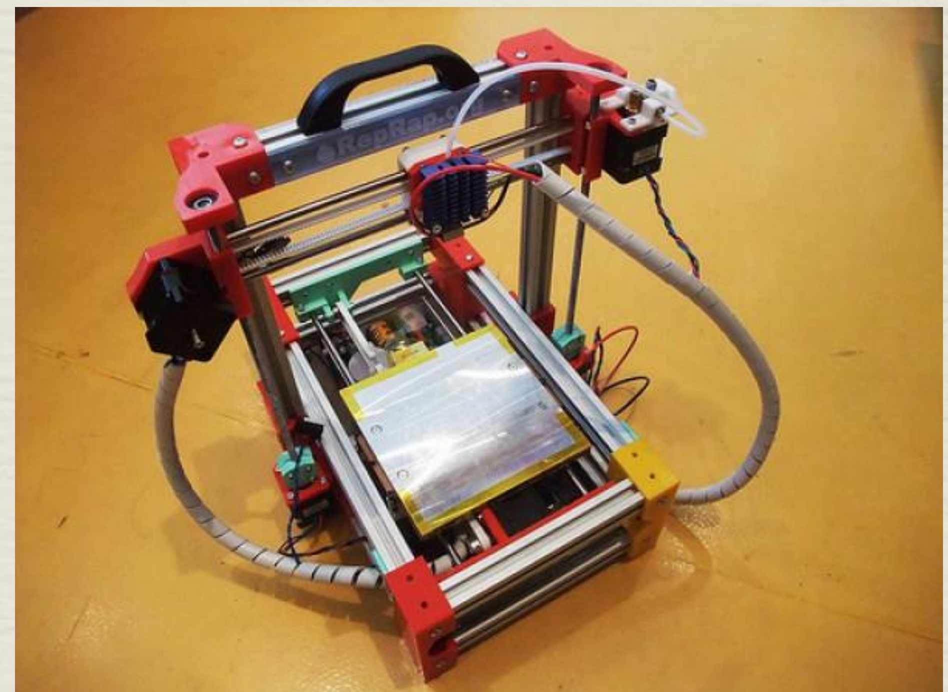
Can we use recycled materials in Open Source 3D Printing ?

How?

Lorraine Fab Living Lab

FDM 3D-printer



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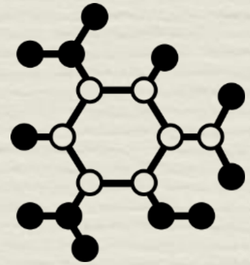

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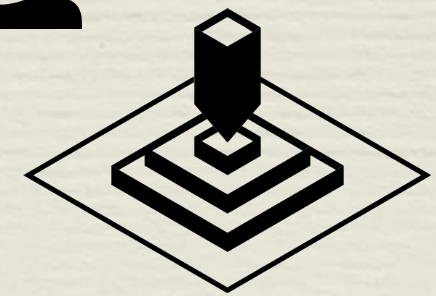
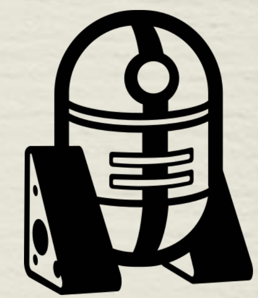
Université de Lorraine





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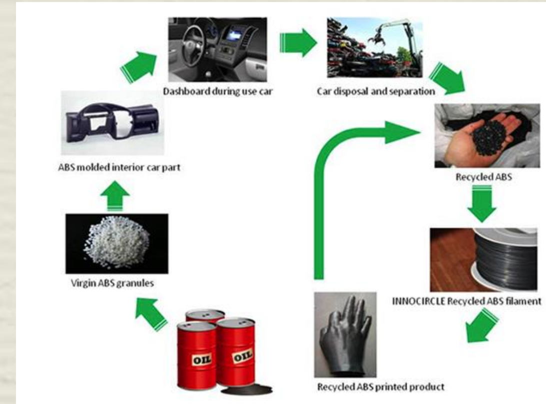
Existing projects



HD PE Milk jungs

Michigan
Technology University

Coca-Cola bottles
PET

EKOCYCLE™ Cube 3D printer

PET and ABS

InnoCircle, project between
2 Dutch companies
Innofil3D et CiorC

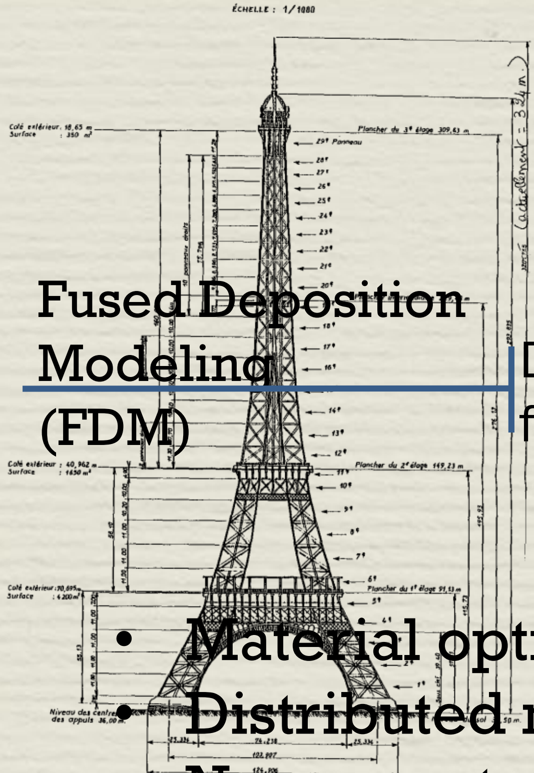
Kreiger, M. a. et al., 2014.
Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament
. *Journal of Cleaner Production*, 70, pp.90–96.

Open source extruders

Additive Manufacturing… (Call me 3D Printing)

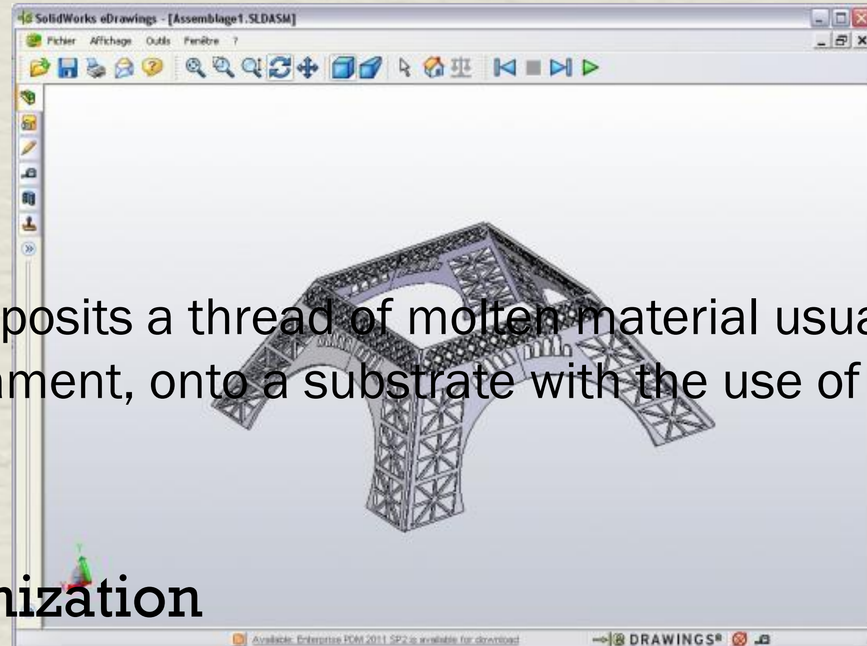
“ A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM,2012) ”

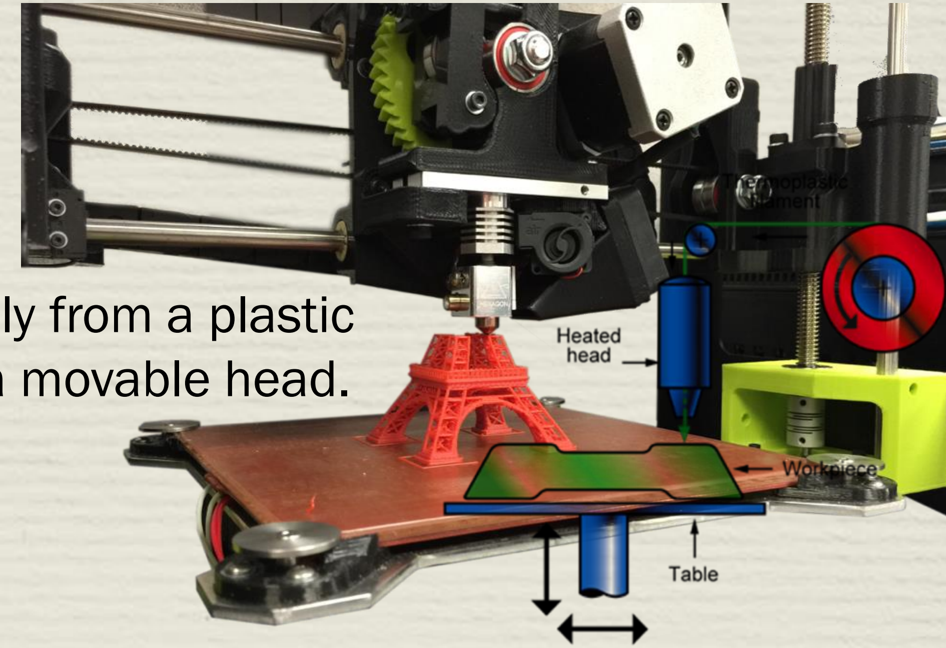
SLA – SLS - LOM – <u>Fused Deposition Modeling</u>



Fused Deposition Modeling (FDM)

Deposits a thread of molten material usually from a plastic filament, onto a substrate with the use of a movable head.





- Material optimization
- Distributed manufacturing
- No geometry restrictions
- Multidisciplinary applications
- Small rate of production
- Standards?, Precision? Limitations of materials?

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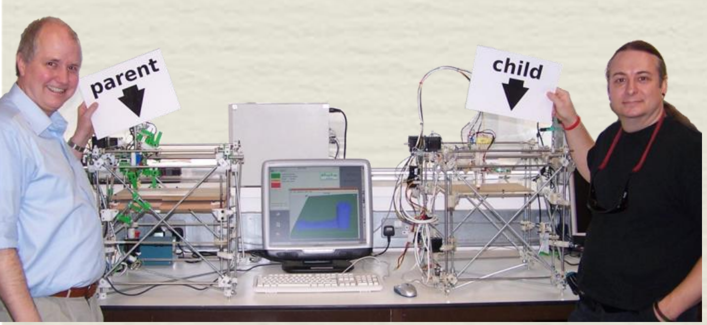
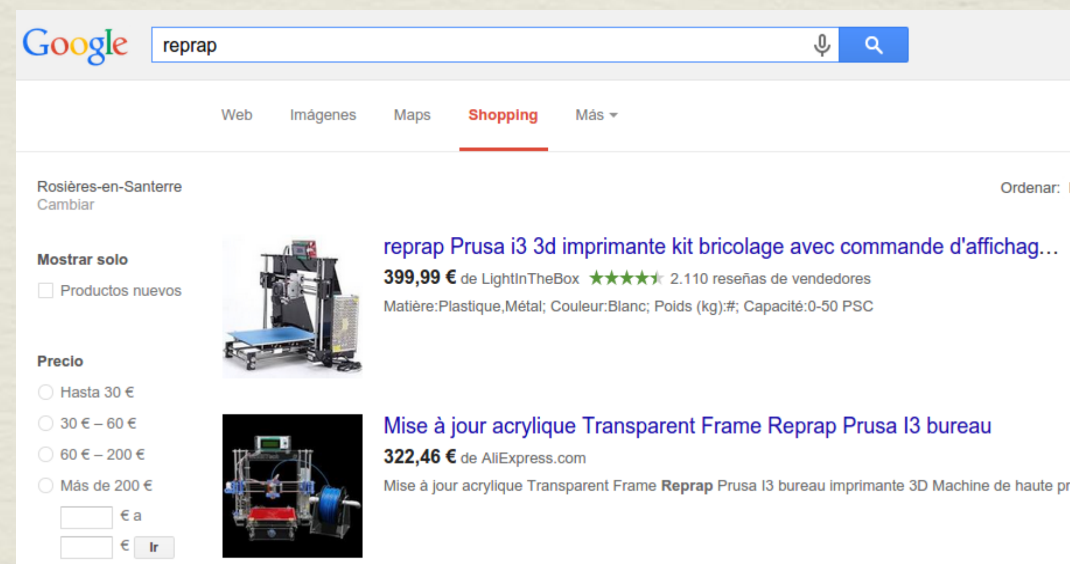
Open Source Additive Manufacturing

-RepRap Project-

- ***FDM** patent expired in 2005*
- **Rep**licating **Rap**id-prototyper *freely Available for the benefit of everyone*
- Open source approach . (available Information)
- Global community / Global knowledge, local needs.
- Low cost (<$5000)
- Quality? Repeatability? …
- **Exponential growth**



Materials: ABS / PLA



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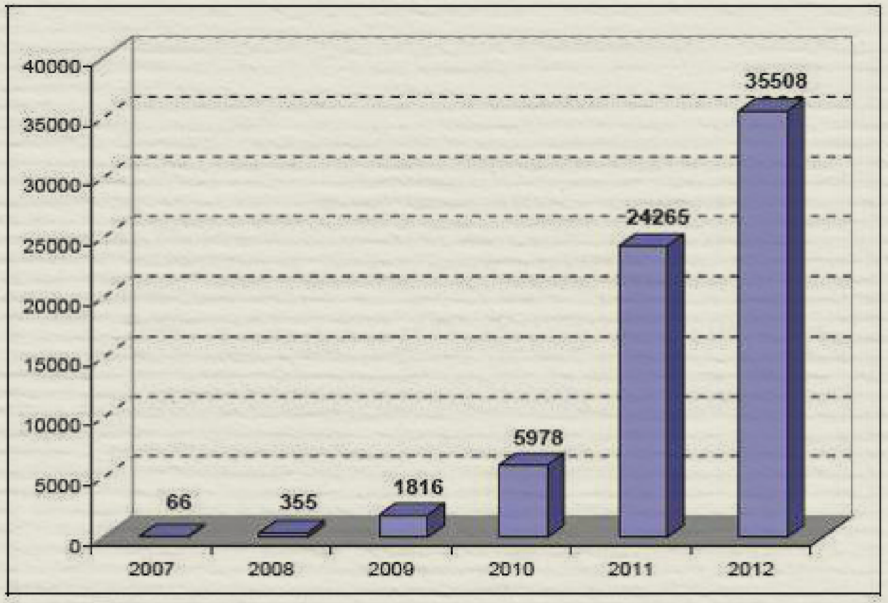
Open-Source Additive Manufacturing

Sales of personal printers

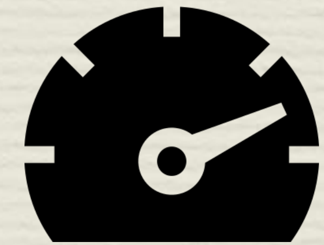


Source: Wohlers Associates, Inc.

High

Low

Enough



- Low cost (< $5000) “personal” 3D printer market averaged a growth of 346% each year from 2008 to 2011.
- 139.584 printers sold in 2014. (Wohlers Report, 2014)

“ ***RepRap*** *was the first low-cost additive manufacturing machine and it has found great popularity in the open-source community. ..*
Today, ***RepRap*** *is more widely used than any other additive manufacturing system. (Ford,2014).* ”

New Market that uses more new plastic…….

Ford, (2014). Additive Manufacturing Technology: Potential Implication for U.S. Manufacturing. *Journal of International Commerce and Economics (USA), (September), pp.1–35.*

II. Main Issue

What are the conditions and scale of the polymer recycling process for open-source AM?

What about the implications of recycling for the appropriation of open-source AM?

II. Research methodology

Towards a methodology for distributed recycling

Research Methodology

What are the conditions and scale of the recycling process for open-source AM

Feasability study

What about the implications for the appropiation of open-source AM?

Theory

Experimental

- Physical properties (micro/macro) of recycled polymer for open source AM.
- Establish the operating conditions for the recycling
- User environment under which this technology will be adopted.
- Composite materials?

Orientations

Additive Manufacturing
Polymer recycling

Extrusion process
Polymer characterization

I
Characterization of polymer recycling process in Open Source AM

II
Optimization of the operating conditions for manufacturing process

Research questions

- Design of experiment
- Statistical validation

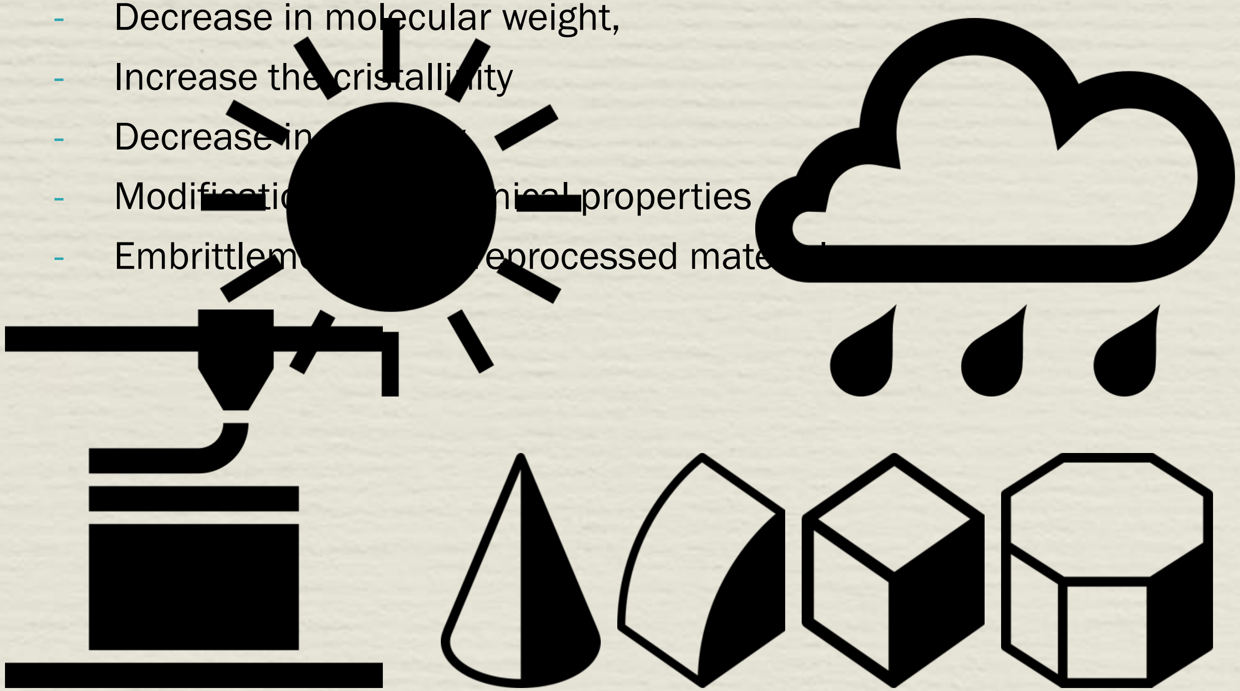
Exploration of composite materials for open source addtive manufacturing

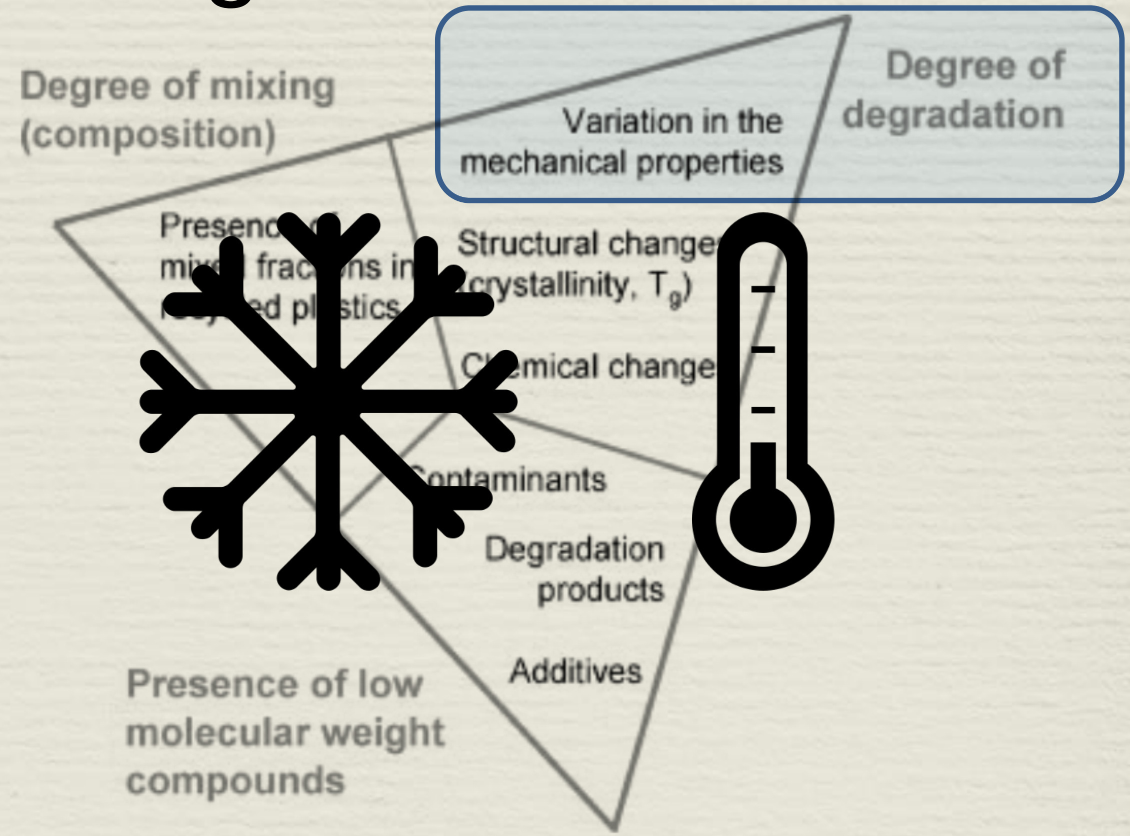
What is Polymer Degradation?

- Thermo-mechanical degradation

- Thermo-oxidative degradation

  - Chain scission
  - Decrease in molecular weight,
  - Increase the cristallinity
  - Decrease in
  - Modificati... ...nical properties
  - Embrittlem... ...reprocessed mate...



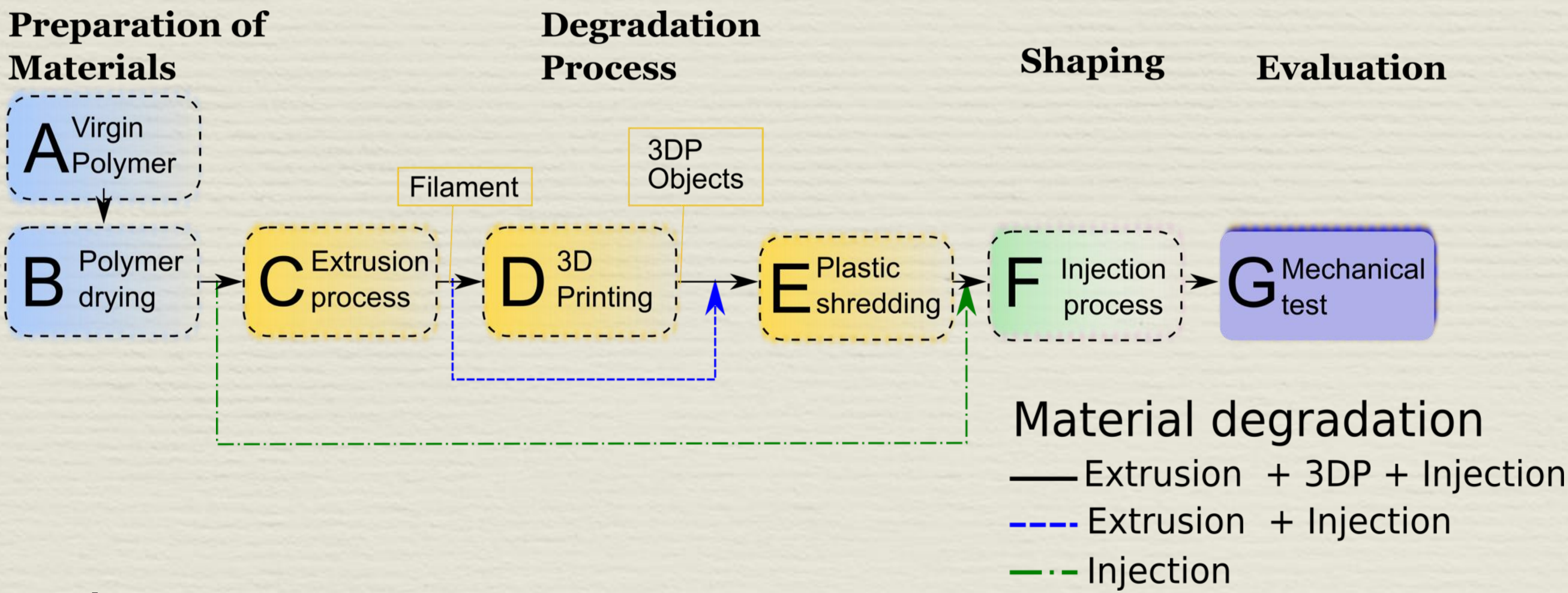


Key properties for quality assessment of recycled plastics

Vilaplana, F., & Karlsson, S. (2008). Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review. Macromolecular Materials and Engineering, 293(4), 274–297.

III. Case study

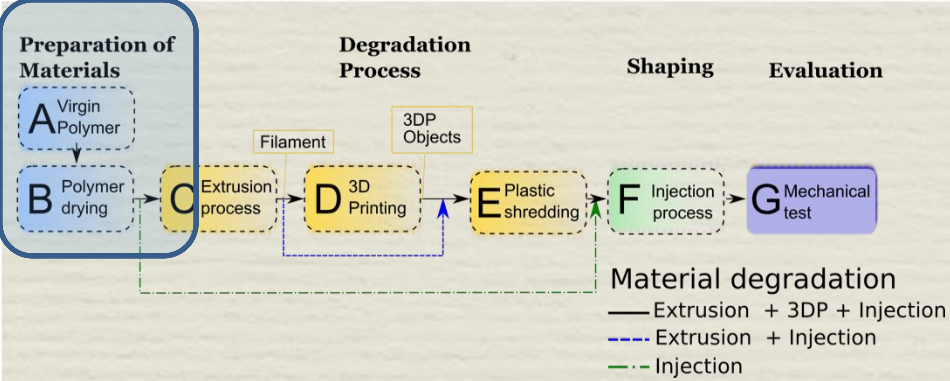
Degradation Polylactic Acid (PLA)



Main goal:

To characterize the degradation of every step in the process of fabrication of 3DP filament.

METHODOLOGY *for* Degration !!!!



A Virgin Polymer

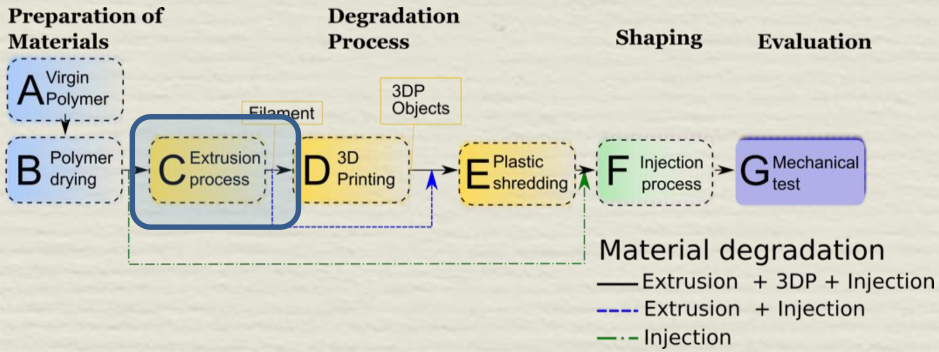
Characterization of virgin material

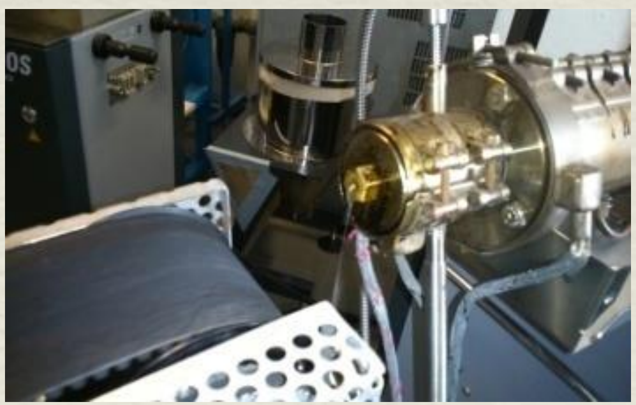
- Thermal Properties
- Rheological properties
- Molecular properties

B Polymer drying

- A moisture content of less than 0.025% (250ppm) is recommended to prevent viscosity degradation.
- Typical drying conditions are 4 hours at 175ºF (80ºC)

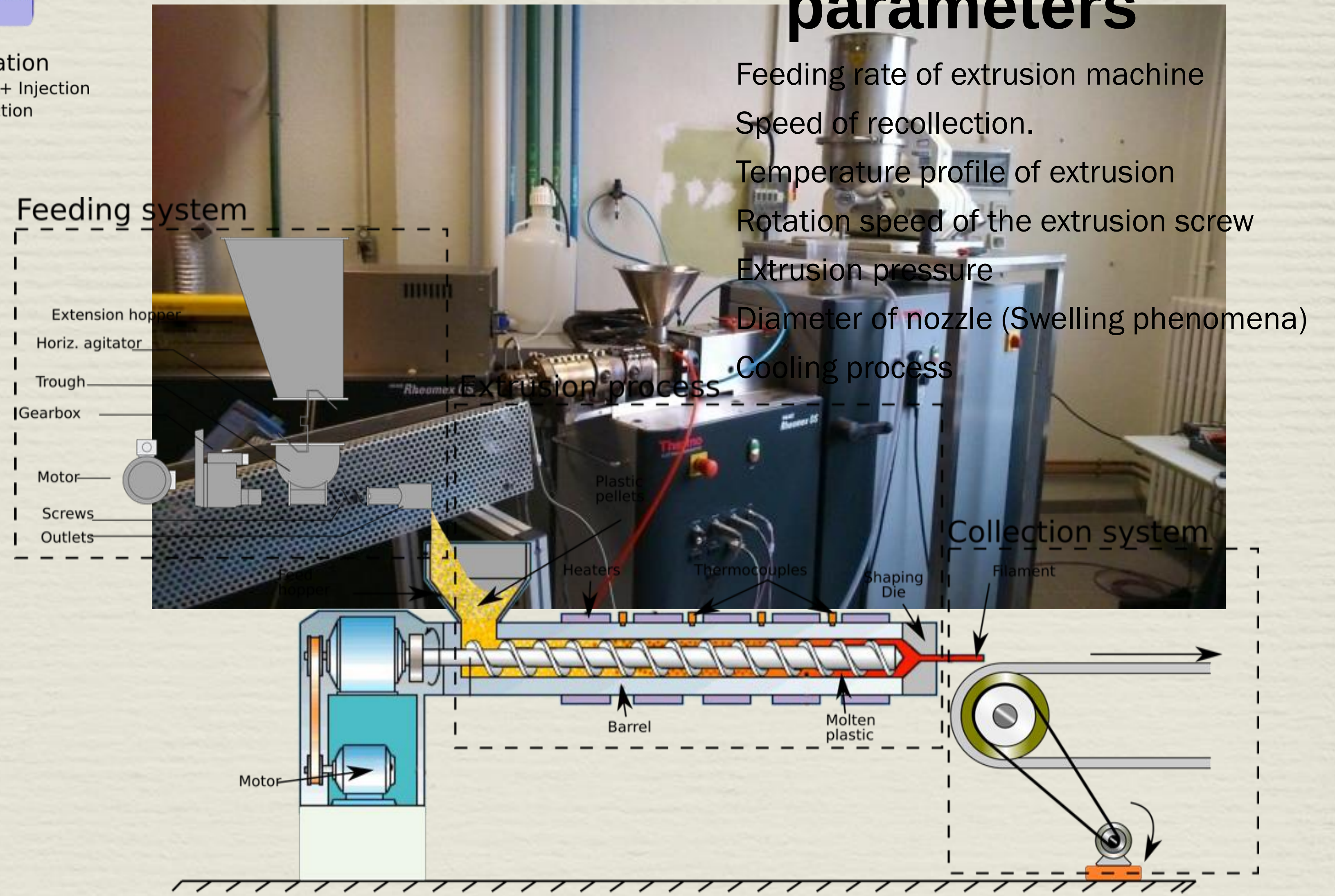
METHODOLOGY *for* Degration !!!!





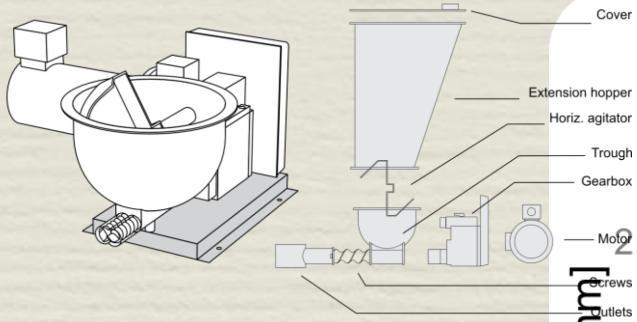
Extrusion parameters

- Feeding rate of extrusion machine
- Speed of recollection.
- Temperature profile of extrusion
- Rotation speed of the extrusion screw
- Extrusion pressure
- Diameter of nozzle (Swelling phenomena)
- Cooling process

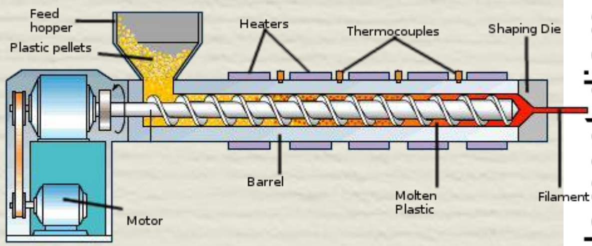


METHODOLOGY *for* Degration !!!!

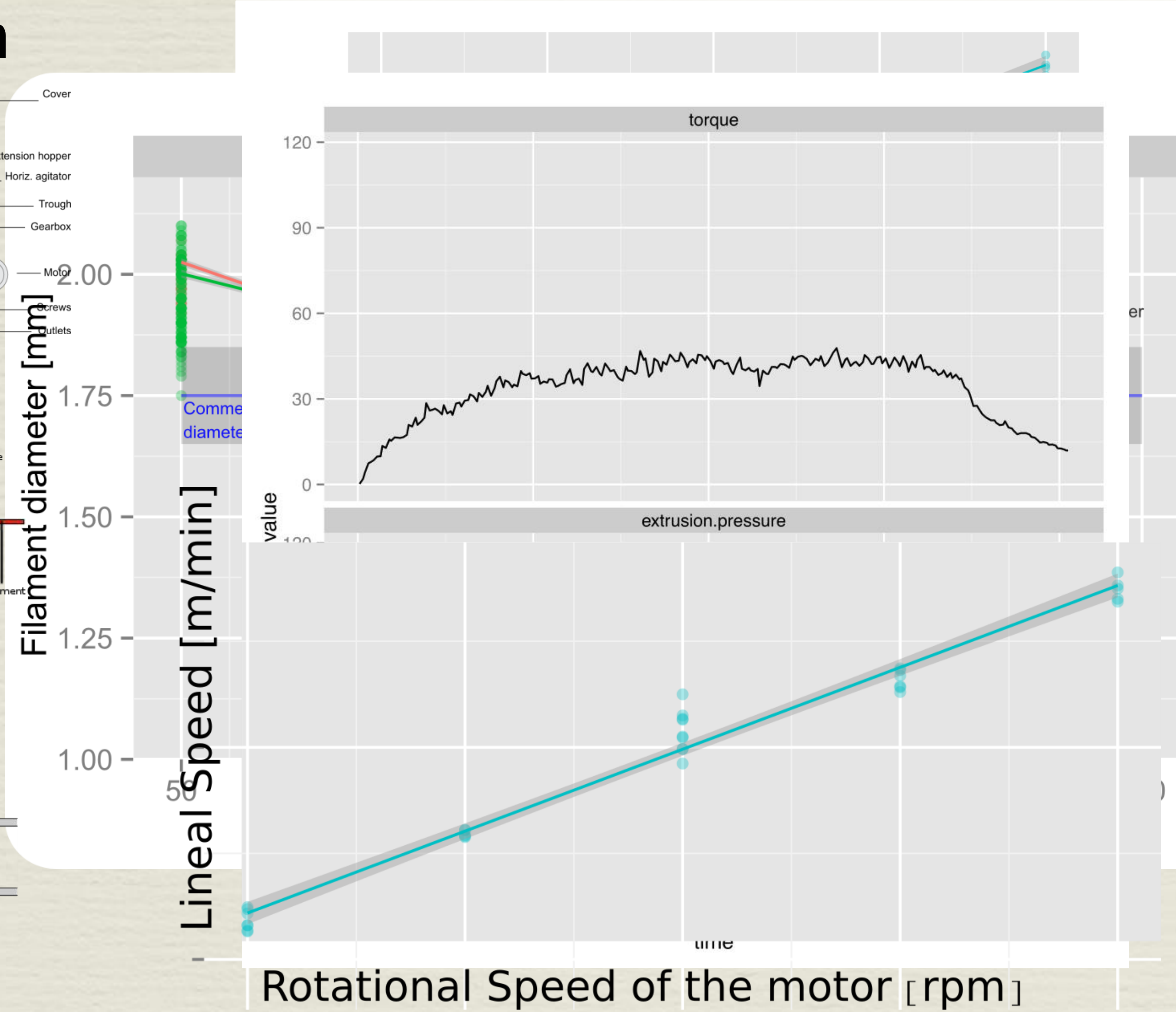
Feeding system



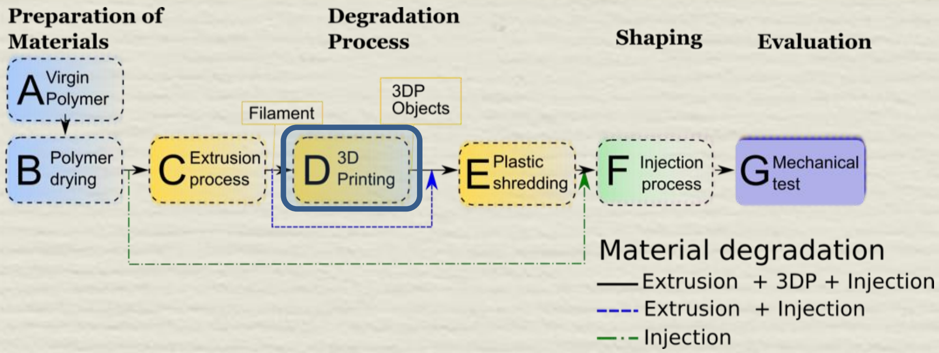
Extrusion



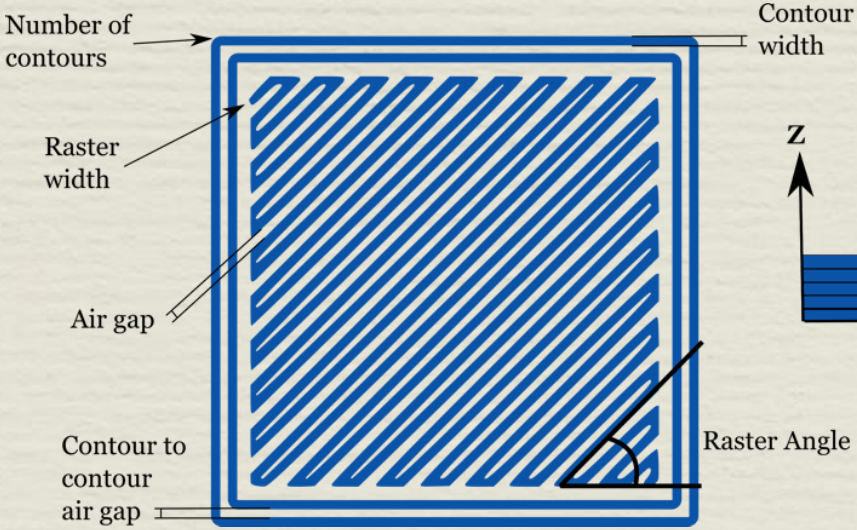
Speed collection

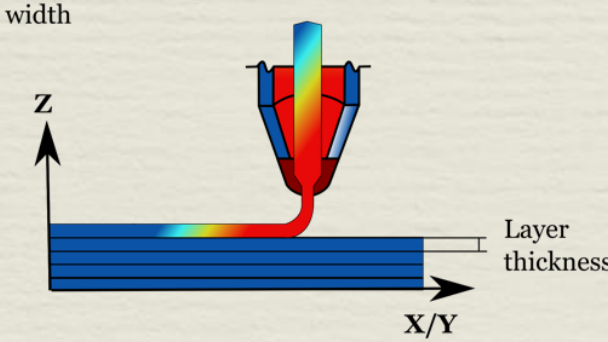


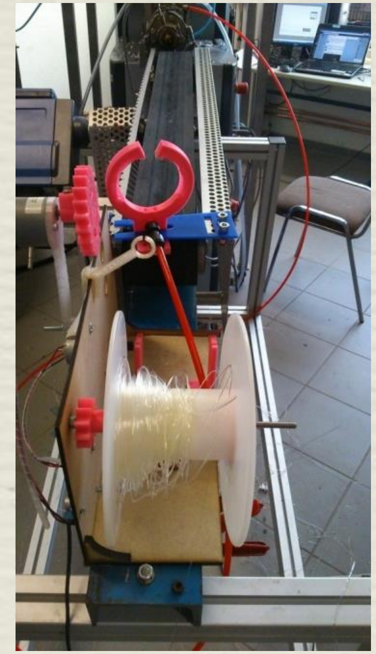
METHODOLOGY *for* Degration !!!!

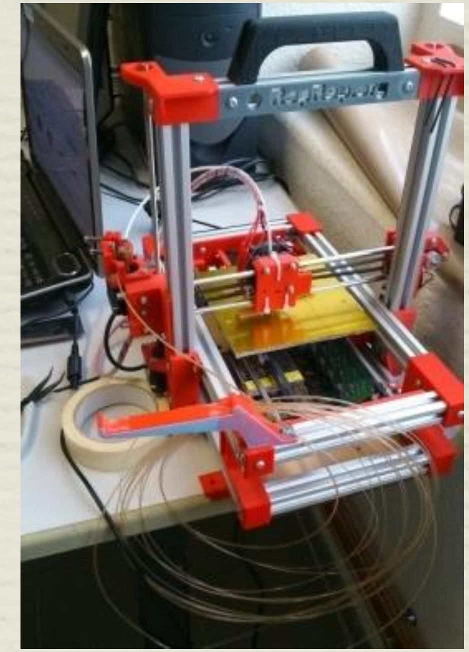


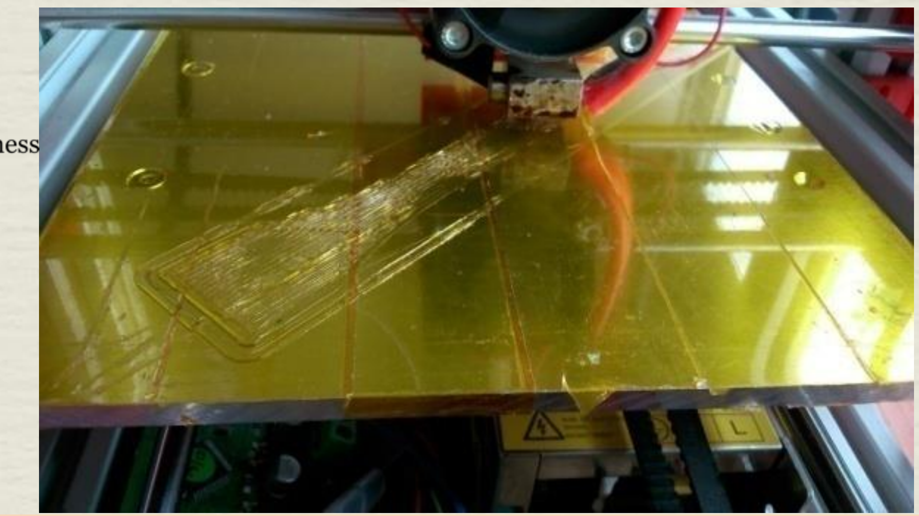
Parameters 3D Printing



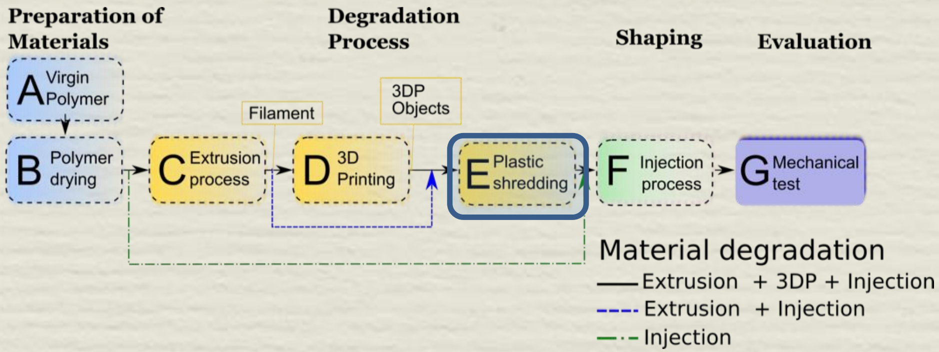


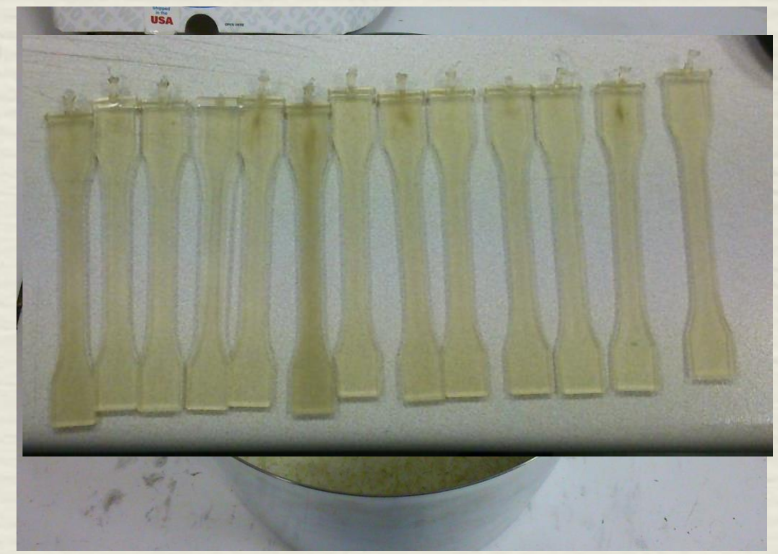




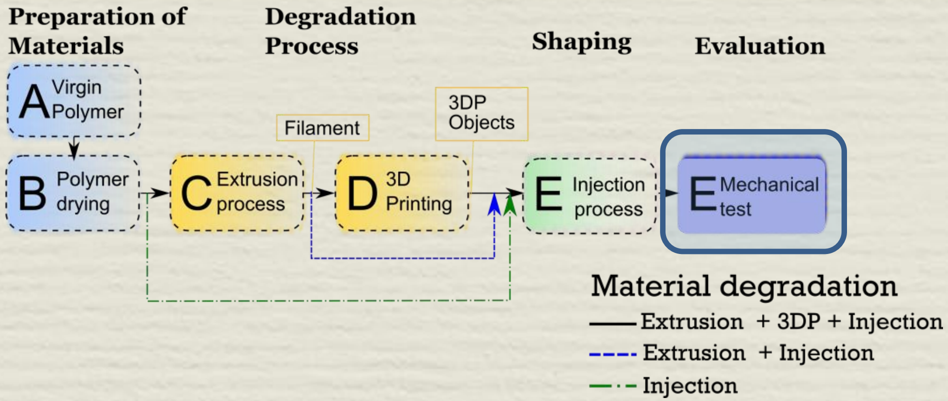


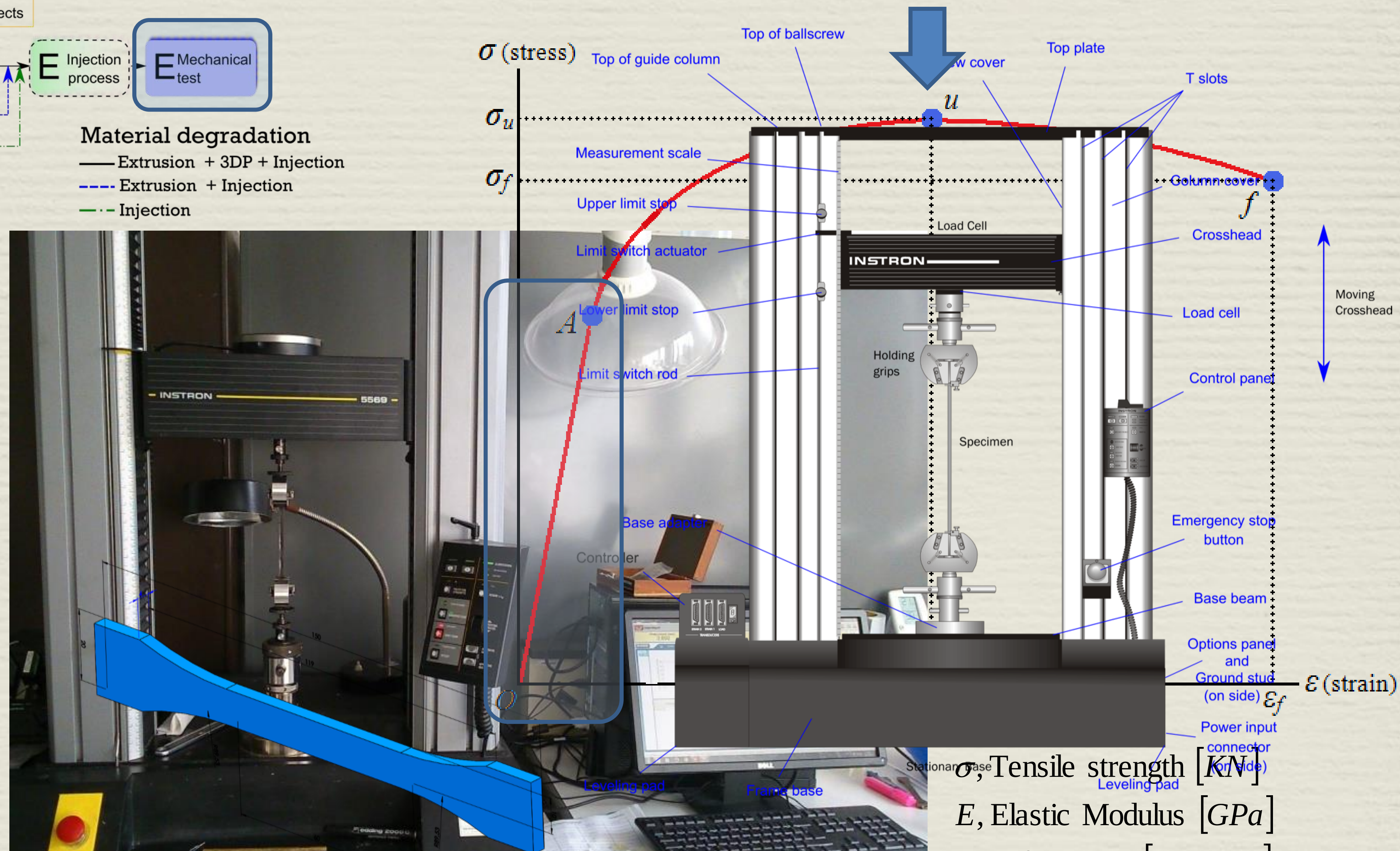
METHODOLOGY *for* Degration !!!!





METHODOLOGY *for* Degration !!!!





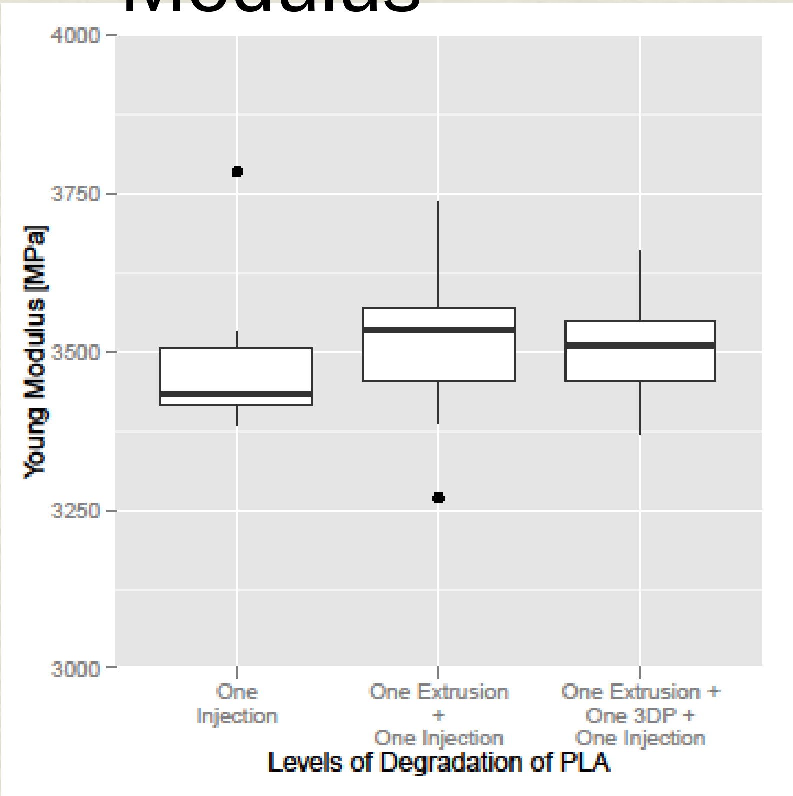
σ, Tensile strength $[KN]$

E, Elastic Modulus $[GPa]$

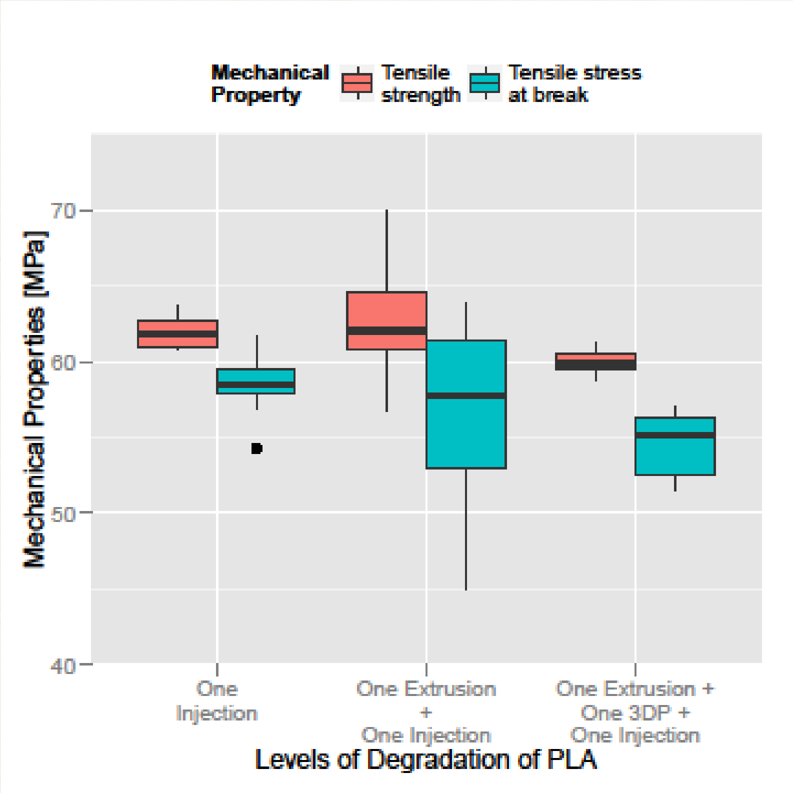
ε, Deformation $[mm/mm]$

METHODOLOGY *for* Degration !!!!

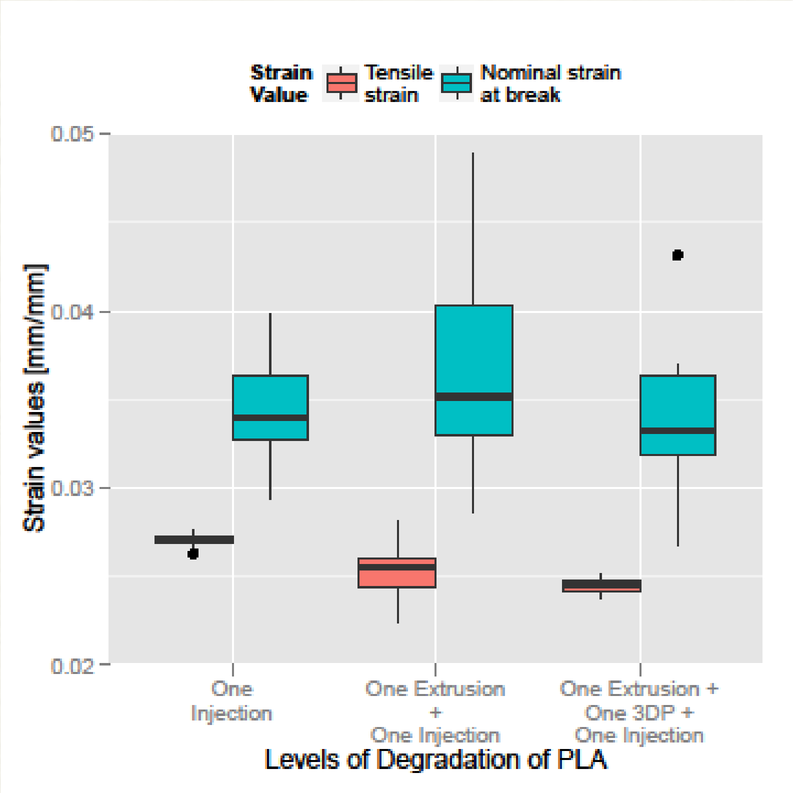
Elastic Modulus



Tensile strength / Tensile strength at break



Tensile strain / Nominal tensile strain at break



15 samples per type of material tested

METHODOLOGY *for* Degration !!!!

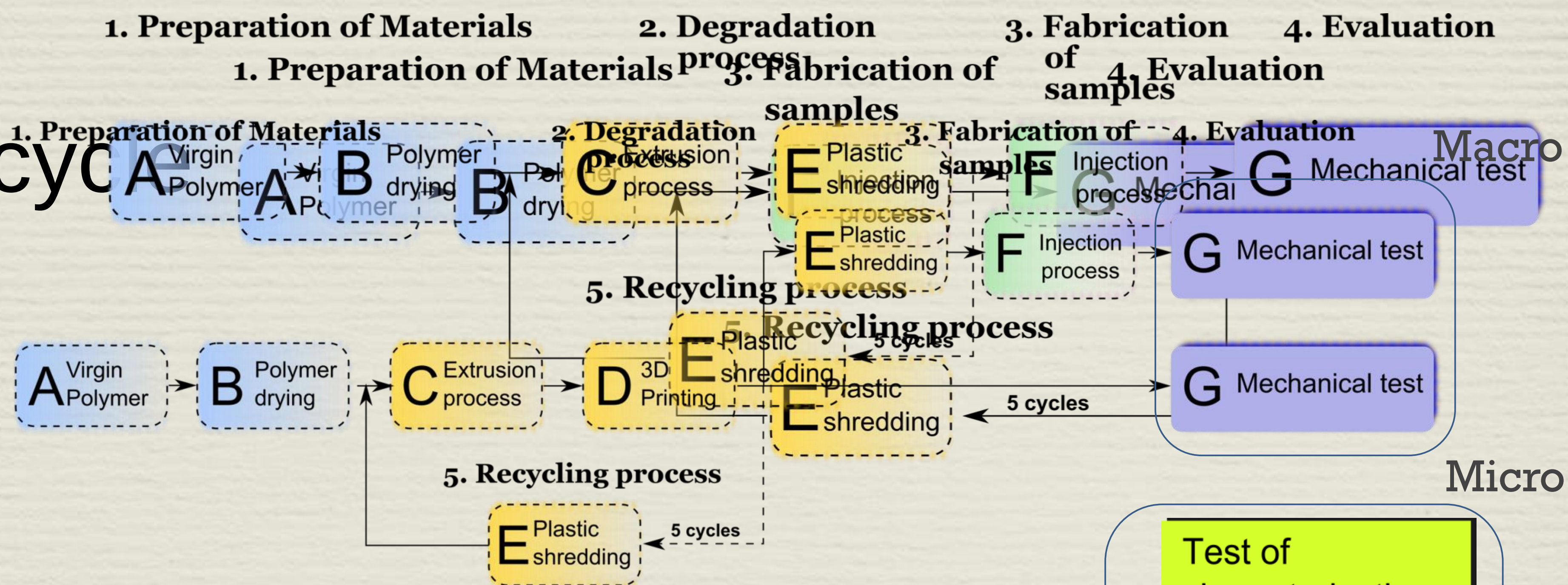
IIII. Case study

Recycling Polylactic Acid (PLA) -Beta version-

Extrusion cycle

Injection cycle (Reference)

3D Printing cycle



Test of characterization

- Size Exclusion Chromatography (SEC)
- Rheological properties
- Melt flow Index (MFI)

Main goal: to characterize the degradation of the polymer material in the course of the recycling process.

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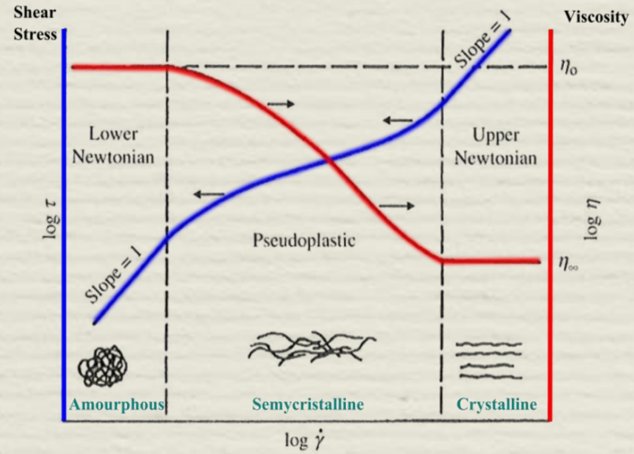
Test of characterization

Size Exclusion Chromatography (SEC)

Molar Mass distribution

- Number average molar mass (M_n)
- Mass average molar mass (M_w)
- Polydispersity index (I_p)

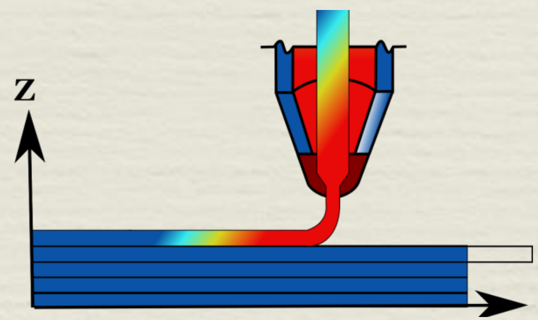
Rheology



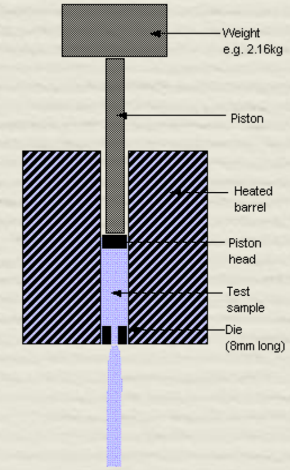
Generalized flow properties of polymer melts and solutions.

The study fluid characteristics.

- Shear stress
- Shear rate
- Viscosity



Melt Flow Index (MFI)

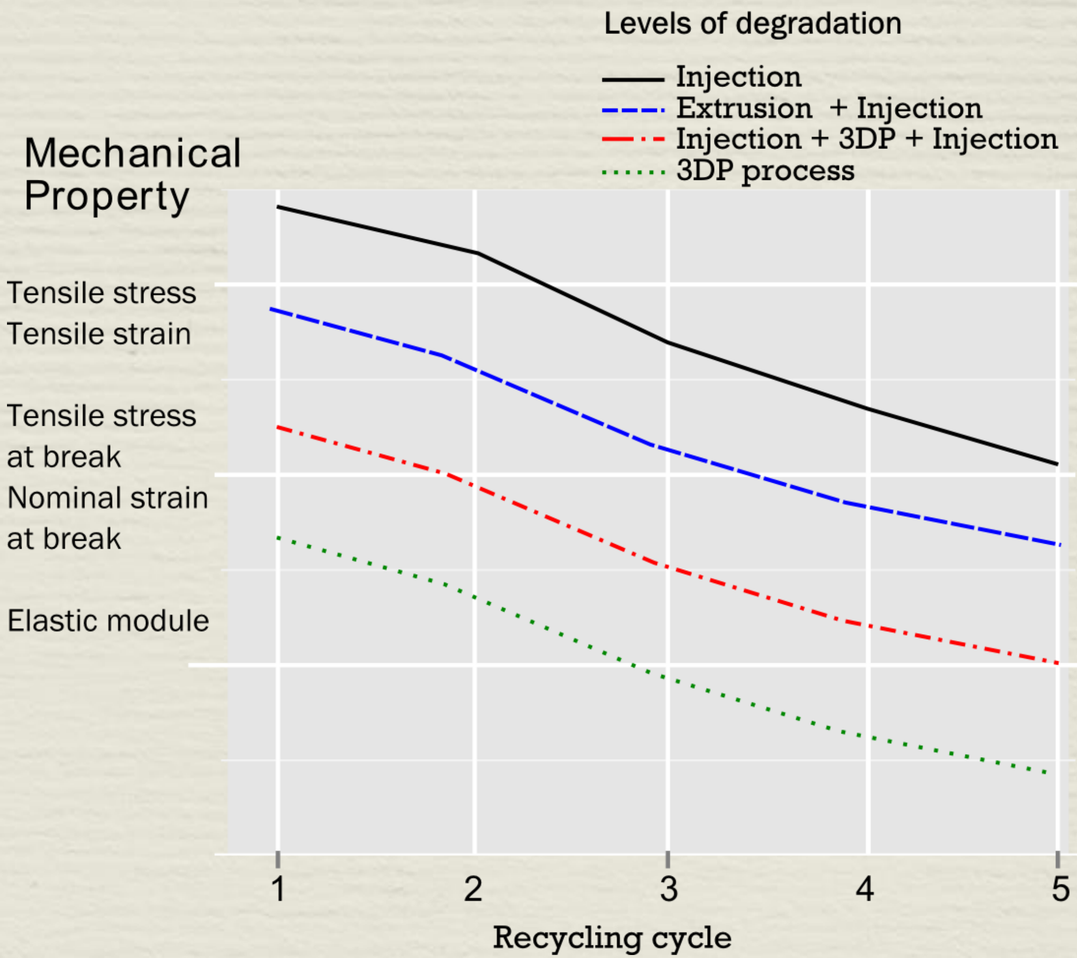


MFI is a measure of the ease of flow of the melt of a thermoplastic polymer.

- Indirect measure of molecular weight,
- The higher MFI, the lower molecular weight is.

METHODOLOGY *for* RECYCLING !!!!

Expected results of recycling.....



METHODOLOGY *for* RECYCLING !!!!

Conclusions and perspectives

Conclusions

- **At which scale can we do distributed recycling?**
  - Personal?,
  - Fablab?
  - Traditional (Centralized?)
- **Personal Open Source extruder**
  - Technical problems of control of temperature and flow rate.
  - Unregular dimensional filament
  - Safety problems (COV)
  - Mixing of polymer
  - Grinding of objects
  - Cleaning

Conclusions

- **What material can we recycled?**
  - Homopolymer (Only PLA, ABS)
  - Formulation

- **What are about the economic issues?**
  - Reduction of transport
  - Viable economic?

Thank you for your attention...

Questions, Comments??

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2015

Perspectives

Evaluation of the polymer’s degradation after printing process.

Link material properties with quality of printing
(MFI impact on printing??)

- Recycling process using injection in order to compare the impact of the degradation

- Cleaning? Other plastics?
- Composite materials?
- User environment under which recycling process will be adopted.

Thank you very much for your attention….

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Characterization of virgin material

2015

1 Virgin Polymer

Polylactic Acid (PLA) Ingeo™ Biopolymer 4043D

Thermoplastic

Semicrystalline

Properties	Value
Mass average molar mass (Mw)	110.000 g/mol
Number average molar mass (Mn)	85.000 g/mol
Glass transition Temperature	57 °C
Fusion temperature	147 °C
Degradation temperature	300 – 370 °C
Density	1,24 g/cm3

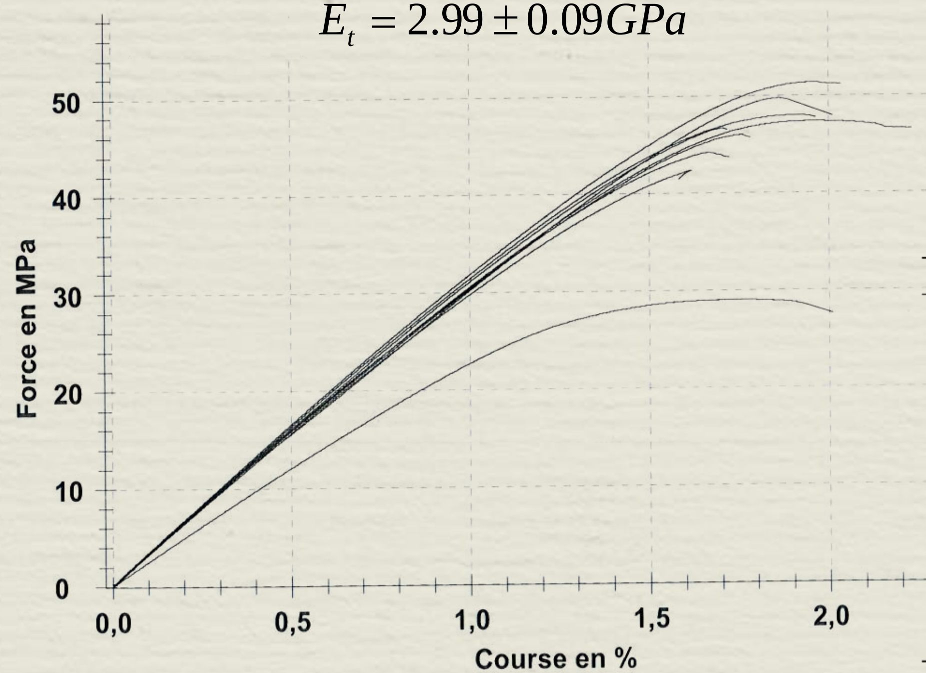
Mechanical properties

$$\overline{F_t} = 1904 \pm 312\,N$$

$$\overline{\sigma_t} = 44,27 \pm 6.81 MPa$$

$$\overline{E_t} = 2.99 \pm 0.09 GPa$$

ISO 527 -B



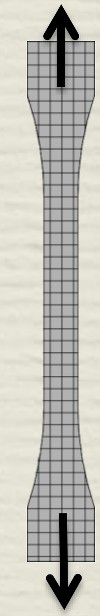


Table 4: Fixed factors

Parameters	Value	Units
Bed temperature	52	°C
Nozzle temperature	190	°C
# of perimeters	2	
Top solid layers	2	
Bottom solid layers	2	
Fill density	100	%
Material	PLA	
# of repetitions	10	
Travel speed	200	mm/s
Nozzle diameter	0.5	mm
Filament Diameter	1.75	mm
Support	Non	
Slic3r software for generation of G-code		

METHODOLOGY *for* RECYCLING !!!!

Preliminar results: Mechanical properties

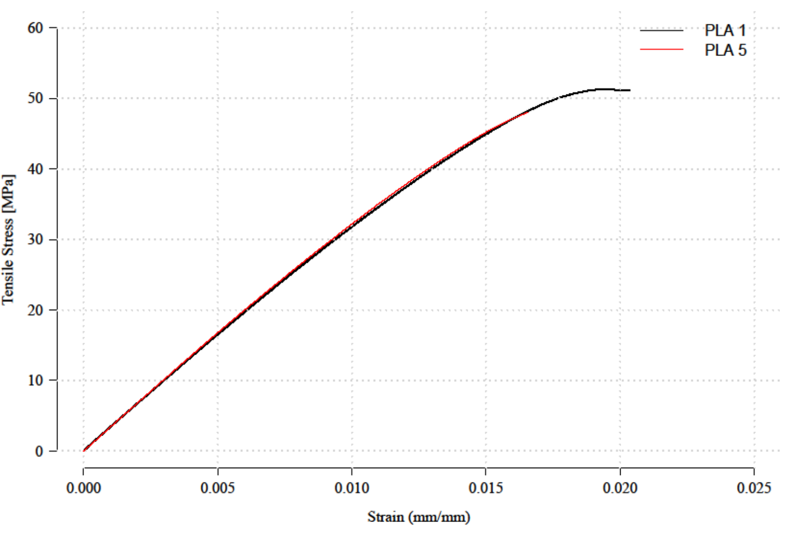
2015

- Evolution of the Mechanical results

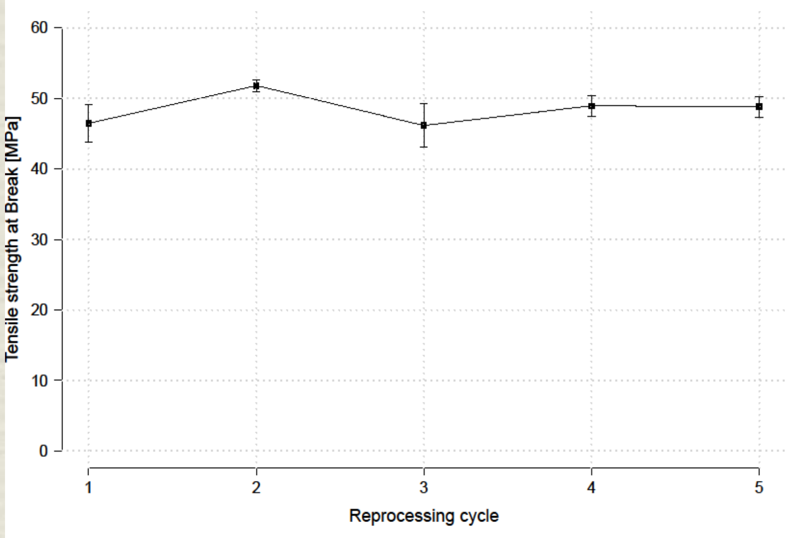
Extrusion number	Tensile modulus (MPa)	Stress at break (MPa)	Strain at Break (%)
1	3093.65 ± 194.99	46.44 ± 2.69	1.88 ± 0.20
2	3556.13 ± 56.86	51.79 ± 0.85	2.25 ± 0.40
3	3356.23 ± 161.70	46.16 ± 3.08	1.85 ± 0.27
4	3441.58 ± 119.05	48.94 ± 1.48	1.98 ± 0.28
5	3491.60 ± 98.14	48.81 ± 1.47	1.68 ± 0.02

- Elastic Modulus remains constant.

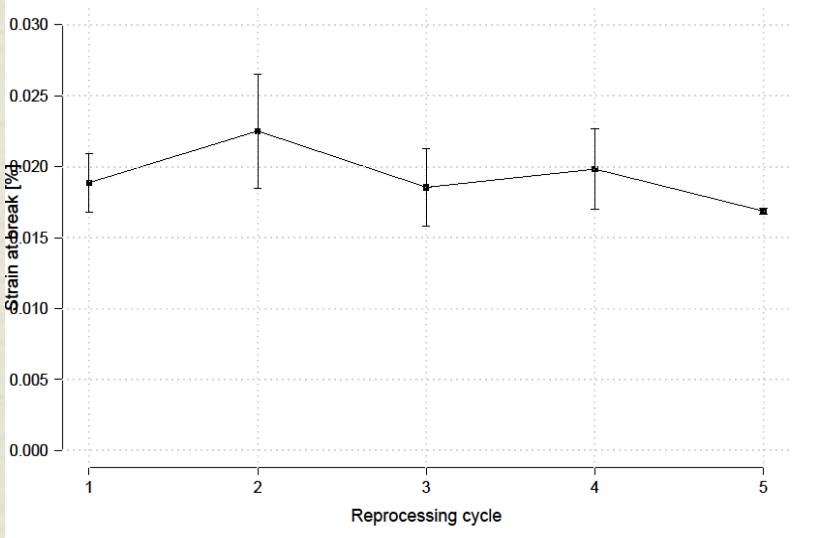
PLA 1 vs PLA5



Strength at Break



Strain at Break

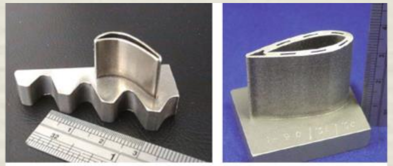


METHODOLOGY *for* RECYCLING !!!!

What can we do with AM ?

Aerospace

Guo, N., & Leu, M. C. (2013). ***Additive manufacturing: technology, applications and research needs.*** *Frontiers of Mechanical Engineering*, *8*(3), 215–243.



(a) Airfoil (material: IN 738) produced by LMD on cast IN 738 substrate; (b) airfoil with embedded cooling channels (material: Ti6Al4V) produced by LMD (Source: [139])

Damaged blisk repaired using LENS

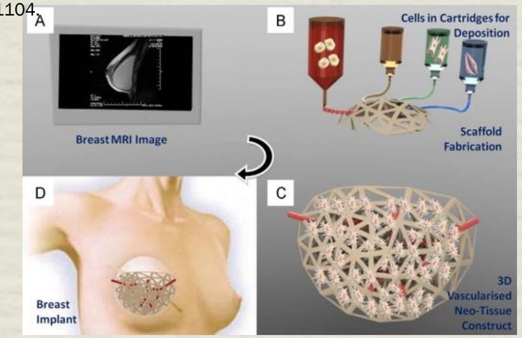
Automotive

Guo, N., & Leu, M. C. (2013). ***Additive manufacturing: technology, applications and research needs.*** *Frontiers of Mechanical Engineering*, 8(3), 215–243.

(a) Final assembly of an intake manifold fabricated by FDM; (b) completed intake system after a composite layup process and final assembly of sensors and mounts (Source: [156])

Biomedical

Melchels, F. P. W., Domingos, M. a. N., Klein, T. J., Malda, J., Bartolo, P. J., & Hutmacher, D. W. (2012). ***Additive manufacturing of tissues and organs.*** *Progress in Polymer Science*, *37*(8), 1079–1104.



Architechtural

Columbano, A., & Dring, M. (2010). ***The pedagogy of using a RP architectural model***. Virtual and Physical Prototyping, 5(4), 195–200.

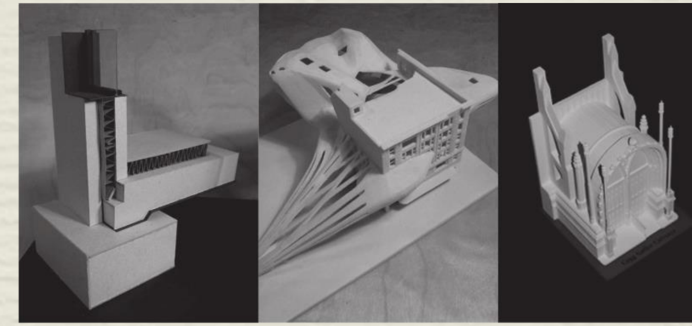


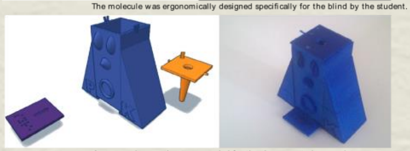
Figure 1. Detail model demonstrating tectonic build up of components.

Figure 2. RP model of new concrete structure intersecting an existing stone building.

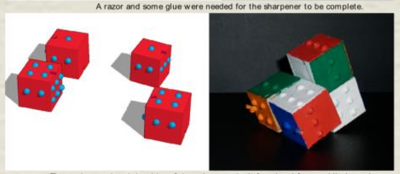
Figure 3. RP model utilised to develop intricate gothic carvings.

Education

The molecule was ergonomically designed specifically for the blind by the student.



A razor and some glue were needed for the sharpener to be complete.



The students painted the sides of the cube to make it functional for non-blind people.

Kostakis, V., Niaros, V., & Giotitsas, C. (2014). **Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece**. *Telematics and Informatics*, 1–11.

Dentristy

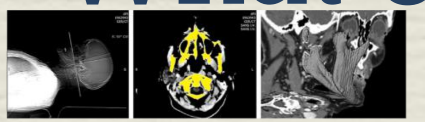


Fig. 1 Computer tomography scan with the orthopaedic tissue density of the mandible highlighted and rebuilt 3D structure

Fig. 2 Rebuilt mandible a data in the form of a G-code based tool path and b orthopaedic surface detail

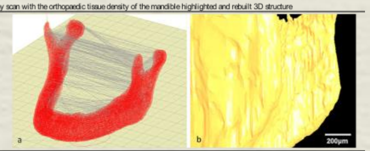
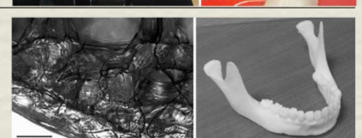


Fig. 3 Plastic extruder-based 3D additive manufacturing system used to produce the mandible to a 50-µm layer resolution

Fig. 5 Micrograph of the porous surface properties of the reconstructed mandible



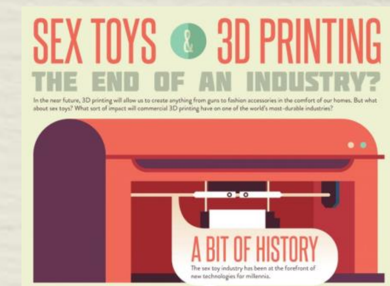
Thomas, D. J., Azmi, M. a. B. M., & Tehrani, Z. (2014). ***3D additive manufacture of oral and maxillofacial surgical models for preoperative planning***. *The International Journal of Advanced Manufacturing Technology*.

Arts

Fashion

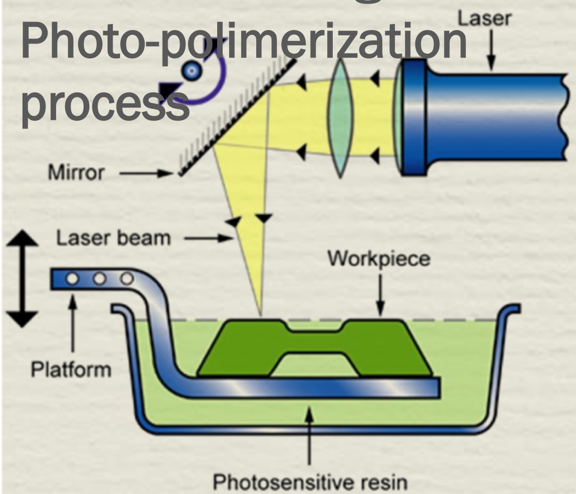
http://www.core77.com/posts/24243/digital-fabrication-and-fashion-intersect-at-paris-fashion-week-24243

Others

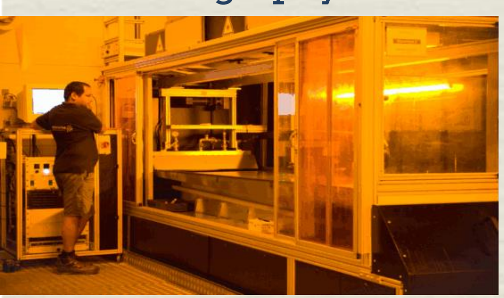


Liquid

Photosensitive resine
+
beam of UV light
Photo-polimerization process

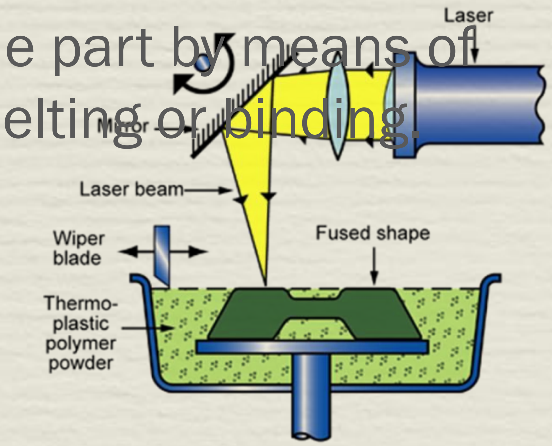


Stereolithography – SL-



Powder

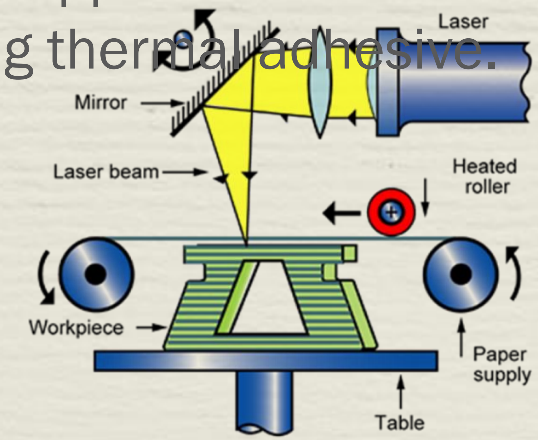
Material in powder form
+
Selective formation of the part by means of melting or binding.



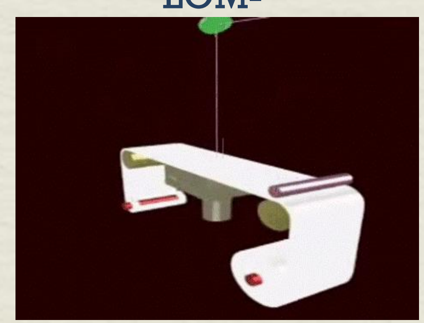
Selective Laser Sintering – SLS-

Sheet

Layers are bonded together by pressure, heat application and using thermal adhesive.

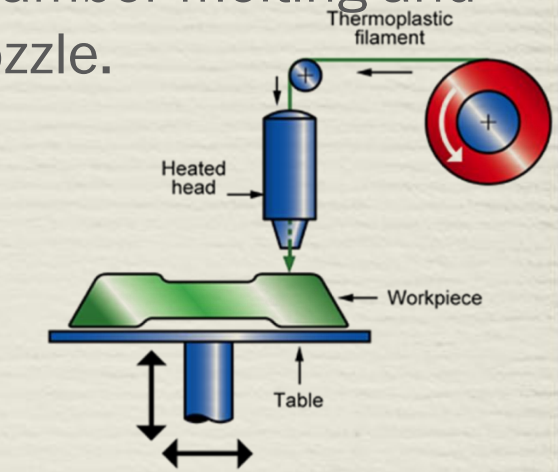


Laminated Manufacturing Object – LOM-

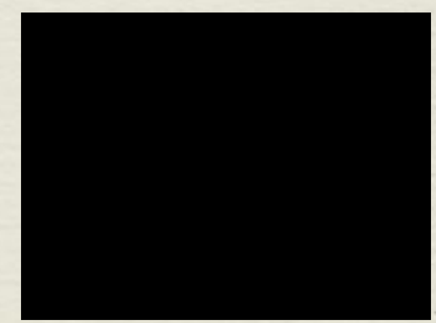


Filament

Thermoplastic filament
+
chamber melting and nozzle.



Fused Deposition Modeling FDM



A Plastic World …

World Plastics Production
(Mtonnes)

299
2013

Source. (Plastics Europe, 2015)

~ 20%

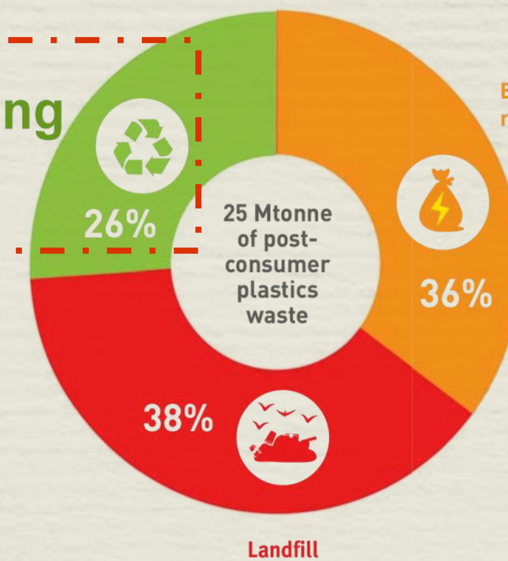
57
2013

European Plastics
(Mtonnes)

~ 50%

Plastics waste

25.2(Mtonnes) of Plastic wastes in Europe in 2012



Treatemen for post-consumer waste plastics in EU27 + Norway and Switzerland
Source: Consultics

Why are the recycling rates very low ?

Recycling rate: USA (6,5% in 2008), EU (26% in 2012).

-Transport problem: (high volume-to-weigth ratio)
- Cost of virgin plastic vs Recycled Plastic
- Degradation of properties. Quality?
- Complexity in plasic sorting

---- No economical net benefit from recycling plastic materials.

-*Landfilling is often the first option. (Longevity?)*

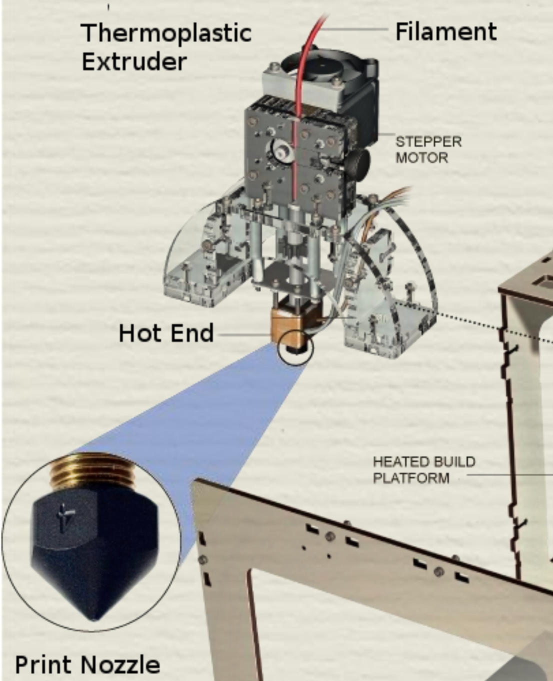
Subramanian, P.., 2000. Plastics recycling and waste management in the US. Resources, Conservation and Recycling, 28(3-4), pp.253–263.

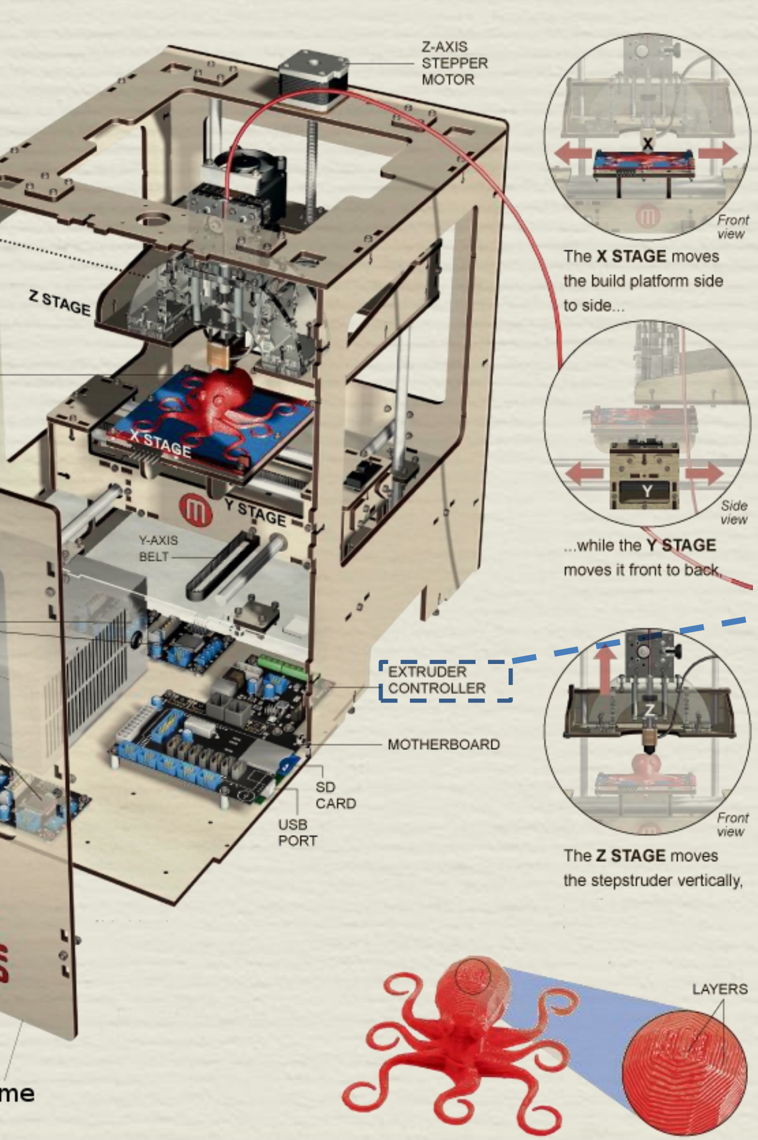
Additive Manufacturing Vs Traditional Manufactucturing

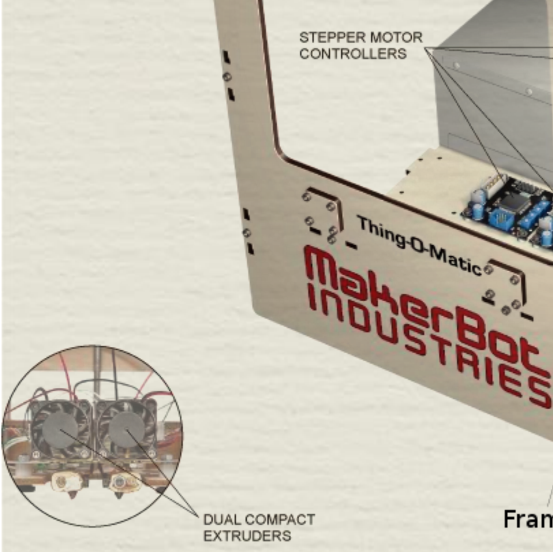
- Material eficiency
- Economically custom products in small quantities:
  - No need for costly tools.
  - No scrap, milling
  - Automated manufacturing
  - Use available supplies
  - Minimal inventory risk
- Ability to easily share designs and outsource manufacturing
- Speed and ease of designing and modify products

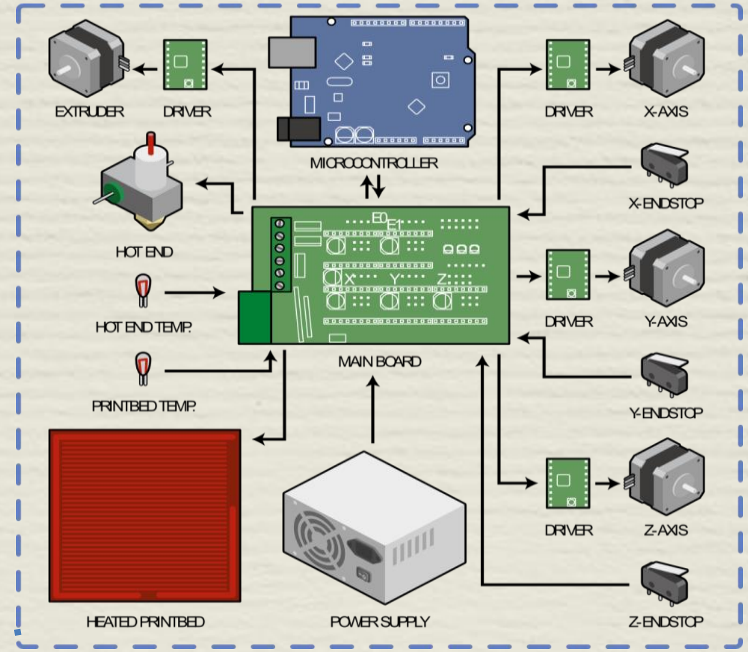
(Berman, 2013)

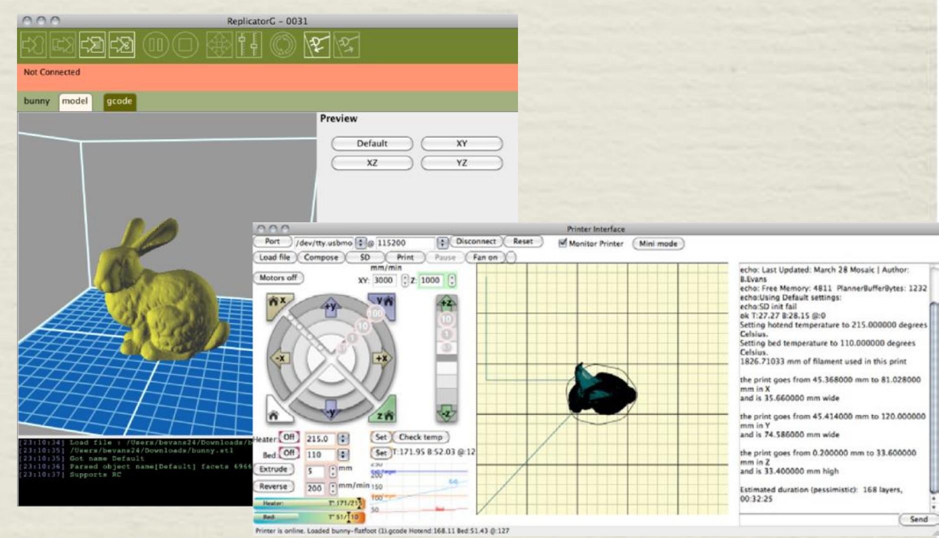
3D Printer architecture





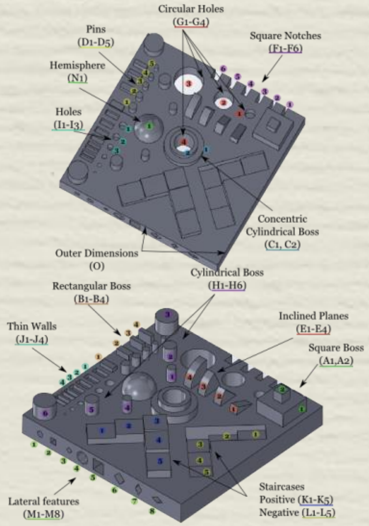






Proposition d'une méthodologie pour l'evaluation d'un machine imprimante 3D du point de vue de la précision dimensionelle.

1. Geometric Benchmarking Model



Proposition de modèle d'analyse comparative à fabriquer por l'imprimante 3D Open Source

2. Plan d'experiences

Paramèters de réglage

Paramètres de contrôle	Simbole	Value			
		1	2	3	Unités
L'épaisseur de couche	F1	0.127	0.178	0.254	mm
Largeur de route	F2	0.54	0.62	0.71	mm
Vitesse de mouvement de la tête	F3	25	50	75	mm/s

Quantité d'essais

# Essai	Facteurs		
	L'épaisseur de couche [mm]	Largeur de route [mm]	Vitesse de mouvement de la Tête [mm/s]
1	0.127	0.54	25
2	0.127	0.62	50
3	0.127	0.71	75
4	0.178	0.54	75
5	0.178	0.62	25
6	0.178	0.71	50
7	0.254	0.54	50
8	0.254	0.62	75
9	0.254	0.71	25

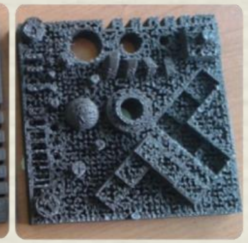
- Utilisation de la methode Taguchi.
- Sélection des paramètres de réglage à tester.
- Determination de la quantité d'essais à fabriquer.

3. Fabrication

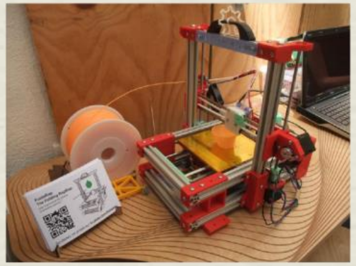
Echantillon 1

F1= 0.13mm
F2 = 0.54 mm
F3 = 25 mm/s

Echantillon 8



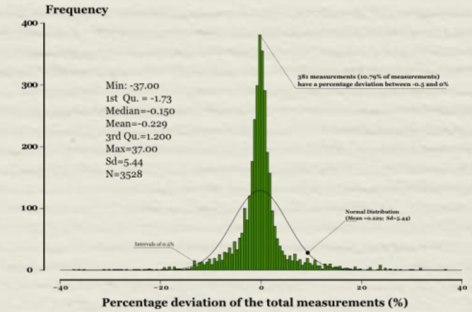
F1 = 0.25mm
F2 = 0.62 mm
F3 = 75 mm/s



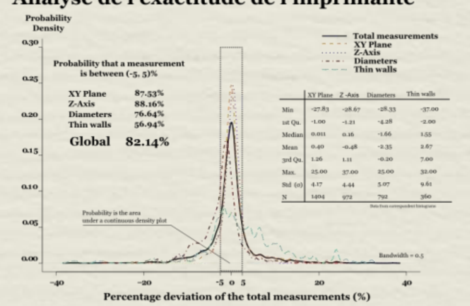
Imprimante 3D Open Source
-FoldaRap-

4. Résultats

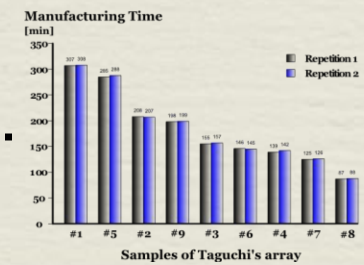
Précision géometrique de l'imprimante



Analyse de l'exactitude de l'imprimante



Temps de fabrication des échantillons



Cette méthodologie permet d'évaluer la performance géométrique d'une imprimante Open Source. À partir de cette évaluation, une comparaison quantitative entre imprimantes est établie.

Cruz Sanchez, F. A., Boudaoud, H., Muller, L., & Camargo, M. (2014). Towards a standard experimental protocol for open source additive manufacturing. *Virtual and Physical Prototyping*, *9*(3), 151–167.

Metals

- Alluminium
- Titanium
- Stainless Steel
- Gold / Silver
- Hastelloy

Plastics

- ABS
- PLA
- Polyamide (Nylon)
- PEEK
- PMMA
- PC (Polycarbonate)
- PPSU or PPSF
- Ultem
- Allumide

Ceramics

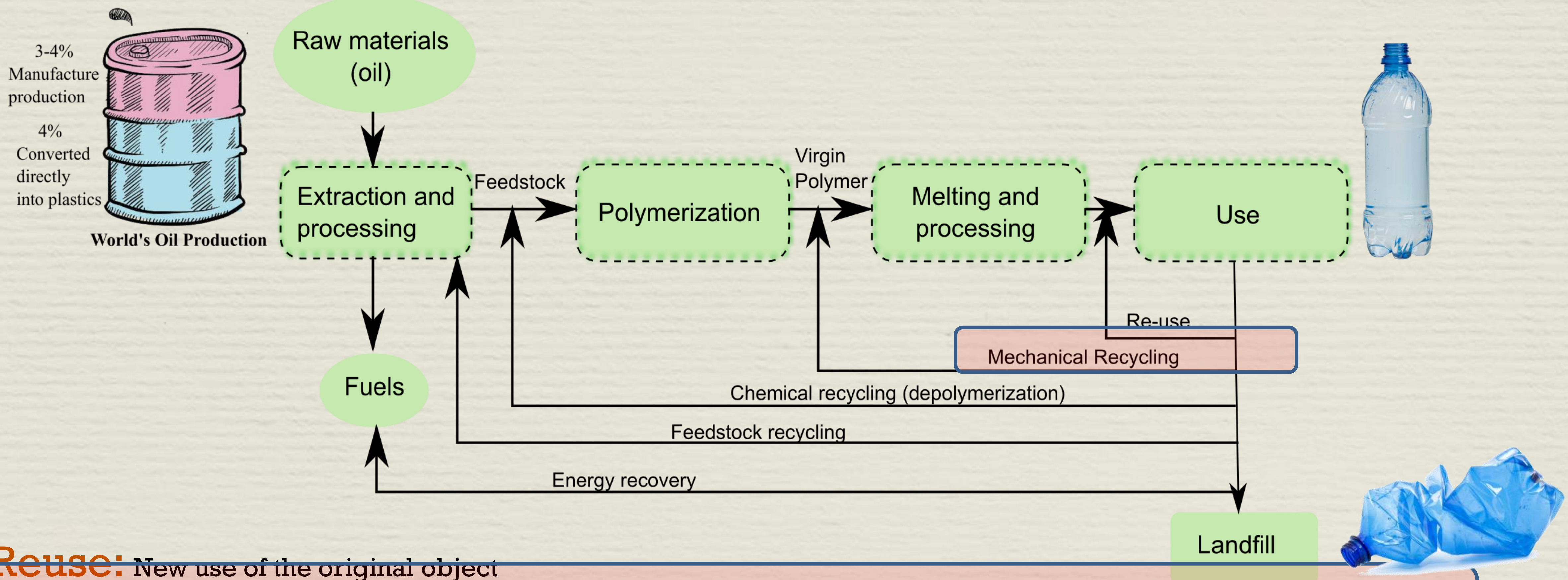
- Aluminium oxide
- Zirconium dioxide
- Silicon carbide
- Tricalcium phosphate
- Silicon
- Sulfate de calcium
- Graphite

Organics

- Cells
- Food
- Chocolate
- Paper

MATERIALS

Polymer Recycling in the literature



Reuse: New use of the original object

Mechanical Recycling: Recovers clean plastics products in order to reuse in the manufacturing process

Chemical Recycling: Recover synthesis monomers or feedstock chemicals by depolymerization.

Feedstock Recycling: Break down the solid polymeric materials into a spectrum of basic chemical components.

Energy recovery: Generation of energy (Pyrolisis)

Perugini, F., Mastellone, M. L., & Arena, U. (2005). A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. *Environmental Progress*,