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How to think like a 3D designer:
A practical guide to additive manufacturing

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CEO, NVBOTS

NVBOTS

AJ Perez CEO

- BS in Mechanical Engineering and Masters of Engineering in Manufacturing from MIT
- Co-developed and lectures Additive Manufacturing class at MIT
- Guest lectures at MIT, Stanford, BNU, KIT, and BU
- Boston Globe 25 Innovators Under 25
- Jerome Lemelson inventor fellow

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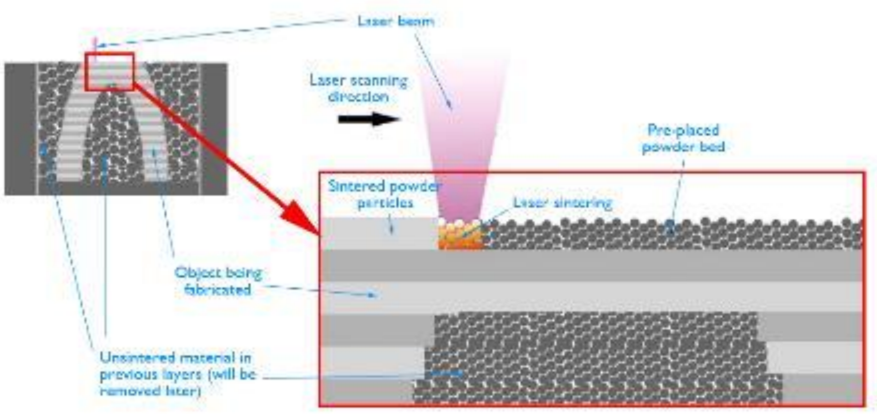
Agenda

- **Introduction to additive manufacturing**
- Overview of conventional DFMA
- What is DFAM and how is it different?
- Design rules and guidelines by manufacturing process
- Case studies in DFAM
- AM process characterization
- Future work in AM process optimization

Selective laser sintering (SLS)



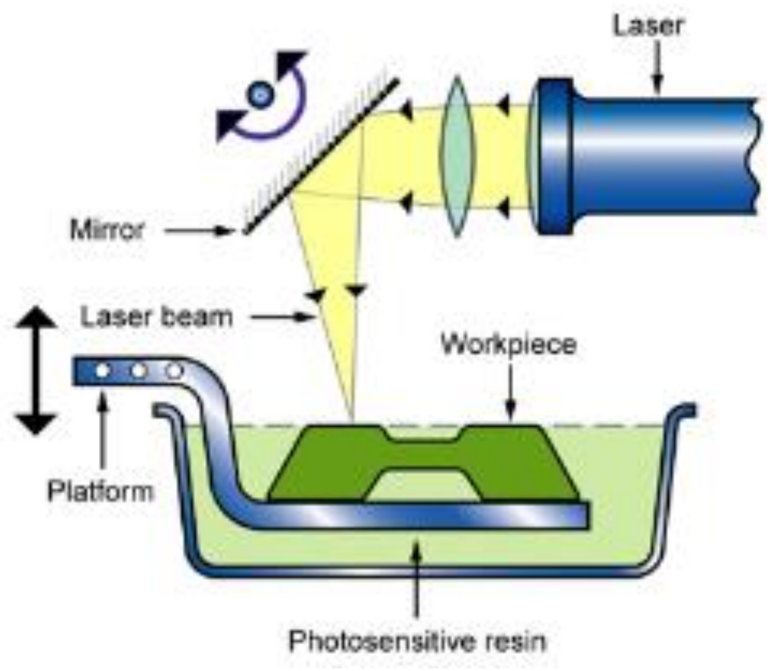
OVERVIEW

Selective Laser Sintering (SLS) is an additive manufacturing technique that uses a laser as the power source to sinter powdered material (typically metal), aiming the laser automatically at points in space defined by a 3D model, binding the material together to create a solid structure.

MATERIAL CAPABILITIES

- Stainless Steel
- Cobalt Chrome
- Titanium
- Inco
- Maraging Steel
- Aluminium

Stereolithography (SLA) / Continuous liquid interface production (CLIP)



OVERVIEW

Stereolithography (SLA) is an additive manufacturing process which employs a vat of liquid ultraviolet curable photopolymer "resin" and an ultraviolet laser to build parts' layers one at a time. For each layer, the laser beam traces a cross-section of the part pattern on the surface of the liquid resin. Exposure to the ultraviolet laser light cures and solidifies the pattern traced on the resin and joins it to the layer below. CLIP is a high speed SLA process which leverages DLP technology to parallelize SLA.

MATERIAL CAPABILITIES

- Liquid polymer resin

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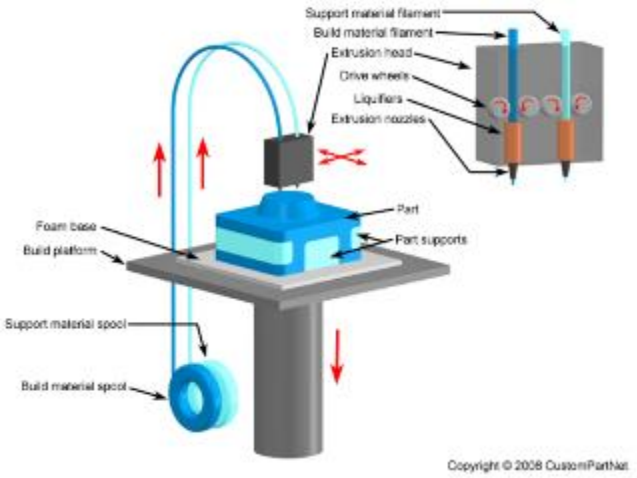
Fused deposition modeling (FDM)



OVERVIEW

Fused Deposition Modeling (FDM) works on an "additive" principle by laying down material in layers; a plastic filament or metal wire is unwound from a coil and supplies material to produce a part, by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle.

MATERIAL CAPABILITIES

- Acrylonitrile Butadiene Styrene (ABS)
- Polylactic acid (PLA)
- Polycarbonate (PC)
- Polyamide (PA)
- Polystyrene (PS)
- Lignin
- Rubber

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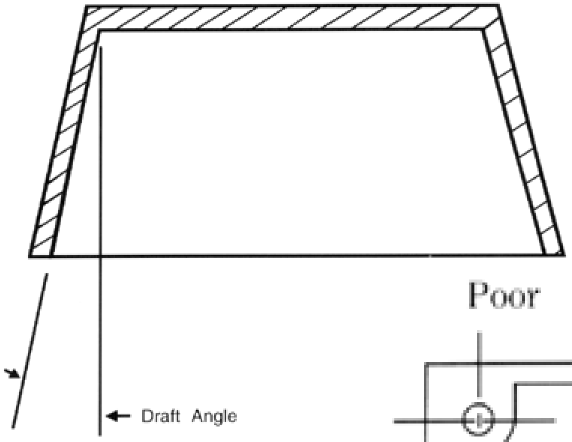
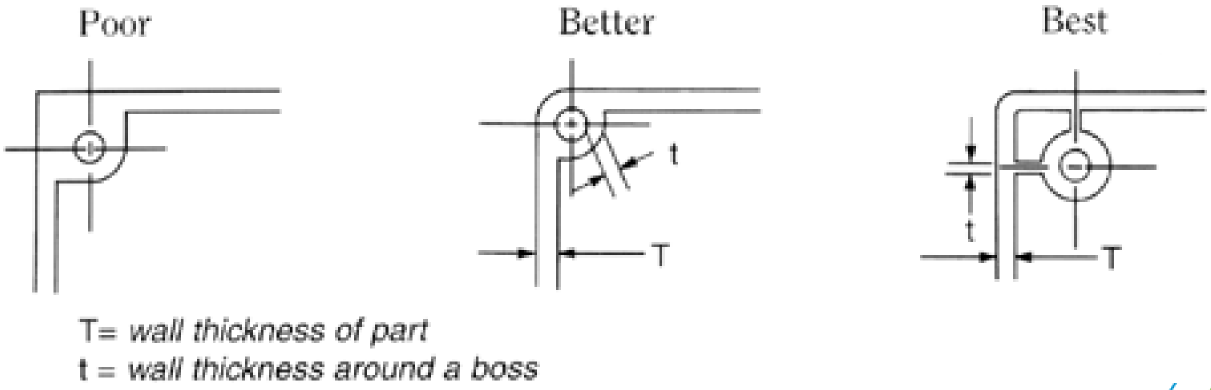
Conventional Design for Manufacturing and Assembly (DFMA) from Boothroyd

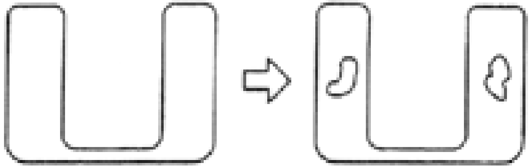
- Use modular subassemblies
- Use as many multifunctional parts as possible
- Use self-selecting features
- Minimize number and types of parts for assembly
- Minimize the use of fasteners
- Minimize operations and process steps
- Minimize part reorientation
- Avoid difficult to handle components
- Avoid special tooling/test equipment

Manufacture of molds and part ejection limit possible geometry

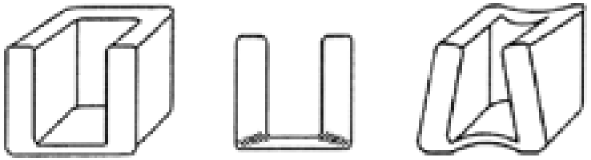




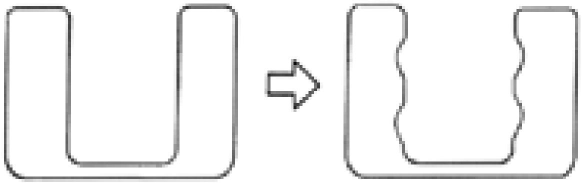
Designers must avoid certain features that cause common defects



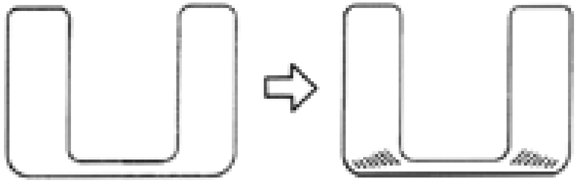
Voids



Warping

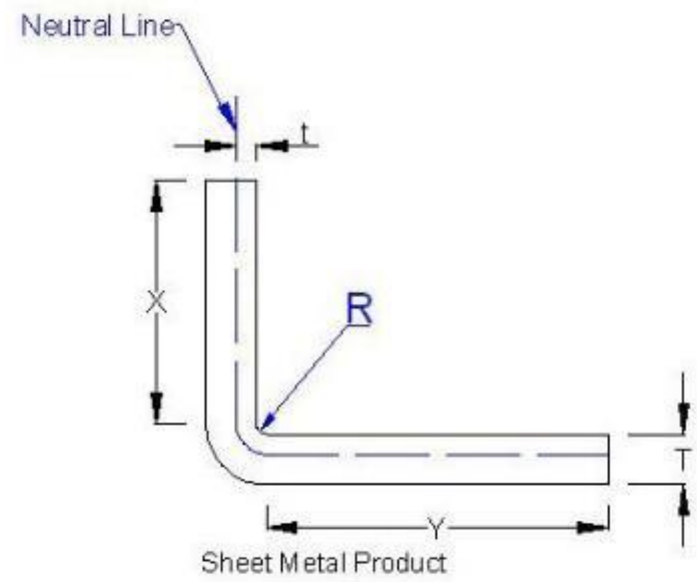


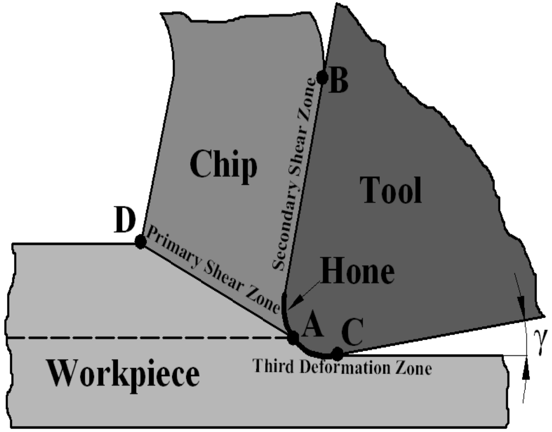
Sink Marks



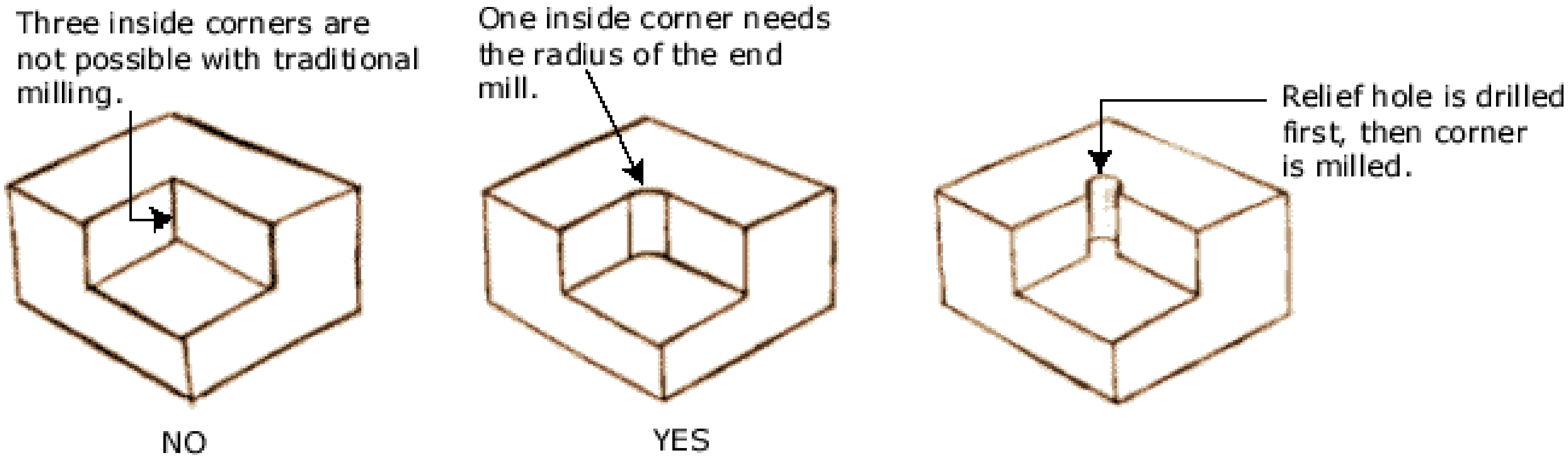
Internal Stresses

Sheet metal and turning minimum feature size determined by radius of tool





Milling internal feature geometry limited by endmill radius



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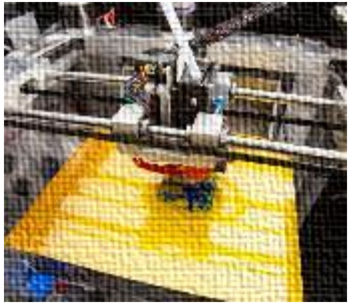
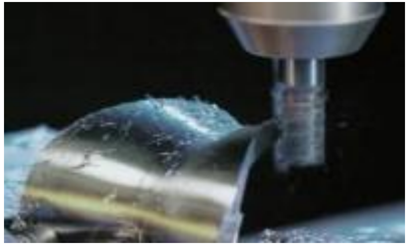
DFAM vs conventional DFM

Additive



- Reduced fixturing
- Internal Features
- Undercuts

Subtractive



- Fixtures Required
- No Internal Features

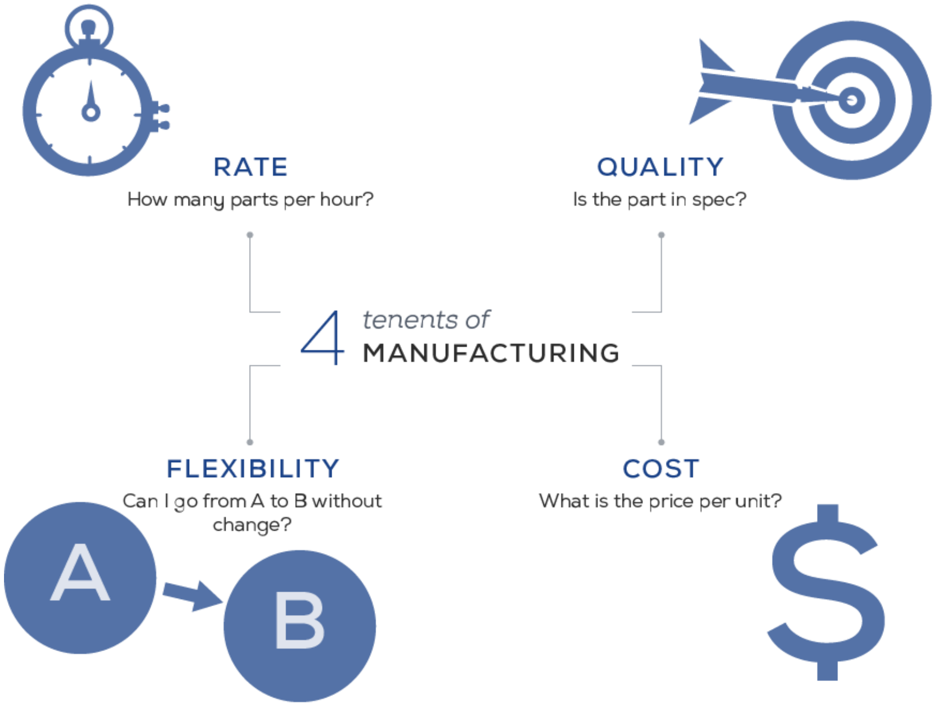
Optimization Problem

Minimize amount of material **laid down each layer;** maximize strength to weight

Optimization Problem

Minimize amount of material **removed from stock**

Why does DFAM matter and why should we care?



Framework to think about DFAM: Perez, Thomas, Feldmann

- Process Limitations
  - Minimum Feature Size
  - Limiting Process Parameters
  - Software Limitations
- Materials
  - Material Characteristics
  - Mechanical Properties of the Part
- Geometric Design
  - Macrostructure
  - Orientation
  - Support Structures

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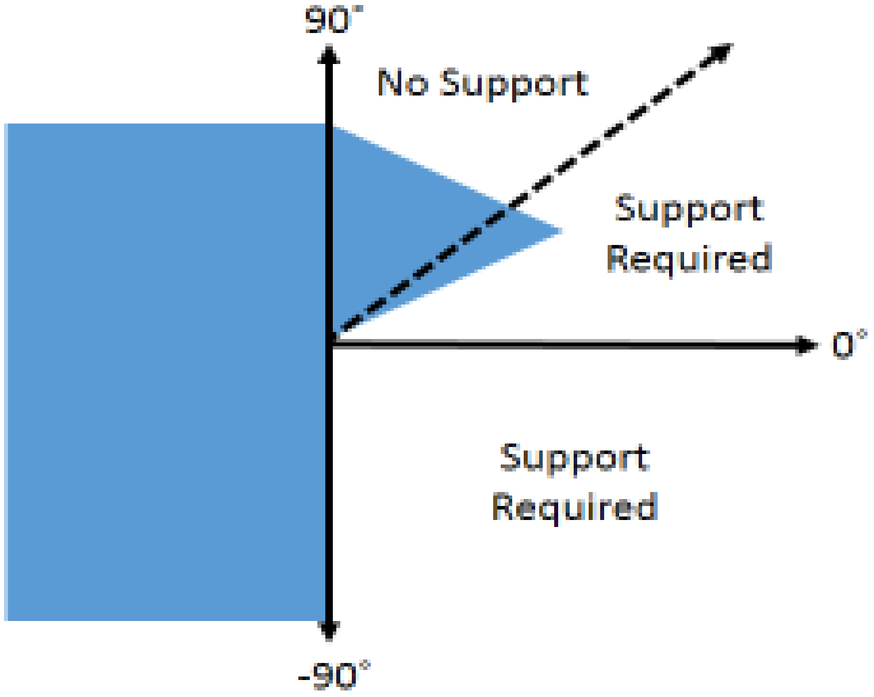
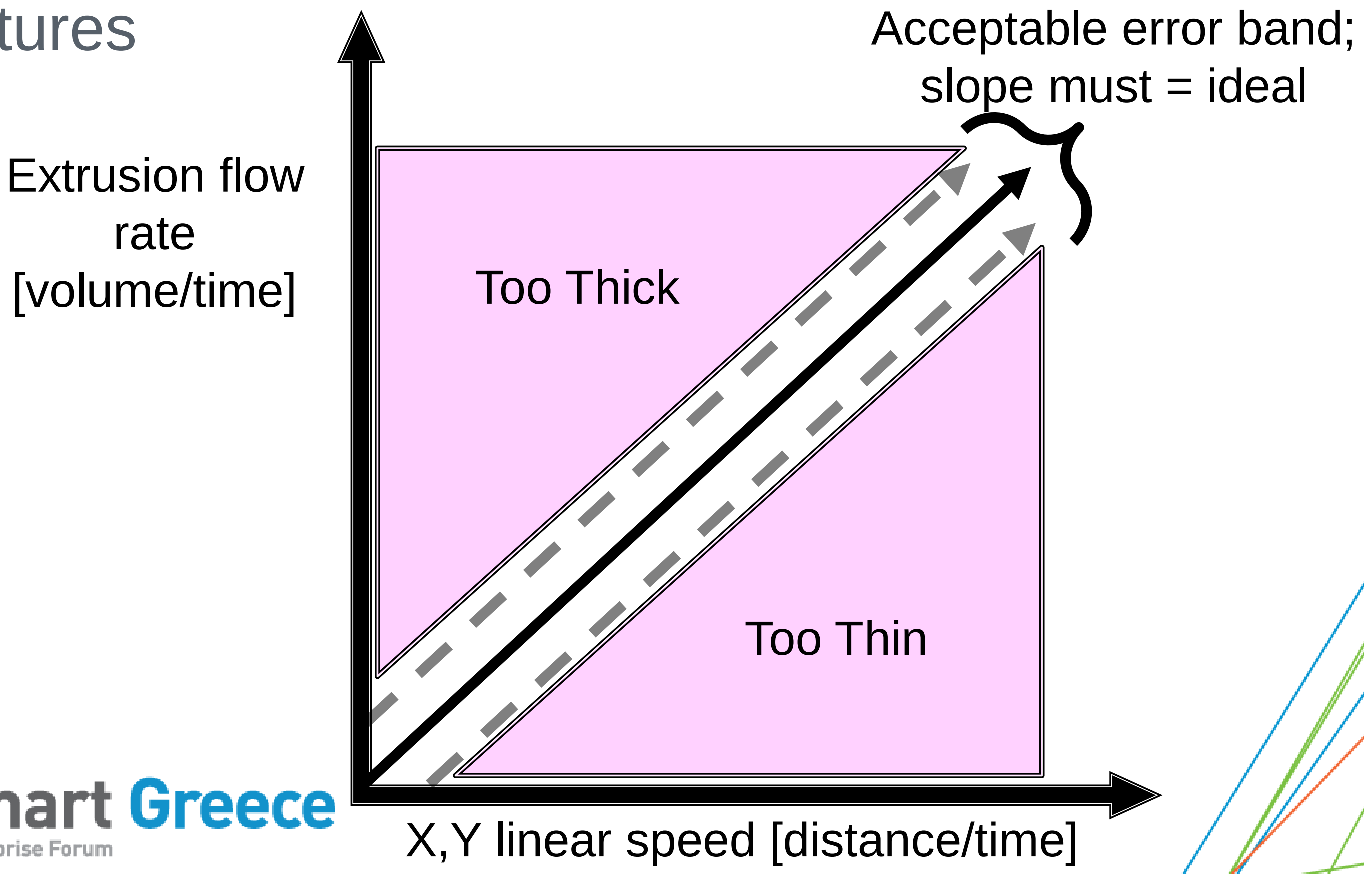
FDM & SLS Support structure 45 degree "rule of thumb"



FDM process quality must be carefully controlled if you want precise features



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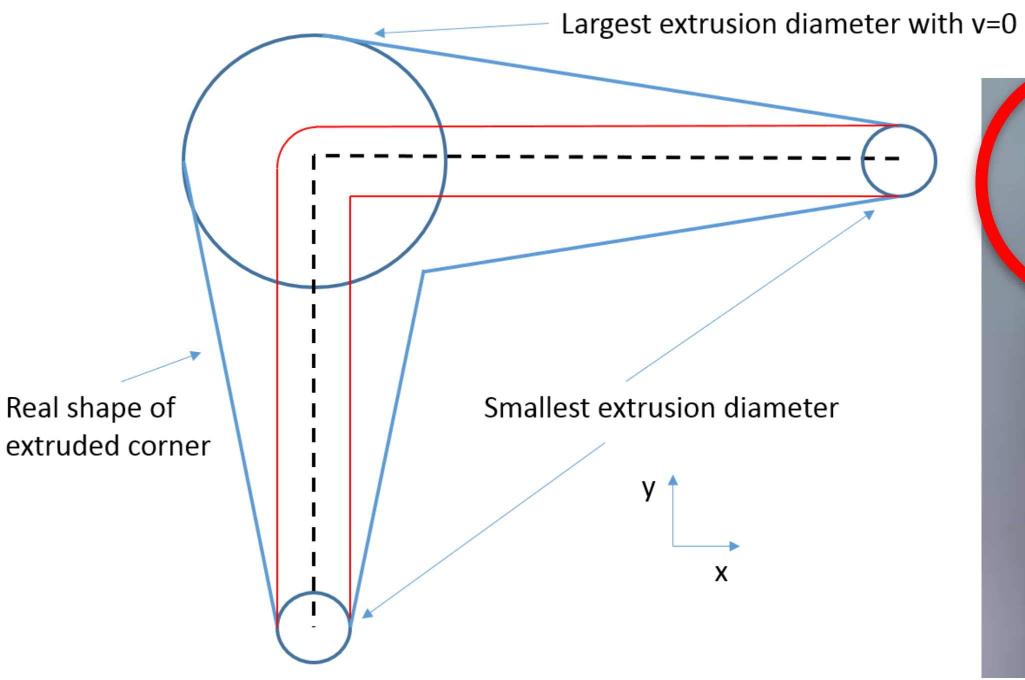
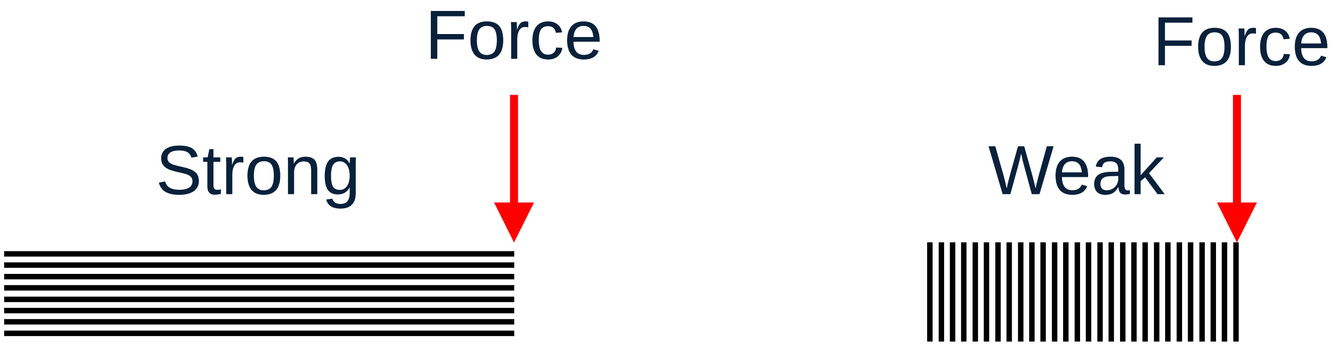
Real world example of FDM extrusion control problem



Stratasys Mojo

Print orientation affects bulk and local mechanical properties



High level cross-process DFAM comparison

Process type	Process resolution	Support type	Post processing	Process limiting variable(s)	Overhangs
SLA	~25μm	Break away	UV curing; thermal	Energy flux on mirror	45 degrees
FDM	~150μm	Break away or dissolvable	Surface treatments; Infusion	Extrudate diameter	45 degrees
SLS	~25μm	Powder	Thermal; Infusion	Laser spot size	Supported
Ink Jet	~20μm	Break away	UV curing	Minimum droplet size	45 degrees
Powder binding	~25μm	Powder	Infusion	Powder size; droplet size	Supported

Designers must consider the effects that post processing have on cycle time and dimensional accuracy

- **Removal of support material**
  - Ultrasonic water bath
- **Surface finish**
  - Bead blasting
  - Mass finishing
  - Finishing Touch smoothing-cool and cut
  - Vapor polishing
  - Lapping
- **Sealing/coating**
  - Electroplating
  - Painting
  - Epoxy infiltration
  - Dipping
- **Assembly of sections**
  - Bonding and gluing

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DFAM case study: General Electric improves product performance and reduces supply chain costs

GE Turbine Fuel Injectors

	CONVENTIONAL		ADDITIVE
	20 Components	➡	**1 Components**
	19 Assembly	➡	**0 Assembly**
	39 QC Steps	➡	**1 QC Steps**

~25% weight reduction
~8% gain in fuel efficiency

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DFAM case study: NASA reduces part count >98%

NASA Turbine Fuel Injectors

CONVENTIONAL		ADDITIVE
115 Components	→	**2 Components**
114 Assembly	→	**1 Assembly**
229 QC Steps	→	**3 QC Steps**

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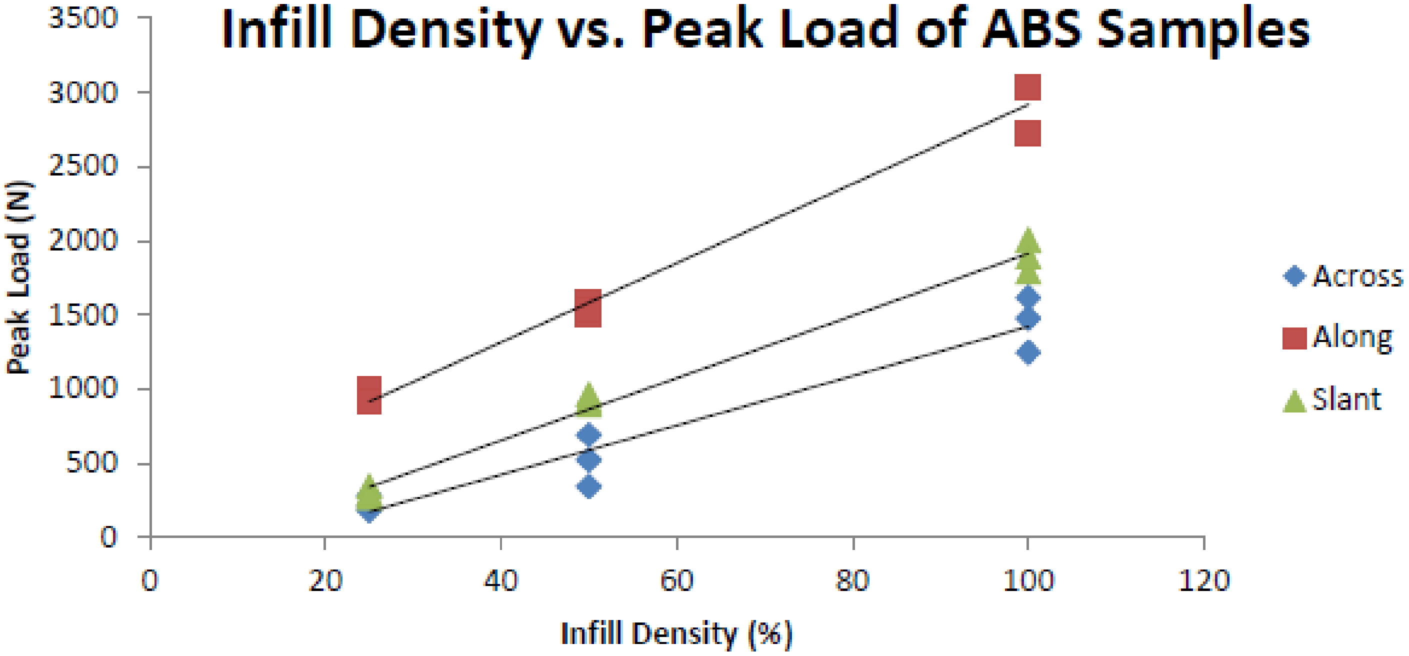
Recent work done at MIT to characterize FDM

- Effect of print parameters on dimensional accuracy, weight, and print time are a non-linear function.
  - Perez et al.
- Characterizing tensile loading responses of 3D printed samples.
  - Christopher Haid
- Force required to remove part from FDM machine.
  - Mateo Pena Doll

Effect of infill density and print orientation on peak tensile load performance of ABS



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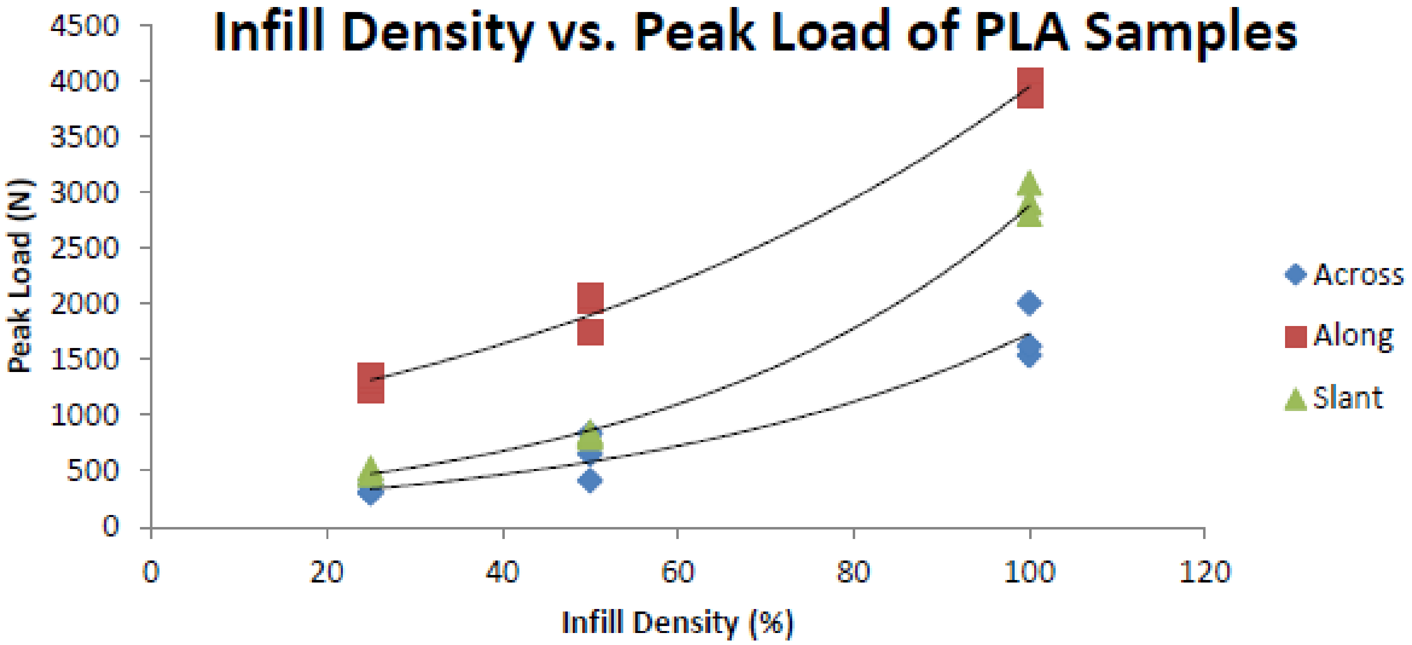
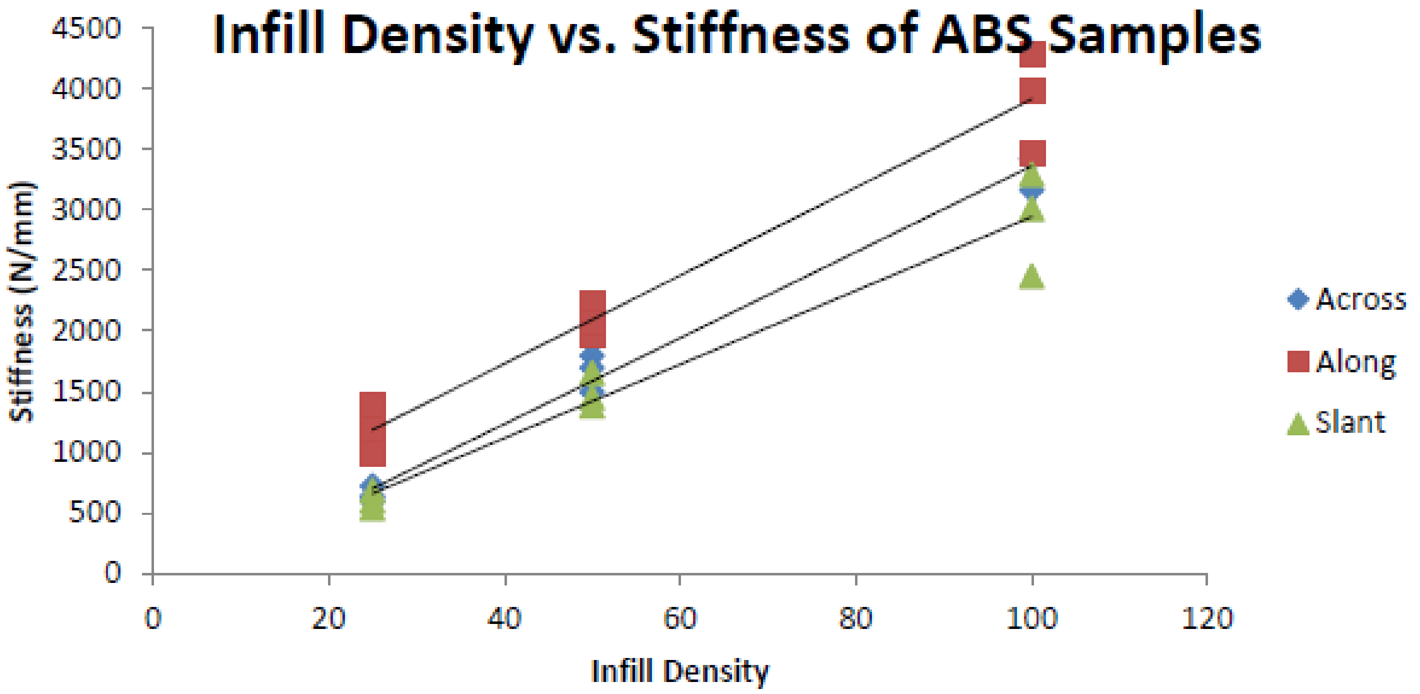
Haid, Christopher. Characterizing tensile loading responses of 3D printed samples. MIT thesis.

Effect of infill density and print orientation on peak tensile load performance of PLA



Haid, Christopher. Characterizing tensile loading responses of 3D printed samples. MIT thesis.

Effect of infill density and print orientation on stiffness of ABS



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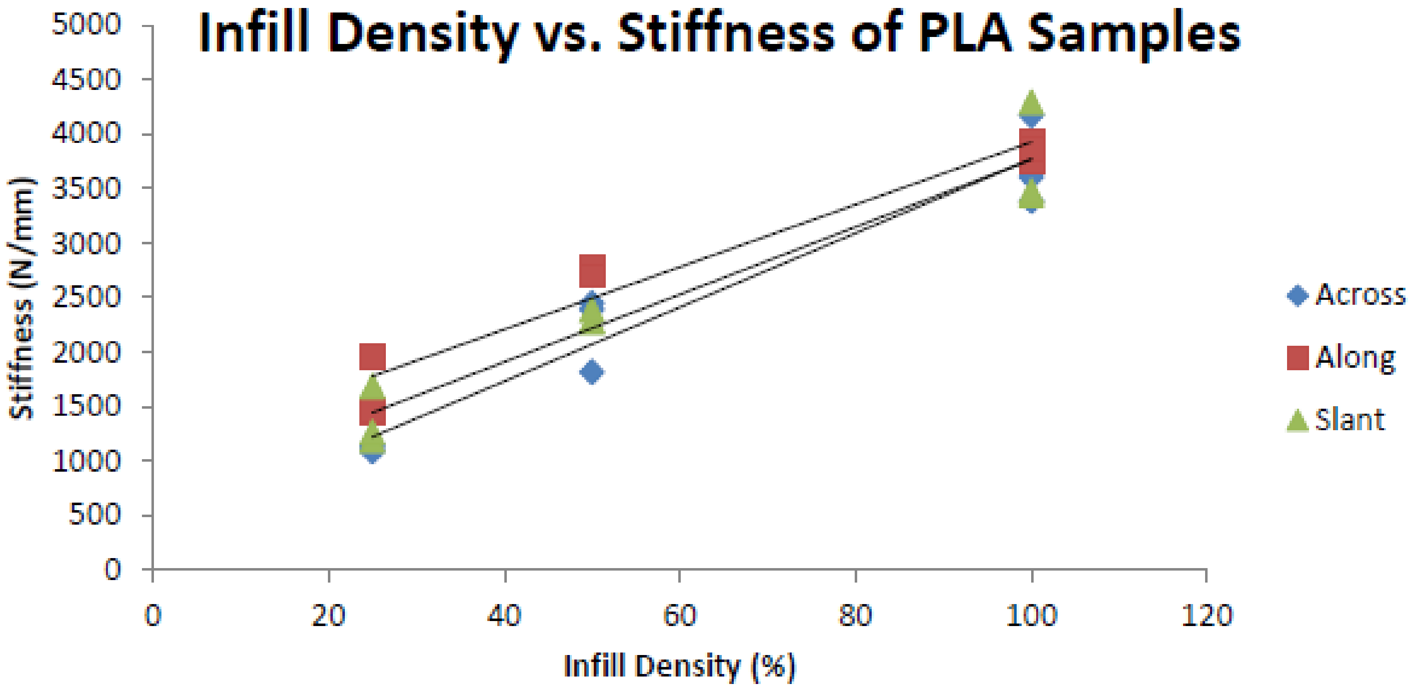

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Haid, Christopher. Characterizing tensile loading responses of 3D printed samples. MIT thesis.

Effect of print bed temp. on force required to remove part

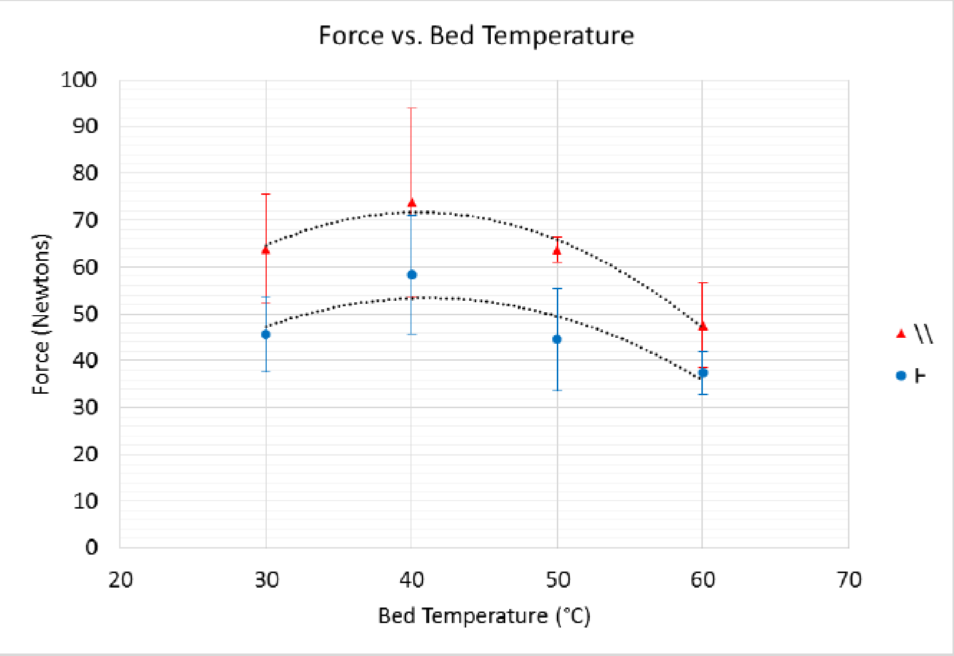

Figure 11: Data for the printing bed temperature test plotted against the resulting force. The bed temperature was varied from 60 to 30°C in increments of 10°. The confidence intervals are of 5% significance.

Pena Doll, Mateo. Part removal of 3D printed parts. MIT thesis.

Effect of extrusion temp. on force required to remove part

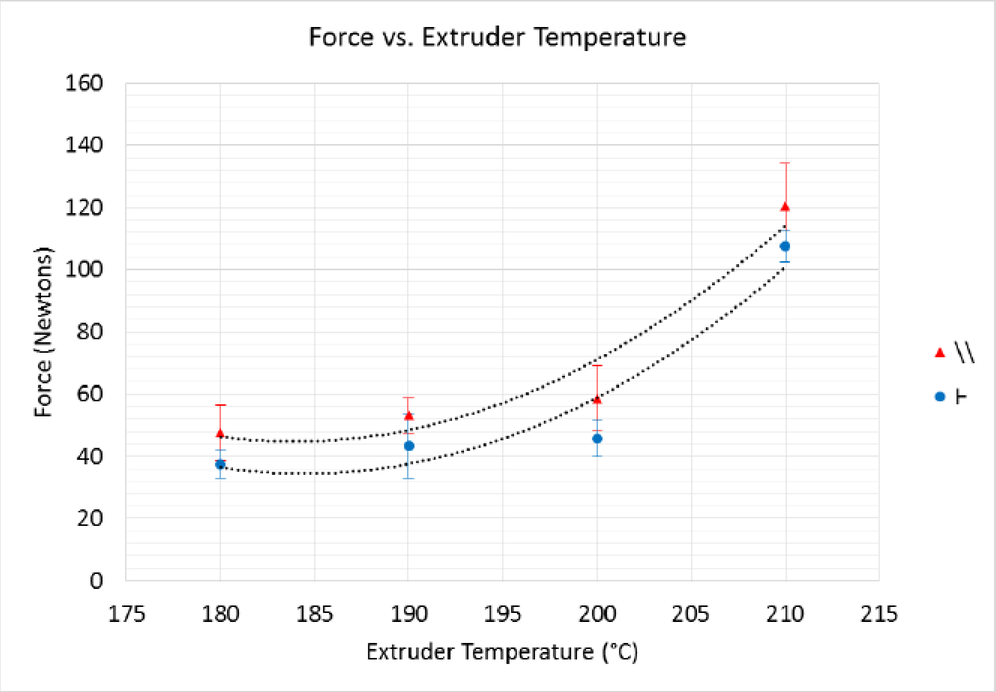

Figure 12: Data for the printing extruder temperature test plotted against the resulting force. The extruder temperature was varied from 180 to 210°C in increments of 10°.

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Pena Doll, Mateo. Part removal of 3D printed parts. MIT thesis.

Effect of first layer thickness on force required to remove part

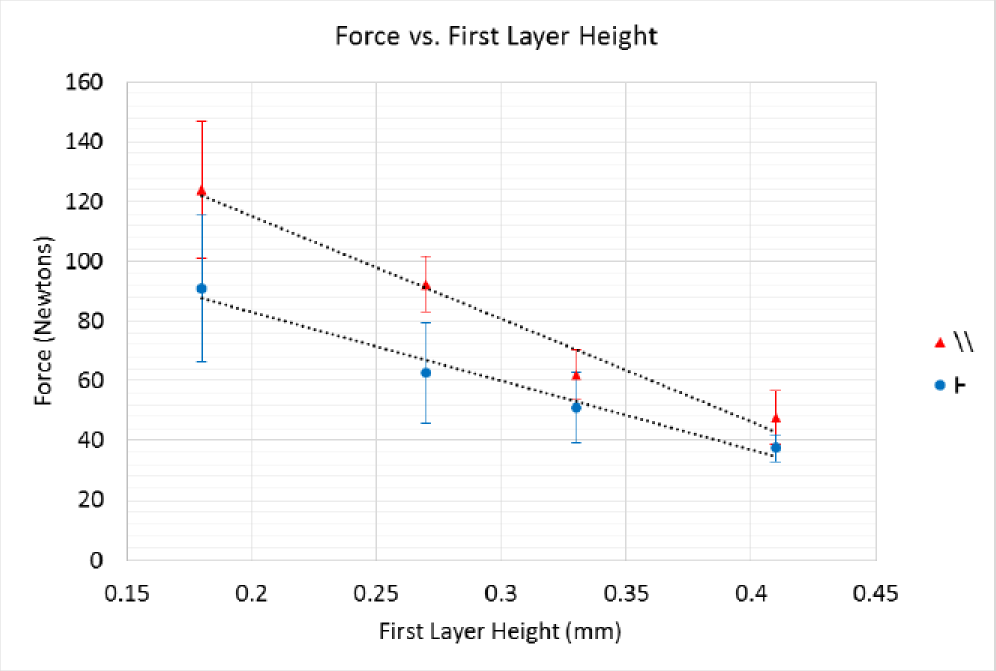

Figure 13: Data for the first layer height test plotted against the resulting removal force. The first layer height was varied from 0.18 ± 0.01 to 0.42 ± 0.02 mm.

Pena Doll, Mateo. Part removal of 3D printed parts. MIT thesis.

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3D printing is an ecosystem, not just hardware

- ◉ SELECT A PART
- ○ PRINT PREVIEW & CLOUD SLICING
- ○ QUEUE MANAGEMENT & CONTROL
- ○ AUTOMATED PRINTING
- ○ USE 3D PRINTED CURRICULUM

- More than 100 expert approved lesson plans
- More than 850 3D models

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NVBOTS has the first cloud 3D printer system

- ○ SELECT A PART
- ◉ **PRINT PREVIEW & CLOUD SLICING**
- ○ QUEUE MANAGEMENT & CONTROL
- ○ AUTOMATED PRINTING
- ○ USE 3D PRINTED CURRICULUM

- First cloud 3D print preview
- Cloud based 3D printer drivers
- Enables mobile 3D printing

NVBOTS has the only multi-user 3D printer

- SELECT A PART
- PRINT PREVIEW & CLOUD SLICING
- **QUEUE MANAGEMENT & CONTROL**
- AUTOMATED PRINTING
- USE 3D PRINTED CURRICULUM

- Verify every part is approved by admin
- Simple drag-and-drop control

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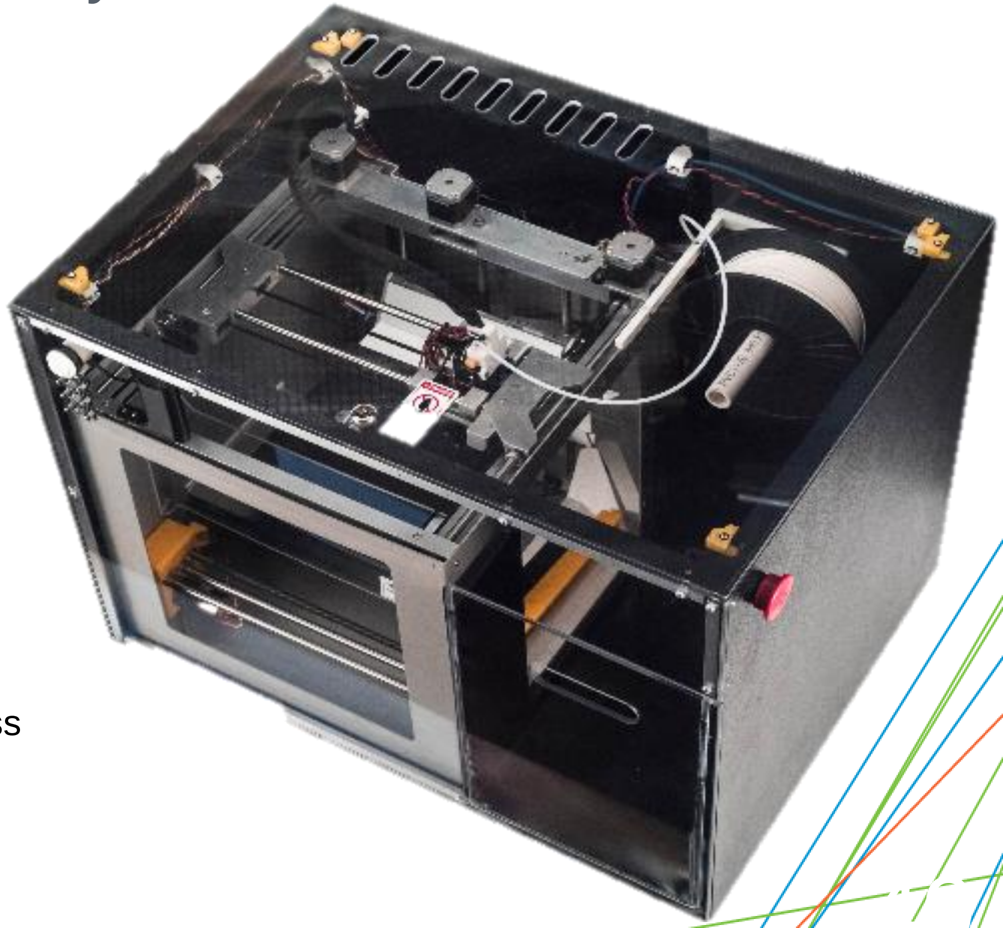
Easily 3D print 24x7 from any device

- ○ SELECT A PART
- ○ PRINT PREVIEW & CLOUD SLICING
- ○ QUEUE MANAGEMENT & CONTROL
- ◉ **AUTOMATED PRINTING**
- ○ USE 3D PRINTED CURRICULUM



- Watch print from anywhere
- First automated part removal
- Trade secret manufacturing process

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Use the 3D object and lesson plan to make STEAM hands on!

- ○ SELECT A PART
- ○ PRINT PREVIEW & CLOUD SLICING
- ○ QUEUE MANAGEMENT & CONTROL
- ○ AUTOMATED PRINTING
- ◉ **USE 3D PRINTED CURRICULUM**

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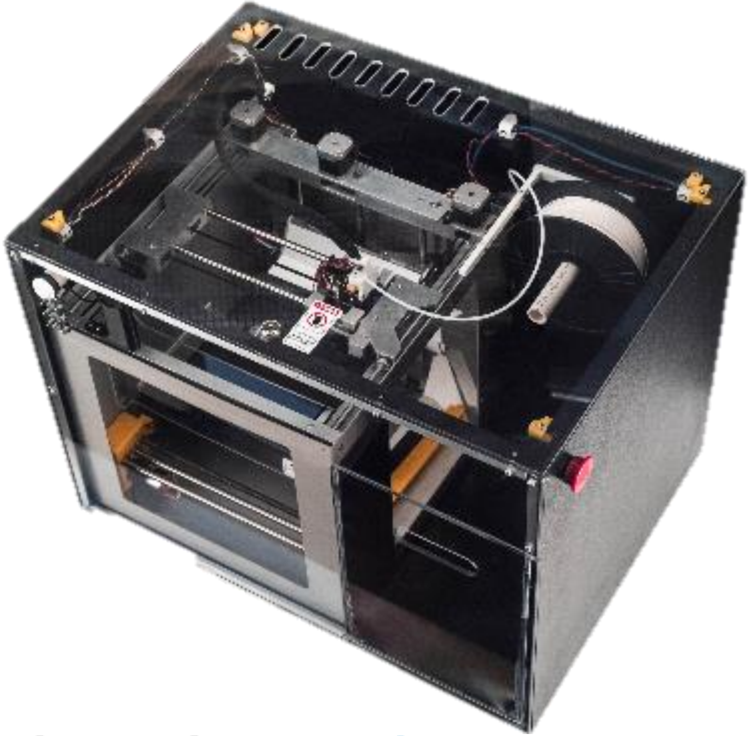
NVBOTS automated 3D printer



Product Specs

- Precision flat and level print plate (3µm)
- 8”x8”x10” build vol.
- 5,000 mm/s^2 print acceleration
- 20,000 mm/s^2 max acceleration
- 6.5 µm X,Y steps
- Automated part removal

Sensors, sensors and more sensors

Filament Motion (rad/s)

Power (on/off)

Current (A)

Bump Sensor (V)

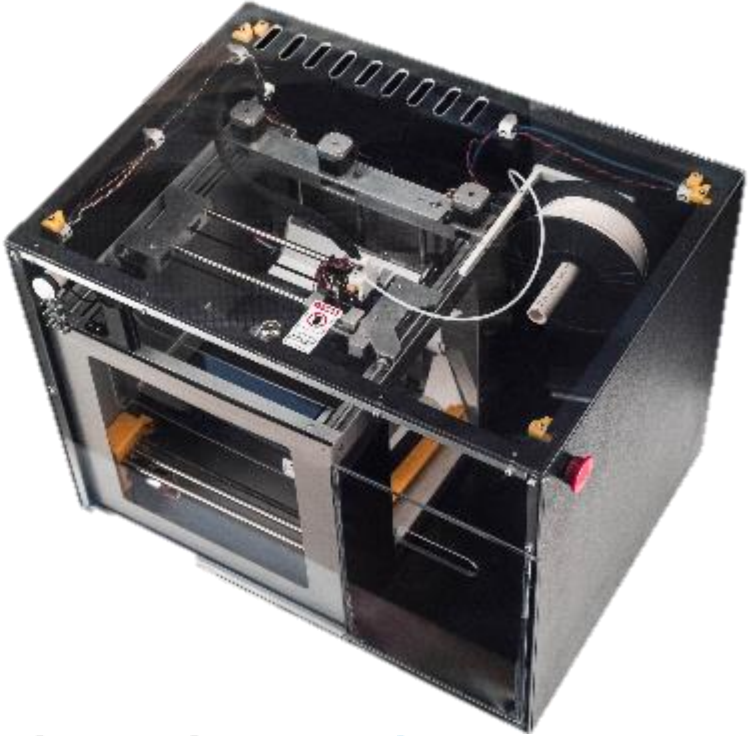
Camera (video data)

Extruder Temp (C)

Bed Temp (C)

Ambient (C, psi, %h20)

Data we capture and what we know



- Machine state
  (server signal + power data + camera to confirm)

- What is being printed
  (.stl file)

- Status of build volume
  (camera)

- Operating condition impact on process variability
  (camera + conditions)

- What failed, MTTF, MTTR

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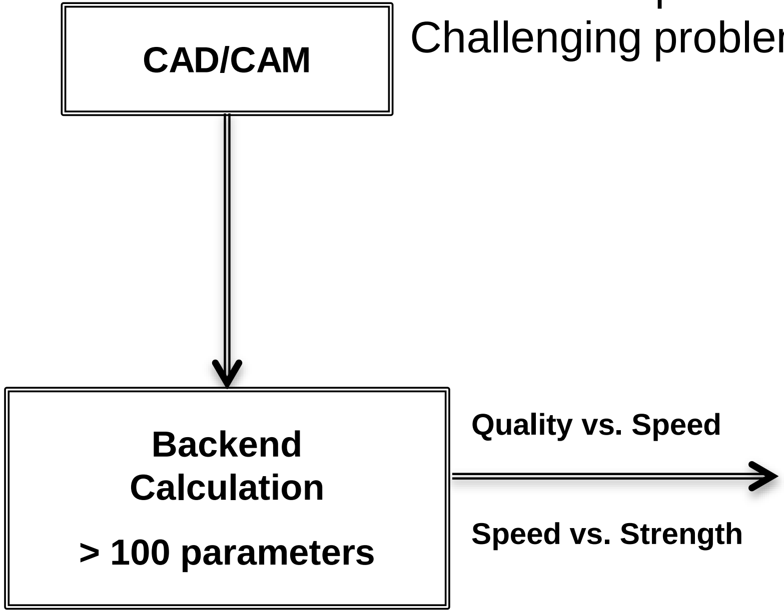
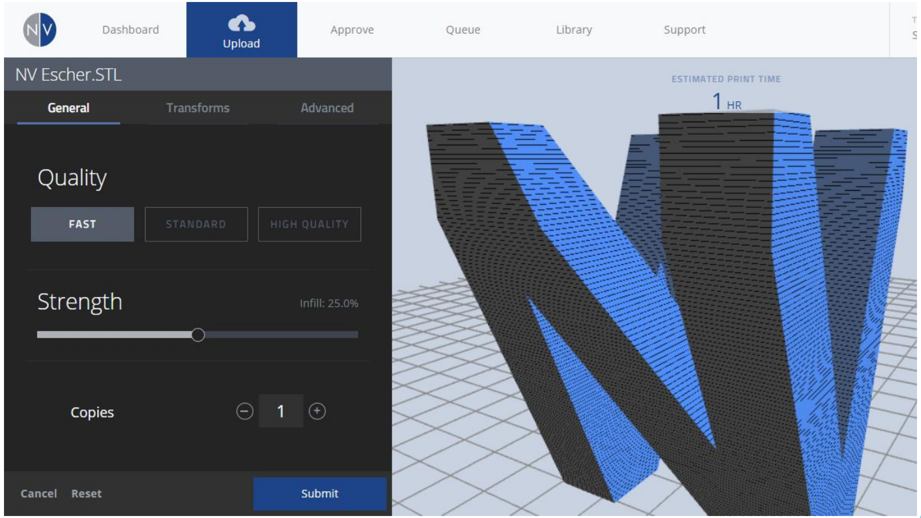
Cloud print parameter mapping simplifies CAD/CAM process

Two slider inputs determine the part quality, printing time and strength. Challenging problem because **parameter dependencies are non-linear**.





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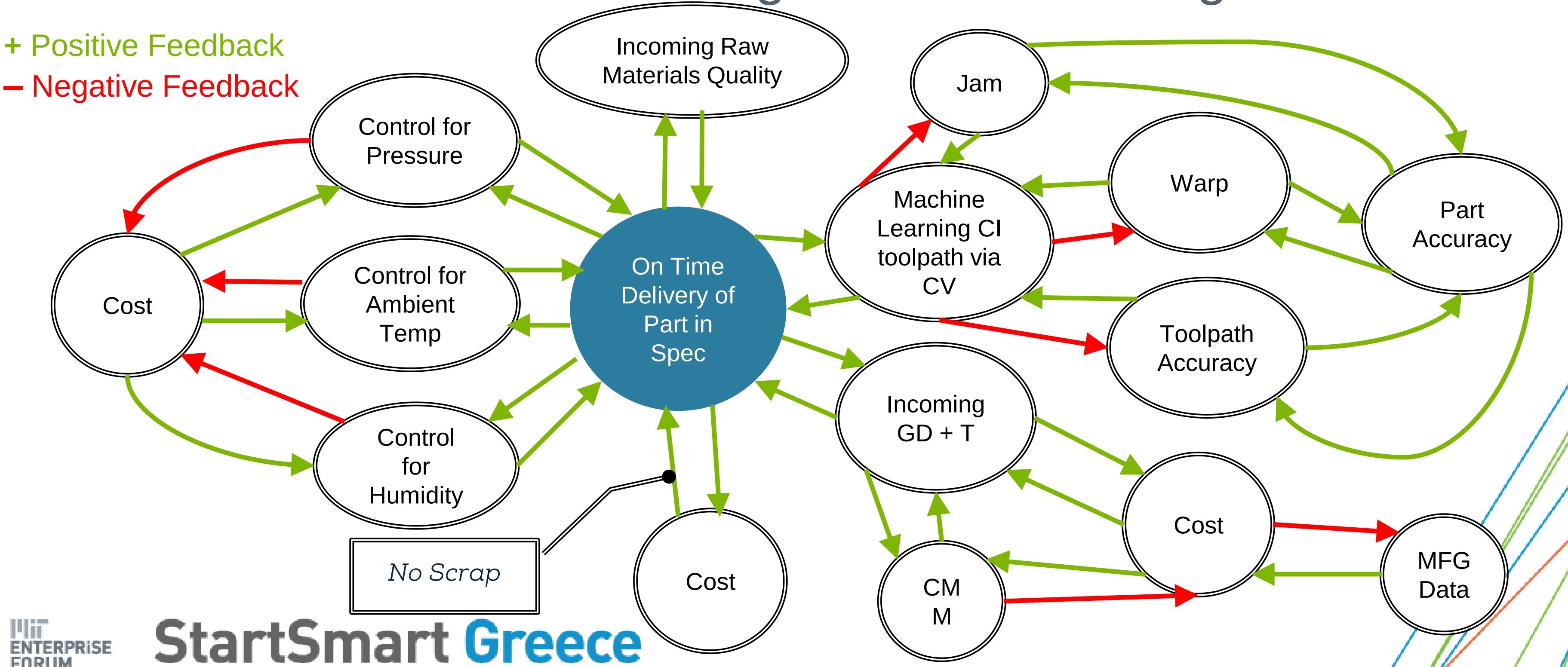
DOE, process characterization and optimization for NVBOTS automated FDM printer using nested ANOVA

1. Determine the effect of modifying the Quality vs. Speed (Q) and Strength vs. Speed (S) sliders on the **dimensional accuracy** of a printed cube.
2. Determine the effect of modifying Q and S on the **weight** of a printed cube.
3. Determine how many replicates of data are necessary to provide significant information concerning the effect of the two sliders.
4. Determine how many replicates are necessary for the NVBOTS printing process to have consistency of residuals.

Machine learning applied to NVBOTS 3D printer data system enables us to build an intelligent manufacturing network



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