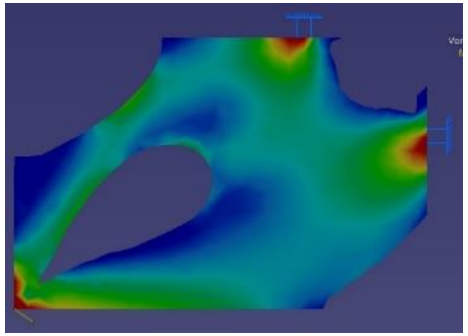
- Simplified 2D cross-section of a part under load
- 100x150mm with a load case of F_x=10N and F_y=-7.5N
- **Results:**
  - Differences on overhangs in the lower left and upper right corners
  - TMI = 95.0%
  - Added material serving AM Manufacturability is far less than the material used for the part to receive the developed stresses
- **Conclusions:**
  - Method compensates for both optimal material distribution based on load-case and manufacturability for AM at early design stages
  - Resulting geometry is not 100% material optimized as additional voxels are used to secure manufacturability
  - Additional design aspects/rules for specific AM technologies can be integrated











Agenda

- Introduction to DfAM
- Design aspects for MEx
- Design limits determination
- Design guidelines
- Design optimization methods
- Conclusions

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- In this presentation all the aspects of designing a part in order to be manufactured with MEx processes have been presented

- It is very important to understand the mechanisms of the process and the machine specifications in order to extract the most from the process

- However, the user has to be sure about the functionalities of the part in order to be happy with the final part of an MEx process.

- The well-known benefits of a part which have been made with AM, have been improved further by investigating optimization techniques such as Topology Optimization and Generative Design

- The future of MEx process and the related outputs depends mostly on these techniques as well as on the improved performance of machines in order to be capable to provide satisfactory products.

SAM: Conclusions

- Do tests to determine the limits of the machine & material combination, using standard test artefacts
- Scale/oversize/undersize features based on the obtained results from testing
- Pockets and height should be an integer multiple of layer thickness
- Avoid sharp edges (stress concentration) and add fillets/ribs

Thickness

- Recommended thickness depends on the machine, nozzle diameter and material
- For MEx machines, thickness equal to 2-3 times the nozzle diameter should be considered
- Wall thickness especially in thin walls should be an integer multiple of the printing thickness and nozzle diameter

Holes or gaps

- The MEx process typically produces undersized holes. This means that, for example, a hole designed with a 5mm diameter may be printed with a diameter around 4.8mm. Therefore, it is best practice to design oversized holes.
- It is typically recommended to increase a hole diameter by 2% to 4% for holes up to 10mm.
- If the accuracy of a hole diameter is critical, the hole can be 3D printed undersized with enough perimeters to drill through, especially under 3mm (Higher accuracy of the drill diameter)

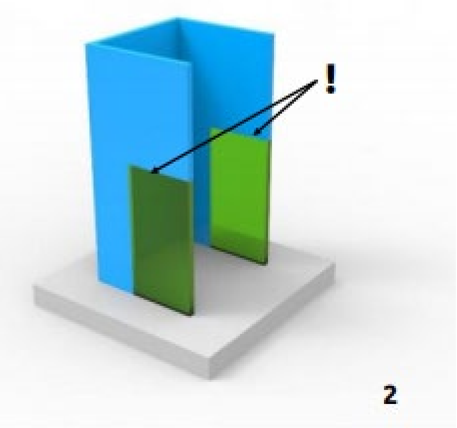
SAM: Conclusions

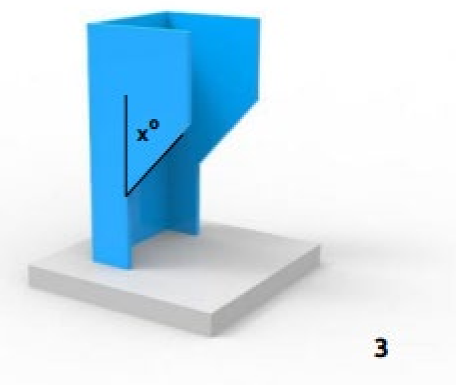
❖ **Angles and overhang**

- Generally, for MEx printers the minimum allowed inclination angle is 45 degrees.
- Reduce need for supports via design or with correct orientation of the part
- If a bridge exceeds 5mm, sagging or marks from support material can occur. Splitting the design or post-processing can eliminate this issue.

❖ **Part orientation**

- Orient the part to obtain sufficient strength (consider anisotropy)
- Orient the part to ensure holes and bores are vertical if possible
- Orient the part to improve surface finish
- Orient the part to minimize supports (if not feasible, splitting the part might be an option)





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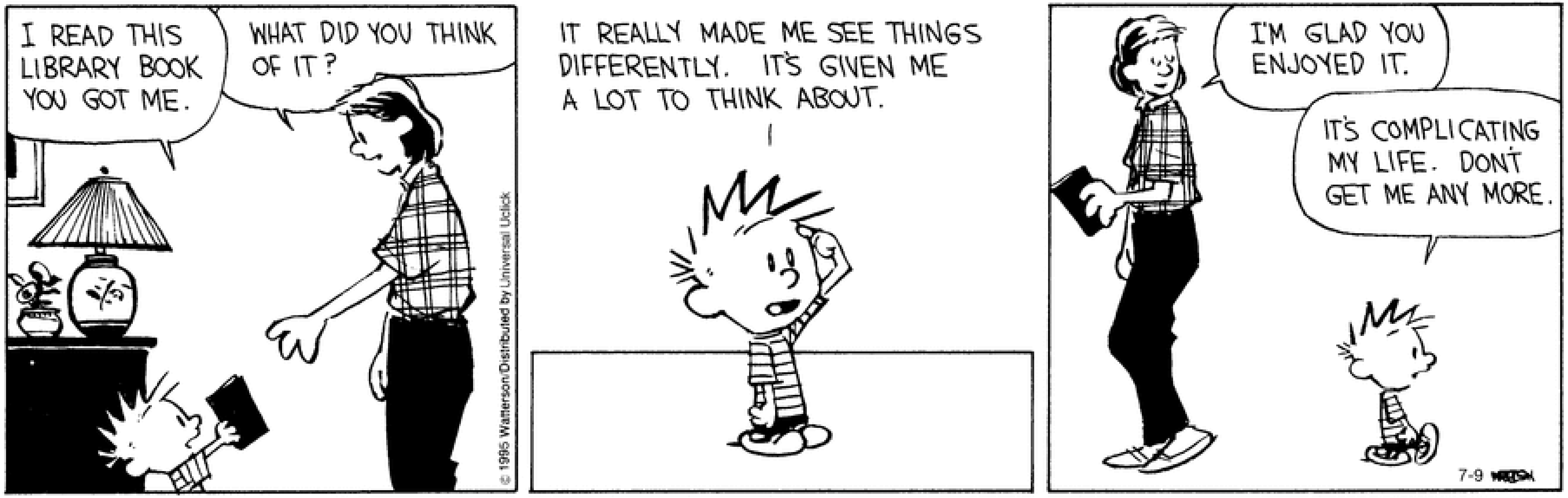
- Include a 45° degree chamfer or radius on all edges of an MEx part touching the build plate.
- For applications with small vertical bosses, add a small fillet at the base or consider inserting an off the shelf pin into a printed hole instead.
- If part needs to be split, pay attention to aligning features and design for bonding.
- Consider bolted connections only when disassembly is needed.
- Plastic threads are weaker and not suitable for multiple cycles.
- Polygon/model resolution when converting to STL is important for the final quality of the part
- Many repair tool for watertight shapes and STL check exist and for each tool there are several examples on how to deal with common issues. Some of the tools are:
- Microsoft STL repair (Netfabb),
- Meshmixer, Meshlab,
- 3D Builder

<u>Overall Comment</u>

- Splitting a model, re-orientating holes, and specifying build direction are all factors that can lower cost, speed up the printing process, and improve the strength and print quality of a design.

Questions?



Watterson, Bill. The Essential **Calvin and Hobbes**: A **Calvin and Hobbes** Treasury. , 1988. MLA (7th ed.)

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Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

CU 68: Design for Material Extrusion
SESSION 05: Case Study

23 JUNE 2021

Harry BIKAS – LMS

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

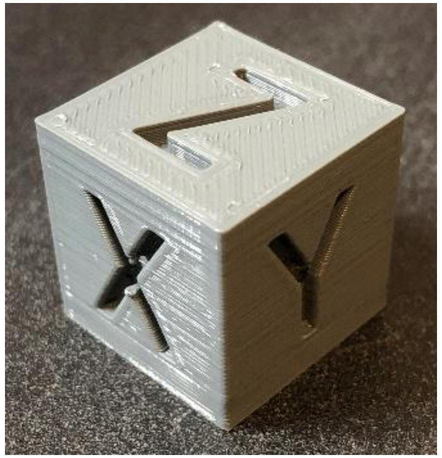
Case study: Material selection

Functional requirements

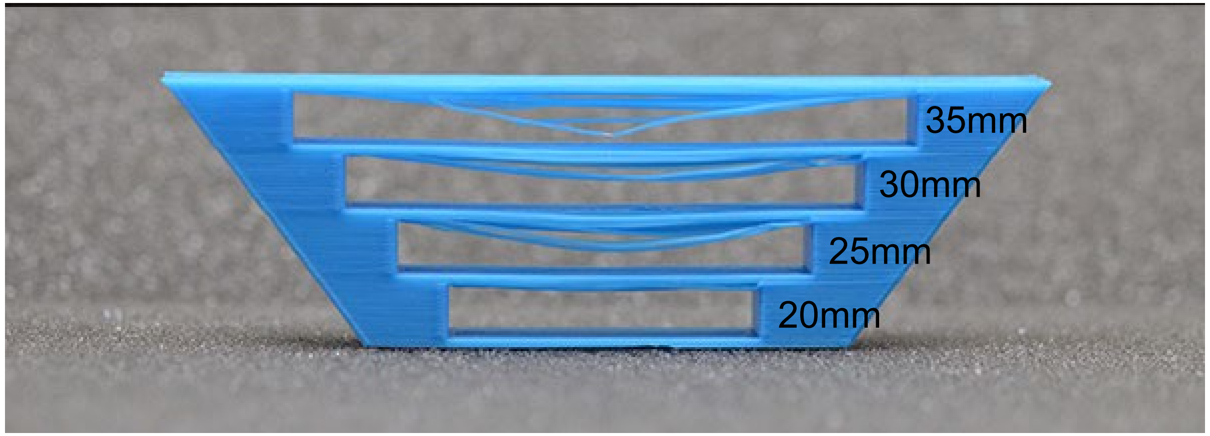
- .....
- .....

Properties	PLA	ABS	PET/PETG	Nylon	TPU/TPE	PC	PEEK
Tensile Strength (MPa)	37	27	55-75	40-50	26	55-75	90-100
Elongation	6	3.5-5	1.5	0.6-1.1	5.5-5.8	1.5	1.5
Flexural Modulus (GPa)	4	2.1-7.6	2.8-3.1	2.1	0.78	2.2-2.5	3.6
Density (g/cm^3)	1.3	1.0-1.4	1.38-1.45	1.06-1.14	1.21	1.15-1.2	1.32
Melting Point (°C)	173	N/A (amorphous)	250	268	220	100-110	343
Glass Transition Temperature (°C)	60	105	81	70	-24	147	143
Biodegradable	Yes (under conditions)	No	No	No	Yes	No	No
Recyclable	Yes	Yes	Yes	Yes	Yes	Yes	No
Price (per kg)	15-30	15-45	20-60	50-100	90-100	40-90	200-400
Printability (1-10 scale)	9	8	9	8	3	4	4
Other Notable Properties	Biocompatible	Impact Resistant	Chemically Resistant, Fatigue Resistant, Water Resistant	Flexible, Impact Resistant, Heat Resistant, Fatigue Resistant	Flexible	Impact Resistant, Heat Resistant, Fatigue Resistant	Biocompatible, Heat Resistant, Chemically Resistant, Machinable

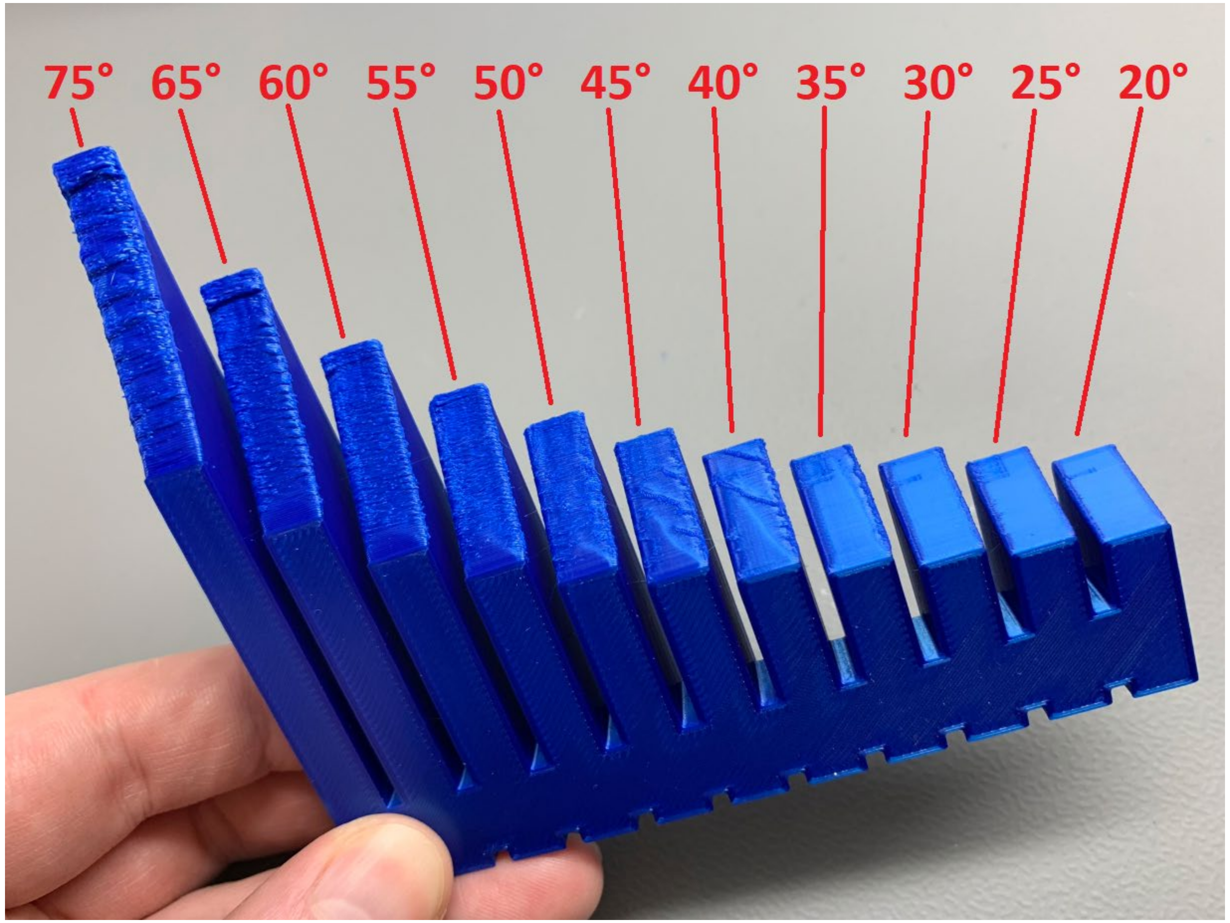
Case study: Limits determination



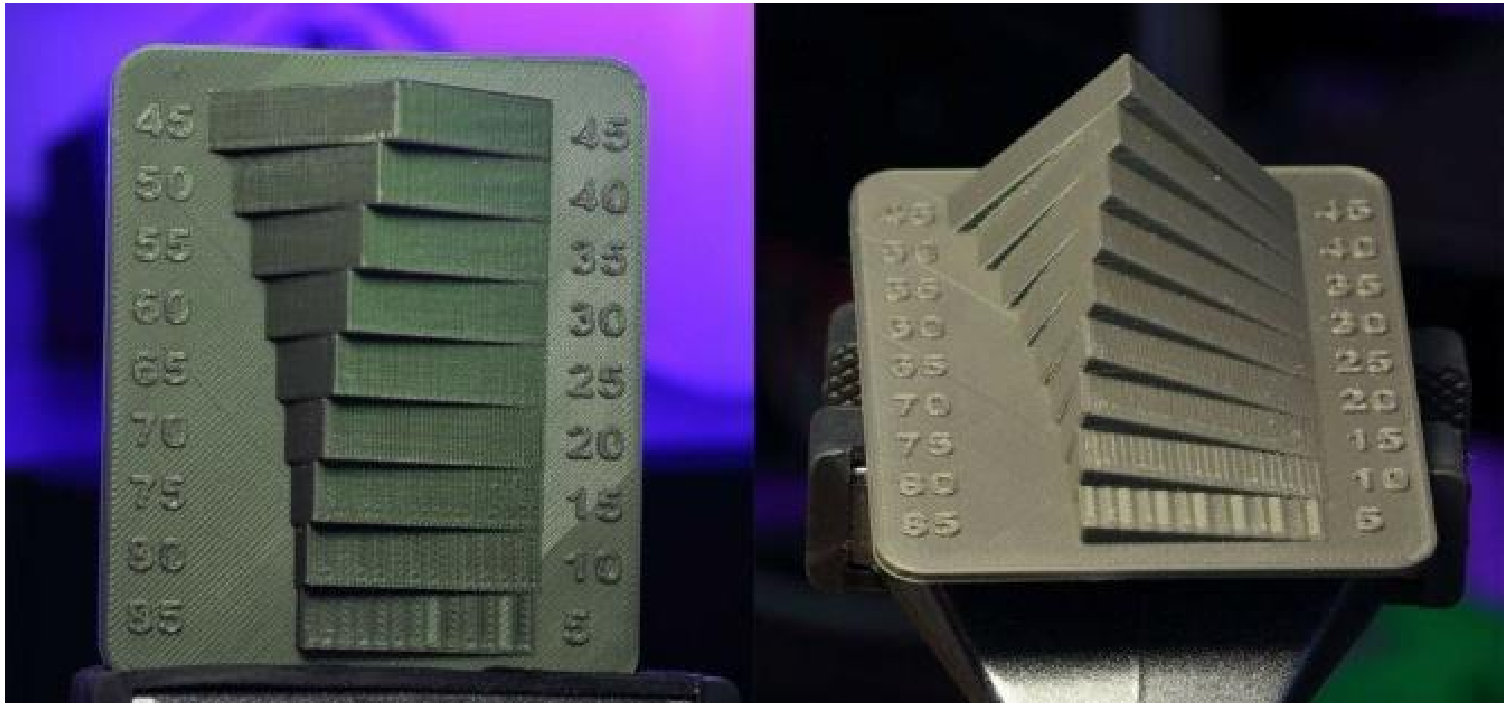
X=20.2mm
Y=20.2mm
Z=19.9mm



Case study: Limits determination



Case study: Limits determination



Case study: General design considerations

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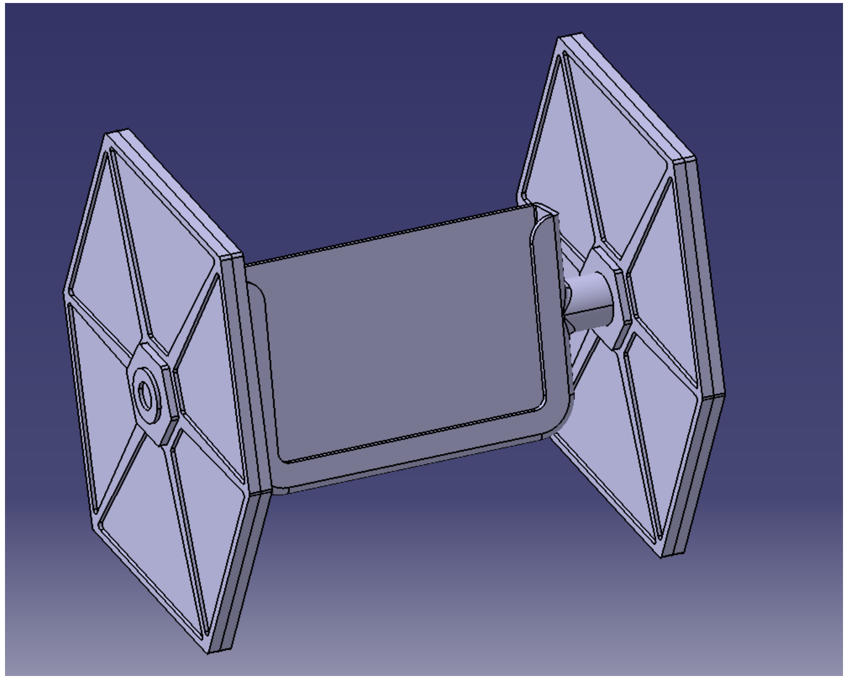
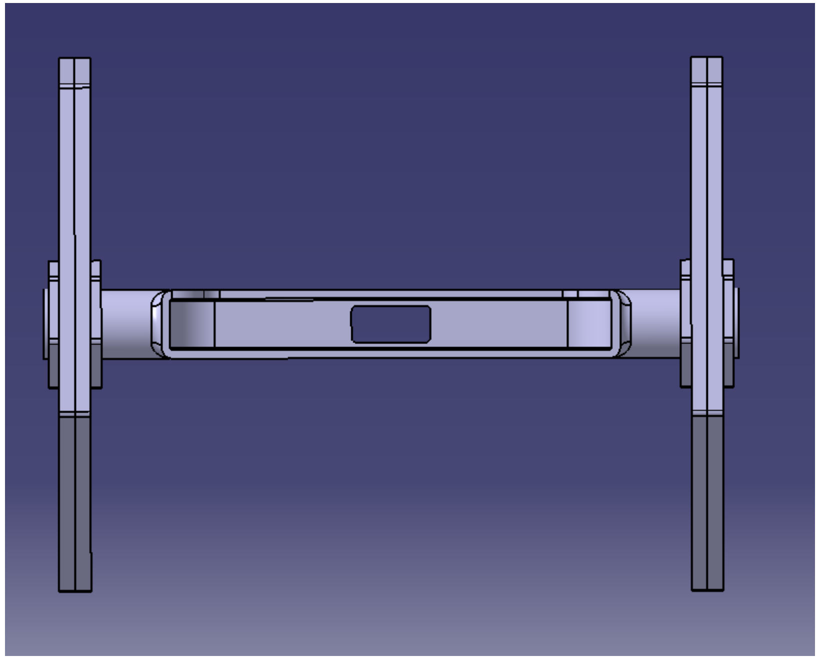
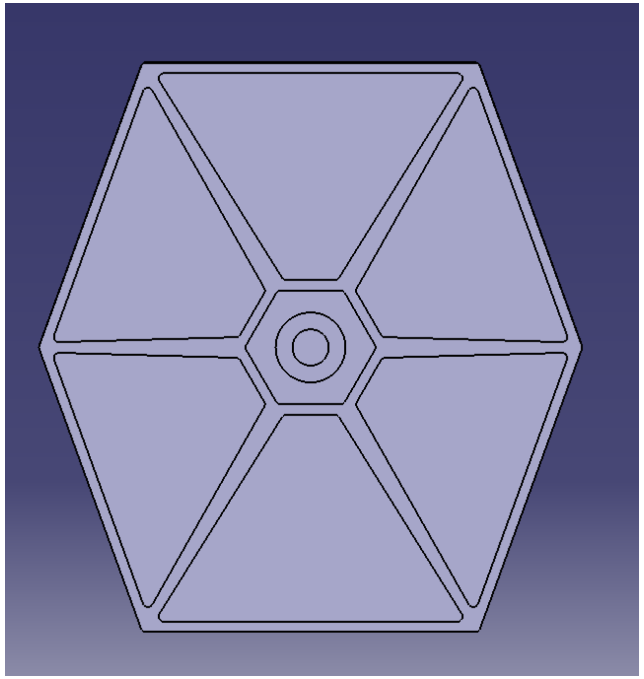
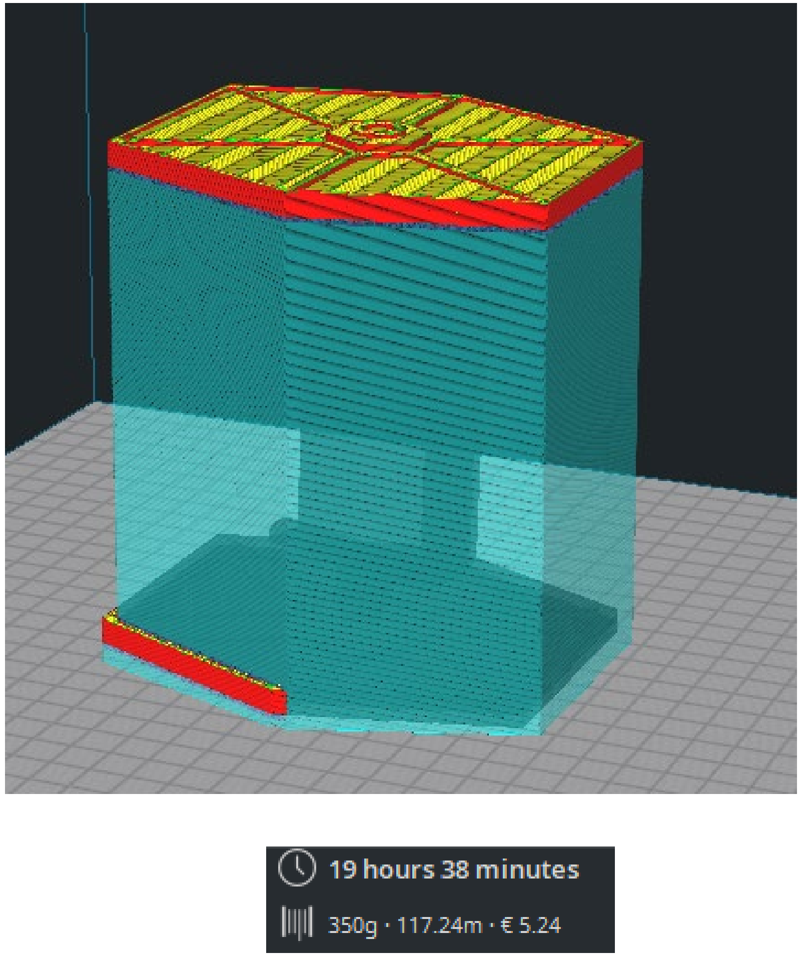
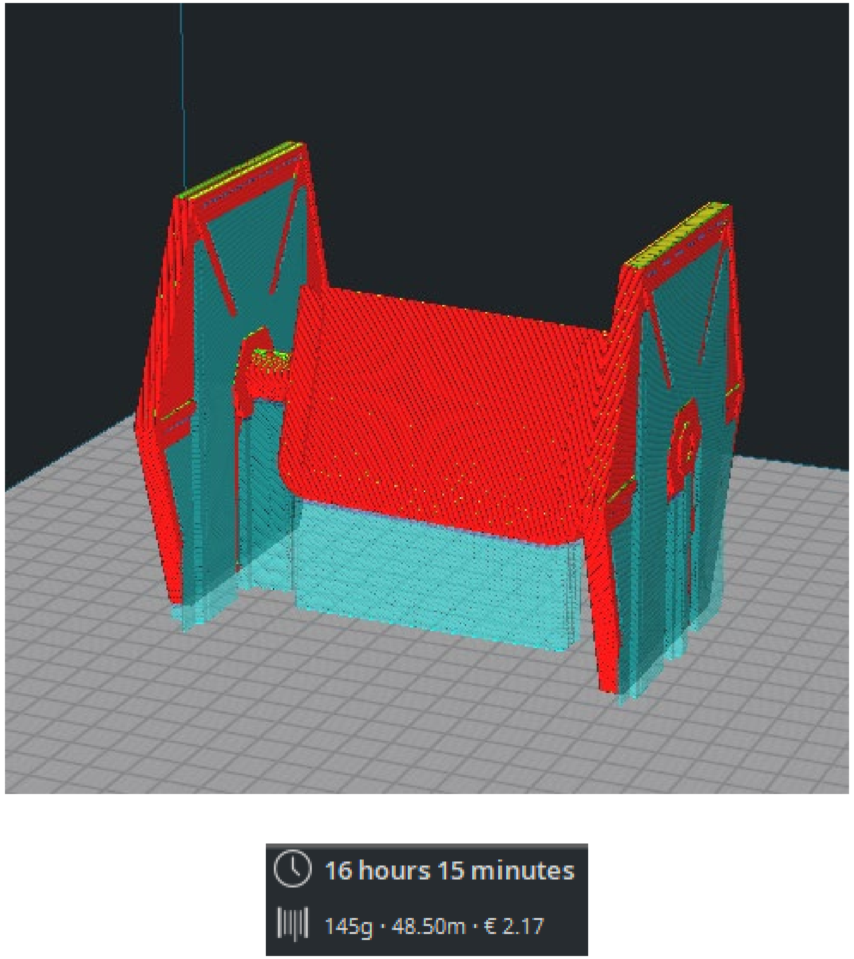






Case study: Part splitting





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Case study: Part splitting

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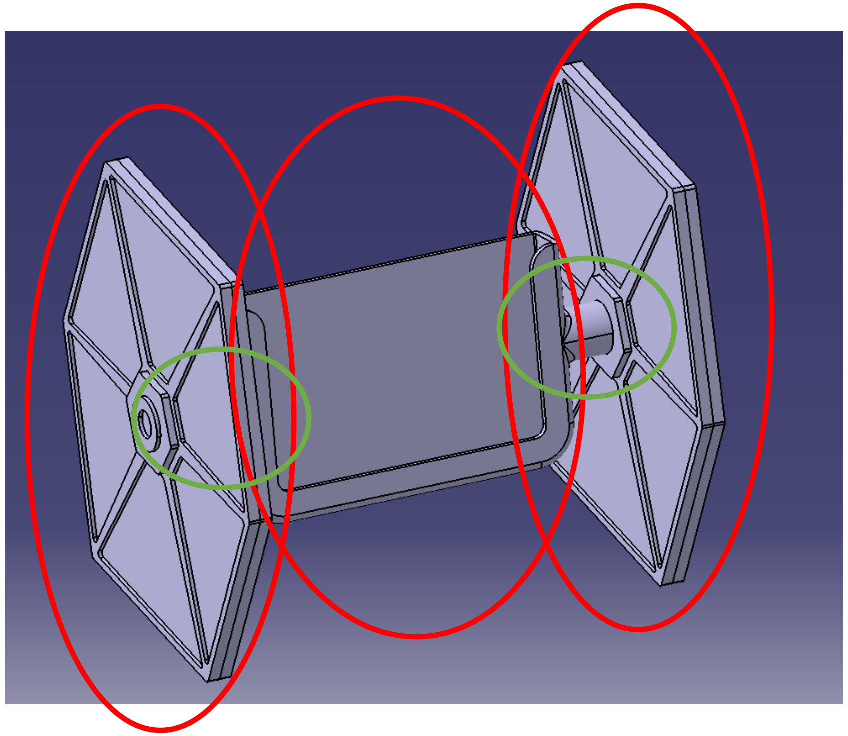

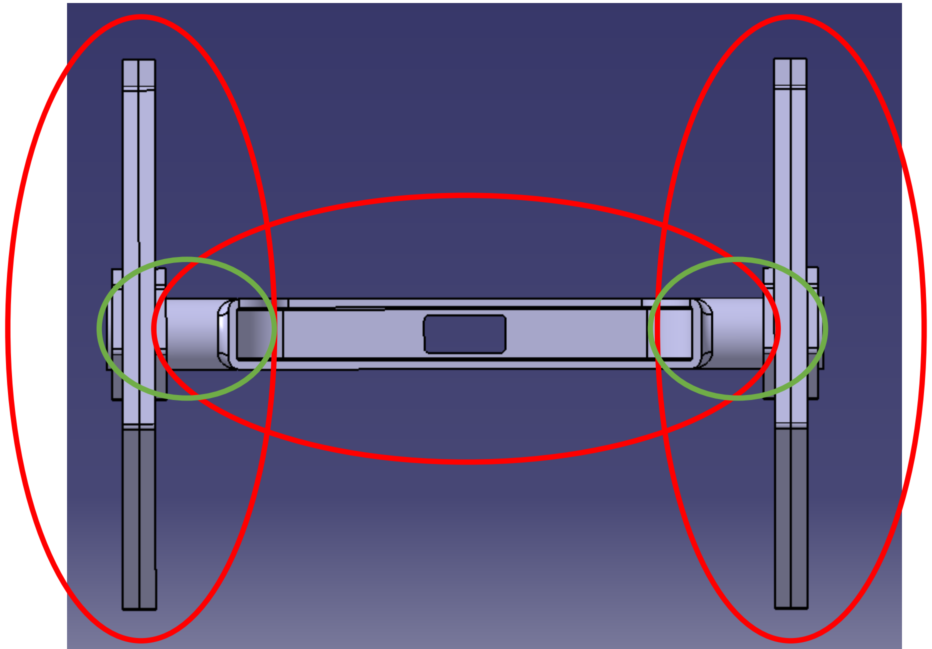

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Case study: Joining methods - Adhesive

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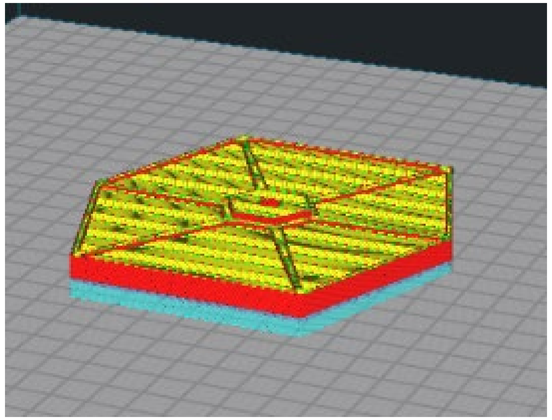
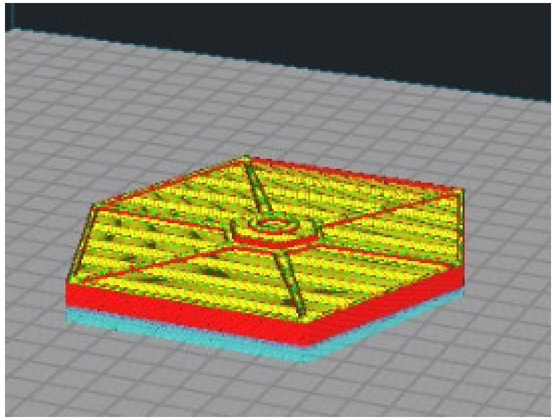
Sides can be 1-piece

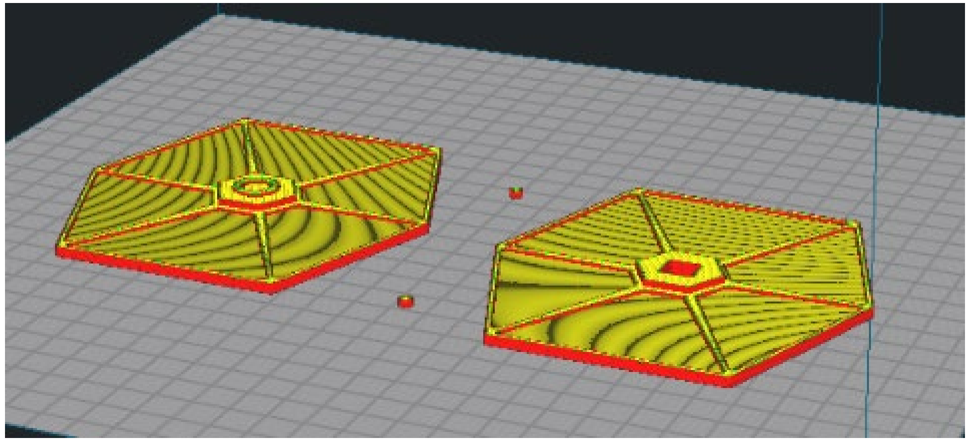
- Embossed details on both sides
- Makes sense to split in half
- Adhesive joining of two halves
- Pockets/bores printed on both halves
- Locating pins for jigging



3 hours 44 minutes
38g · 12.66m · € 0.57



3 hours 37 minutes
36g · 12.08m · € 0.54



2 hours 30 minutes
30g · 10.14m · € 0.45

Case study: Joining methods - Threads

Need to disassemble the sides from the main body

- Clip-on sides
- Threaded joints
  - Printed threads
  - Inserts (expanding, heat, nut) -> Heat due to size limitations
    - Check manufacturer specifications
    - https://www.makertechstore.com/products/heat-set-threaded-inserts-m5-threads?variant=12475431551073

Tapered Long

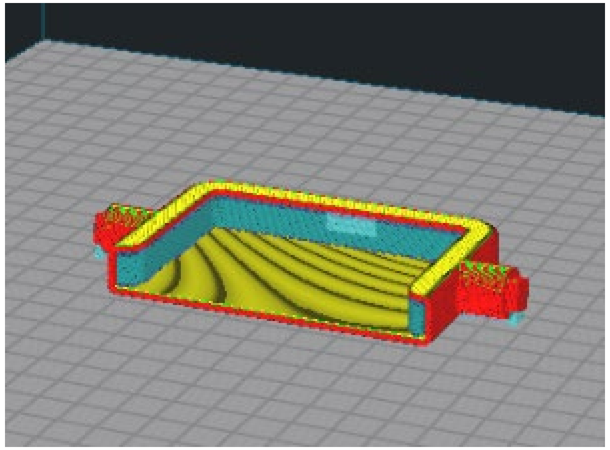
- **Maximum Insert Diameter:** 0.315" (~8mm)
- **Tapered End Diameter**: 0.303"(~7.69mm)
- **Optimum Installation Hole Size:** ~0.30" (~7.62mm) with 8° taper.
- **Length:** ~17/64" (~6.75mm)
- **Vanes:** 1
- **Material:** Brass

Case study: Part orientation

- Sides to be printed flat, with support in the alignment pin bores
- Middle part could be printed either flat or standing

Flat

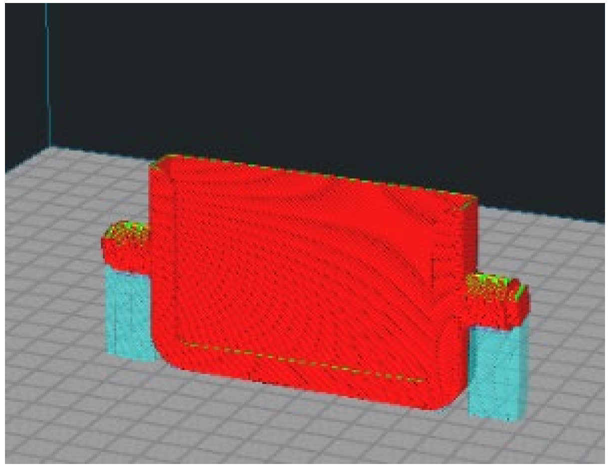
+ Surface area contact with the build plate
+ No support needed for the side bosses
- Support needed for charger hole and sides



1 hour 29 minutes
17g · 5.78m · € 0.26

Standing

+ No support needed for charger hole and sides
+ Easier to remove support as it is external
- Not enough surface area contact with the build plate



1 hour 43 minutes
19g · 6.27m · € 0.28

Case study: Print files preparation

- Usually STL conversion works fine
- If slicer faces issues, STP needs to be repaired

Microsoft STL repair

https://tools3d.azurewebsites.net/

- Login with your Microsoft account
- Upload file
- Download repaired file (*.3mf only)

Windows 3D Builder

- Open -> Load Object
- Top menu -> Import Model
- Popup “One or more objects are invalidly defined. Click here to repair.”
- Edit -> Simplify to reduce STL size
- File -> Save as

Case study: Costing

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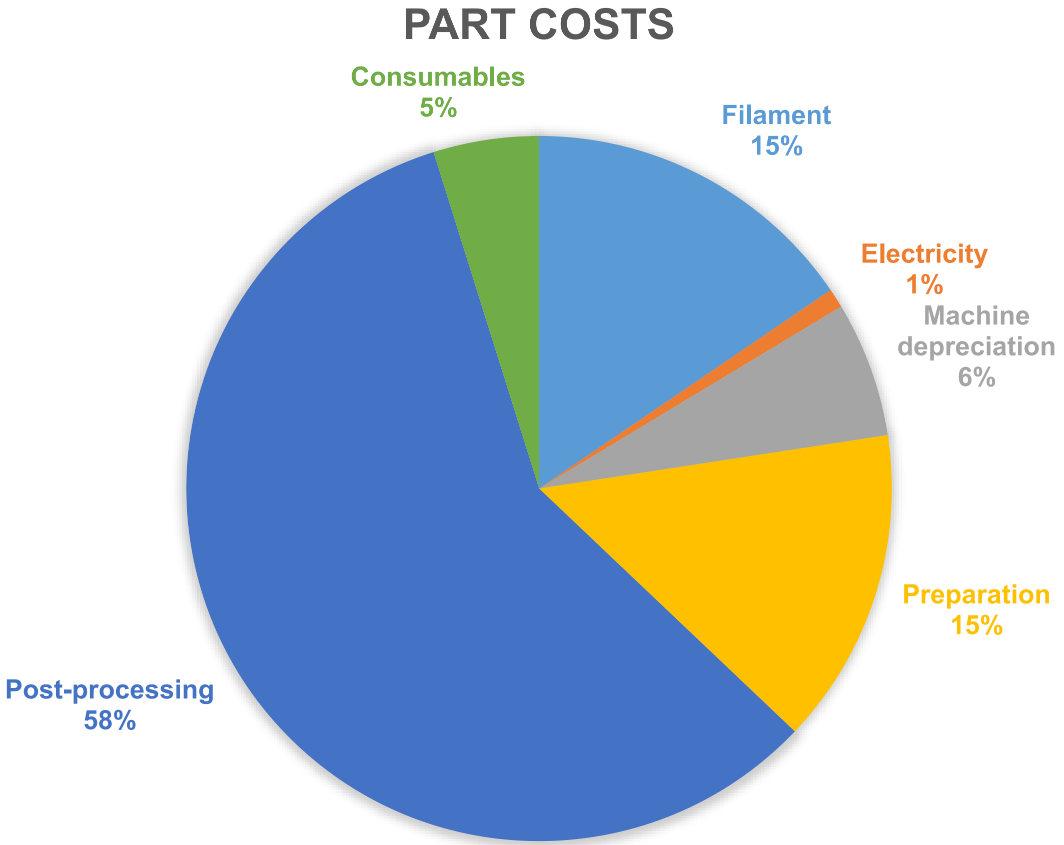
Cost categories

- Material cost (incl. support & failed prints)
- Machine depreciation
- Electricity
- Consumables
- Labor
  - Model preparation (fixing etc.)
  - Slicing
  - Material & printer setup
  - Job removal
  - Support removal
  - Post-processing



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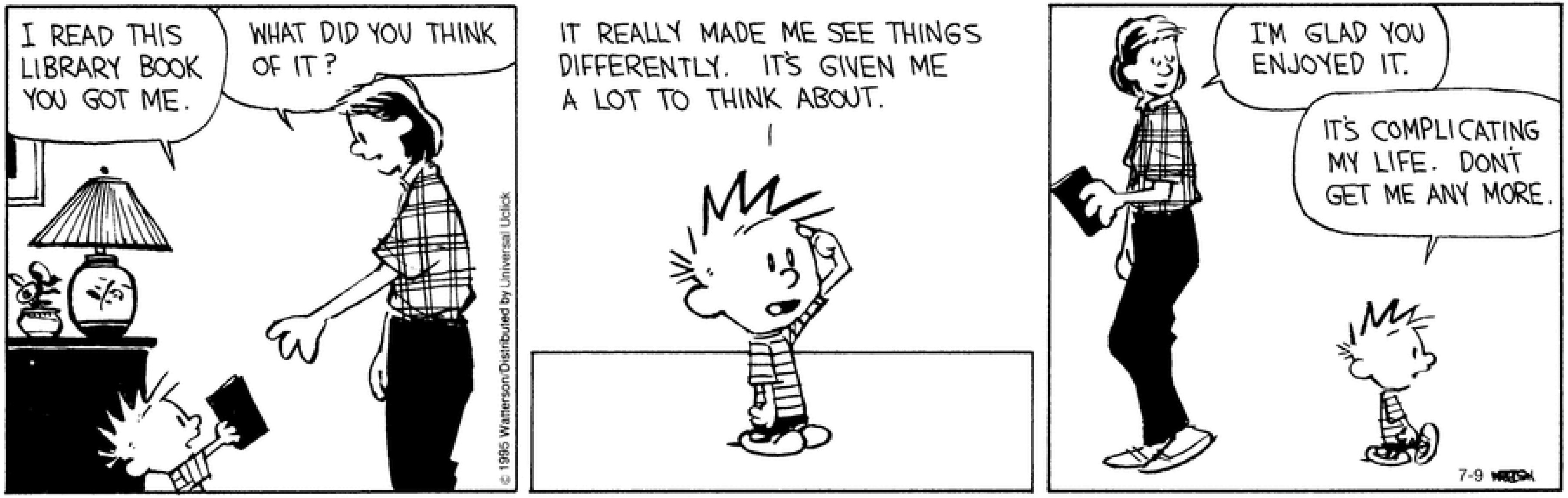
Questions?



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