WELCOME OF PARTICIPANTS AND PRESENTATION OF IAPT ACTIVITIES

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Fraunhofer IAPT located in Hamburg

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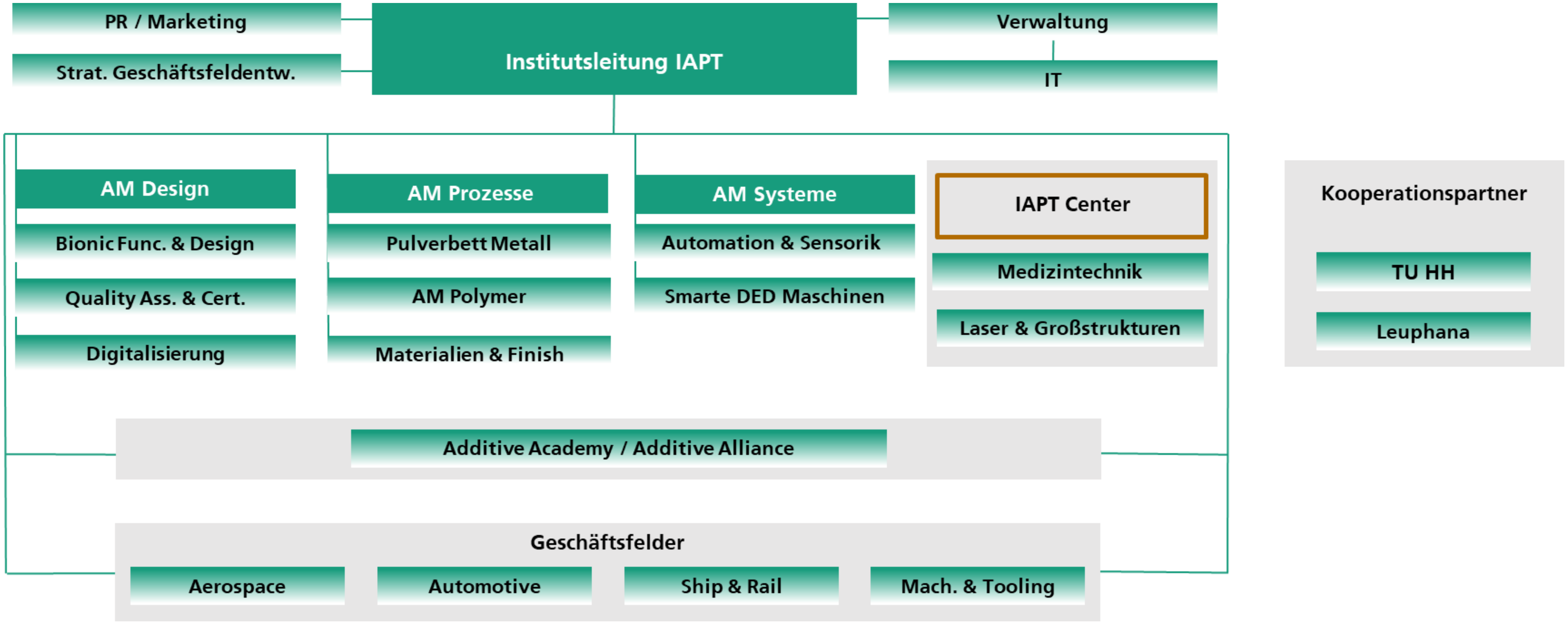
Fraunhofer IAPT

Additive Experts – AM-Supply Chain at its best!



Fraunhofer IAPT – Process Technologies

Metal (Powder bed)

SLM 500HL (SLM Solutions)

Concept M2 (Concept Laser)

EOS M290 (EOS)

TruPrint 1000 (Trumpf)

SLM 250HL (SLM Solutions)

EOS M 270 (EOS)

AconityLAB (Aconity)

DMP 350 Flex (3D Systems)

Metal (Sinter AM)

Granulatbasierte Kolbenextrusion

Renkforce Metal FFF

Desktop Metal Studio System (in acquisition)

DM P2500 Binder Jetting

Polymers

EOS P390 (EOS)

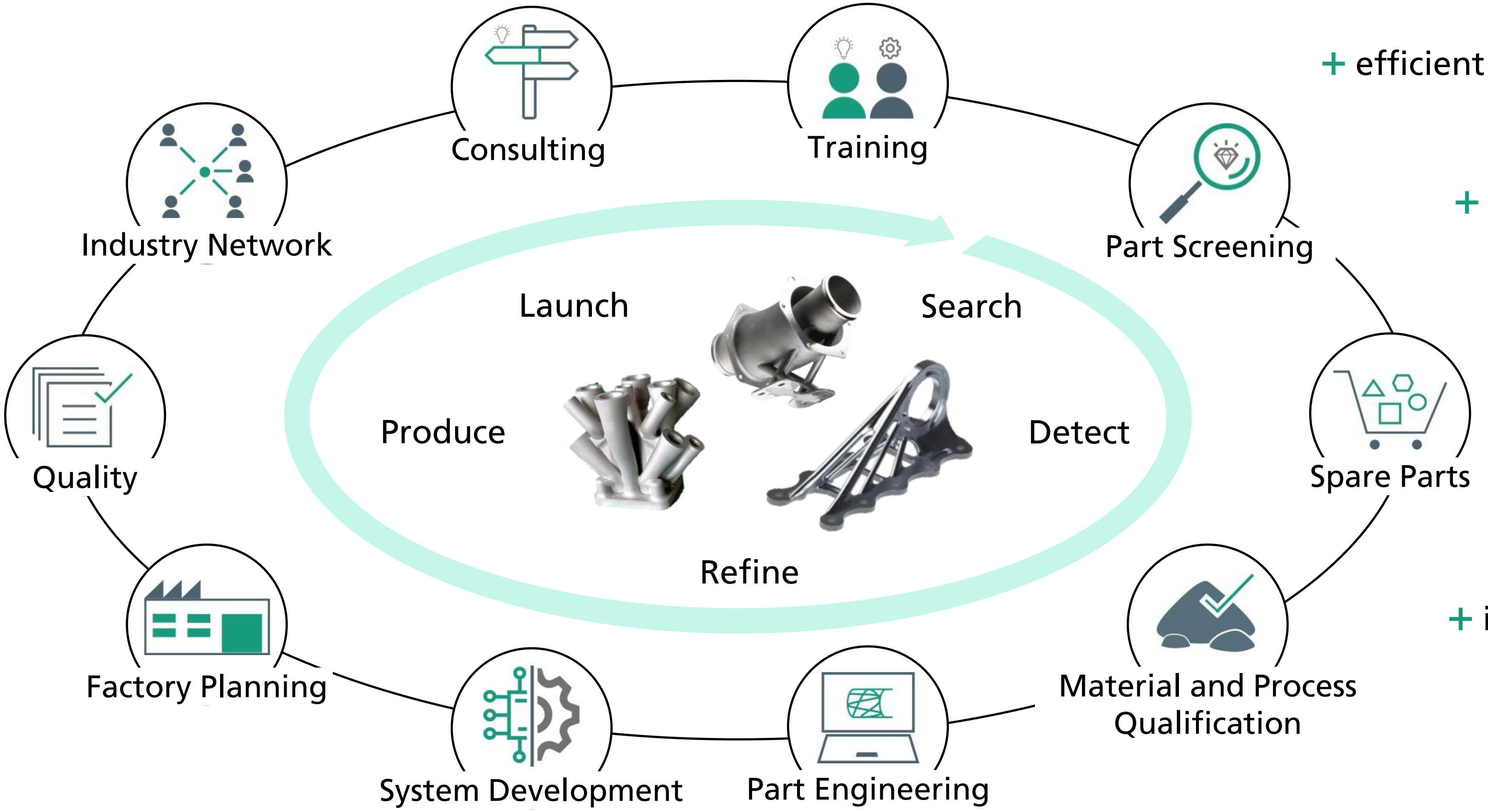
EOS P396 (EOS)

Ultimaker S5 (Ultimaker)

Fortus 450mc (Stratasys)

Quellen: SLM Solutions, Concept Laser, EOS, Trumpf, 3D Systems, Aconity, Desktop Metal, Stratasys

Fraunhofer IAPT – our expertise for your competitiveness



+ efficient material utilization

+ increasing functionality

+ time saving

+ decreasing costs

+ improved quality

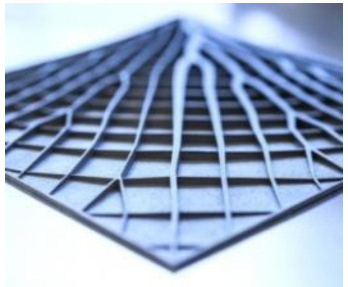
AM-Competence: Leading experience and award milestones

Finalist of "Innovationspreis der deutschen Wirtschaft" 2014 award

Fraunhofer IAPT
CONCEPTLASER
AIRBUS

First additively manufactured metal part for civil aircraft

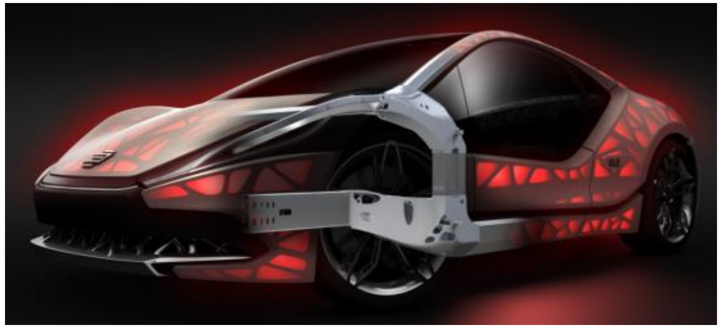
Deutscher Zukunftspreis 2015 – Part of the „Circle of the best"



Fraunhofer IAPT
CONCEPTLASER
AIRBUS

3D printing in civil aircraft production – the next industrial revolution takes off

Materialica Design + Technology Award 2016



Fraunhofer IAPT
CONCEPTLASER
BLM GROUP
EDAG

Next Generation Spaceframe

2017/18: Pioneering application of AM in serial production of automotive components

Fraunhofer IAPT
BUGATTI
BIONIC PRODUCTION

World's largest 3D printed titanium part!

public

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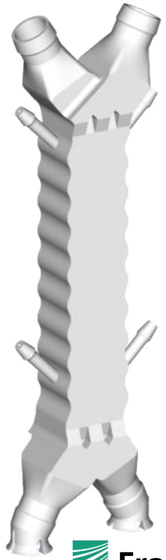
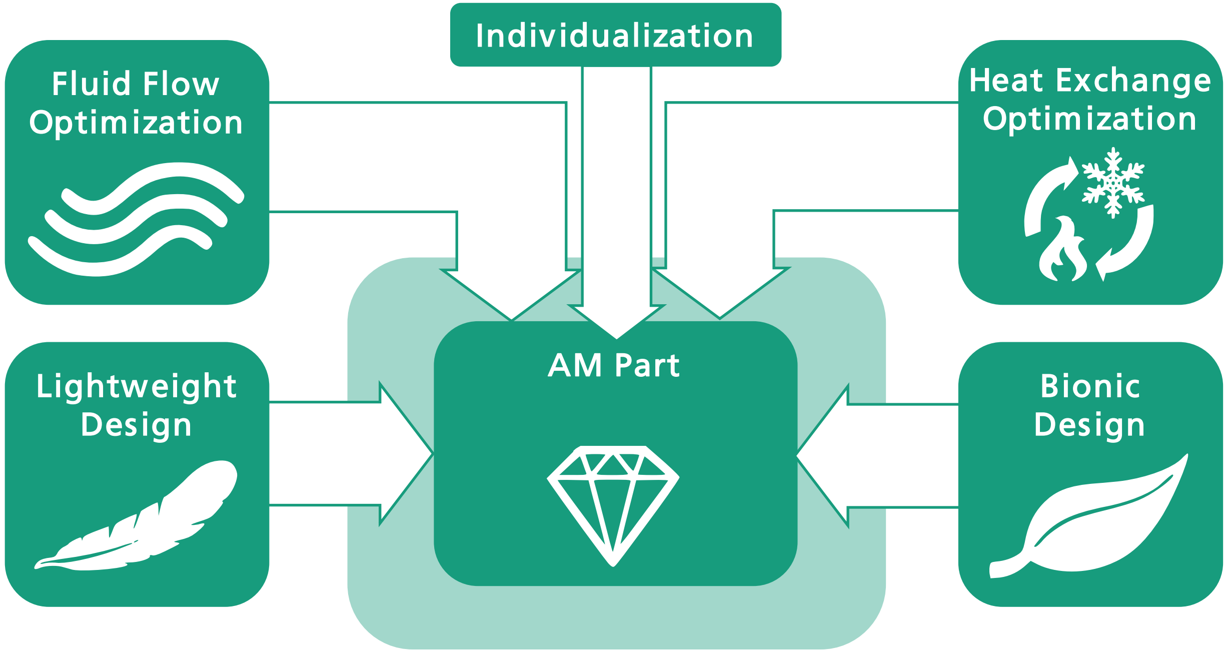
Product design in the context of AM


iLAS
Institute of Laser and System Technologies
Hamburg University of Technology
Fraunhofer
IAPT




Fraunhofer
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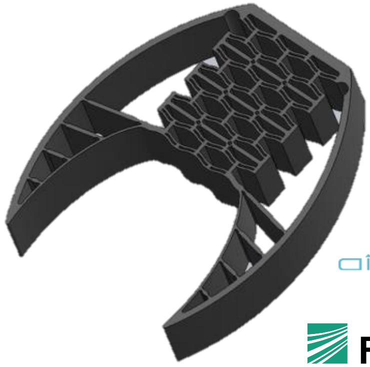
LIGHTWORKS
PASSION FOR LIGHT


AIRBUS
Fraunhofer
IAPT
CONCEPTLASER
a GE Additive company


NASA
DLR
Fraunhofer
IAPT


BIBA
AKON-CAD
Service & Robotics
airstage
We make it fly!
Fraunhofer
IAPT


Fraunhofer
IAPT
BUGATTI
BIONIC PRODUCTION

© Fraunhofer / Marc Steinmetz

Fraunhofer
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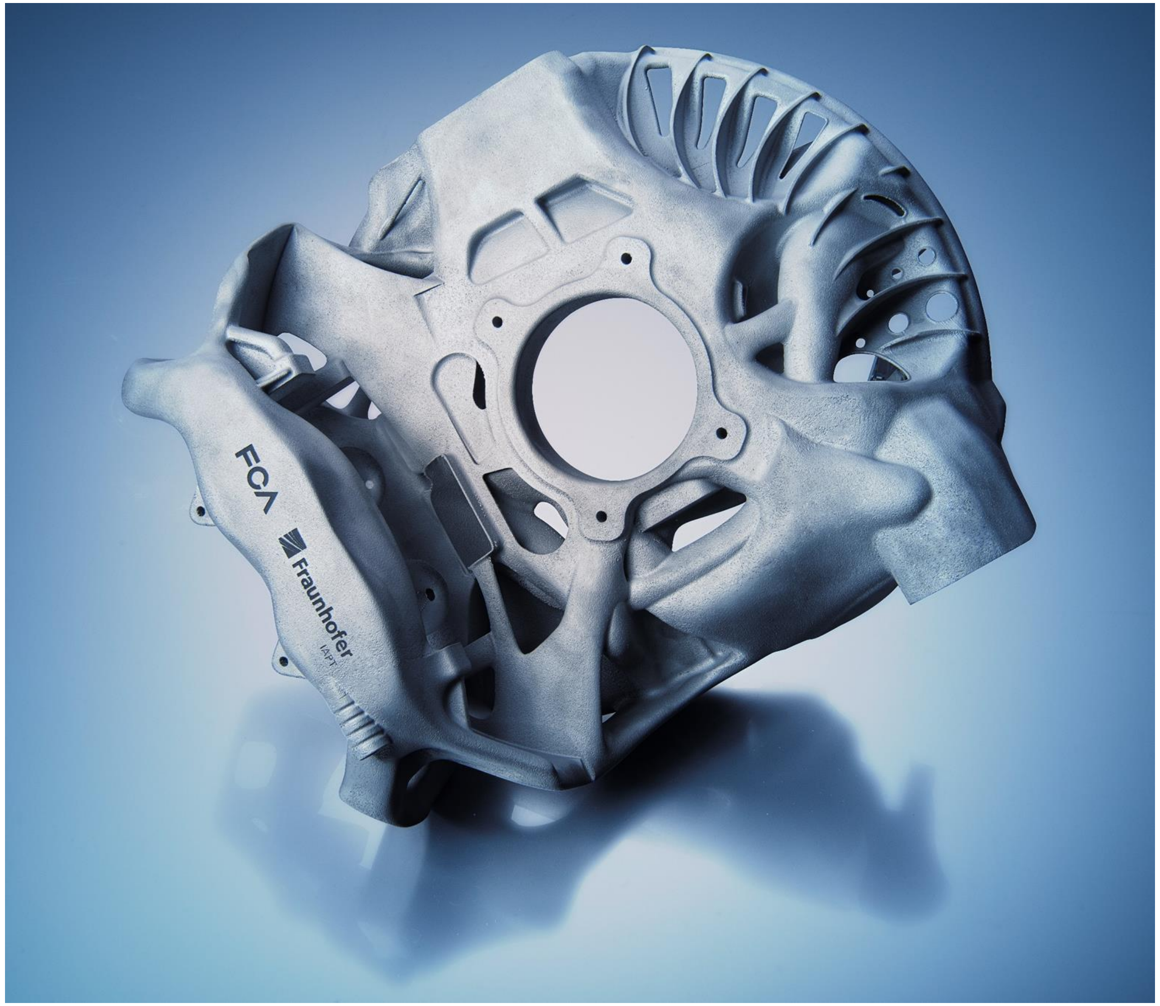
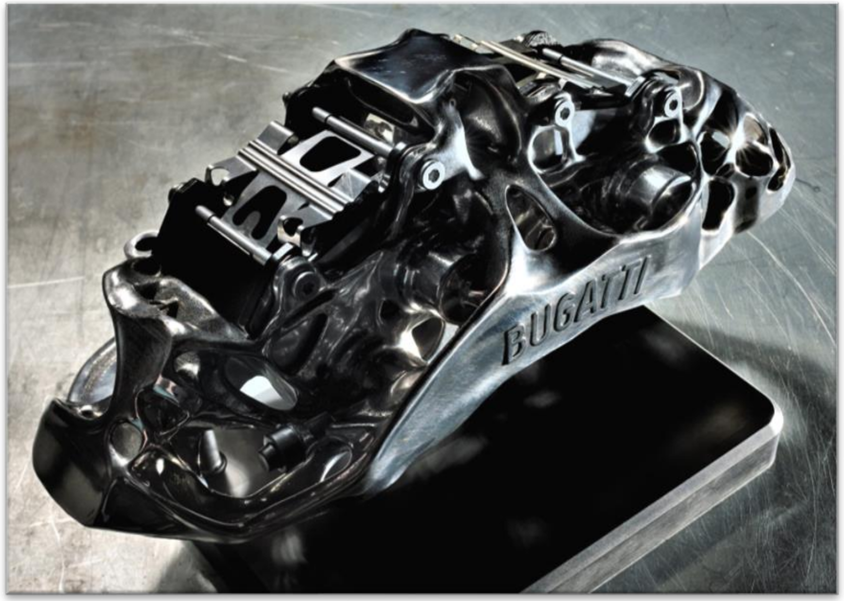
FCA Integrated Wheel Carrier

- Weight: 3.36 kg – 36% lighter
- 12 Parts Integrated to 1
- Material: AlSi10Mg
- Part size: ~345x280x146 mm^3



New eight-piston monobloc brake caliper is the world's first brake caliper to be produced by 3-D printer

- A cooperation between Bugatti, Bionic Production AG and Fraunhofer IAPT
- Designed by Bugatti, prepared and printed at Fraunhofer IAPT
- Caliper to be trialled for series production this year
- Manufactured on SLM500HL with four 400-watt lasers
  - 2,213 layers ~ 45h print time
- Largest 3D printed functional titanium part
  - 410 mm x 210 mm x 136 mm
- Material: Ti6Al4V
- **41% lighter (2,9kg)**



In cooperation with:

BUGATTI

BIONIC PRODUCTION

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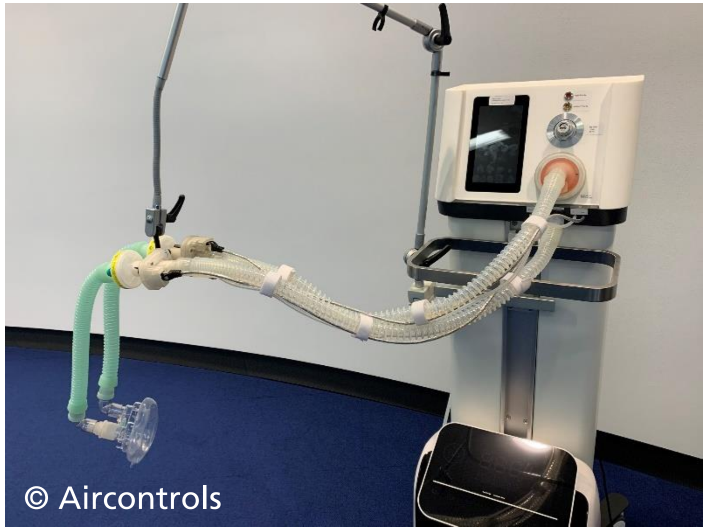
Give a Breath Challenge:
Smart CPAP (Continuous Positive Airway Pressure)

SCAN ME

- Development of a versatile, affordable CPAP for Covid-19 partients to support breathing ahead of intubation
- Designed for decentral on-site production at the countries in need
- All components are readiliy available off-the-shelf or 3D-printed



AIRCONTROLS

Fraunhofer ITEM

Fraunhofer IAPT

Additive Manufacturing - A product developer‘s dream!?

Airbus Innovation Cell, Fraunhofer IAPT

Airbus Innovation Cell, Fraunhofer IAPT

iLAS TUHH

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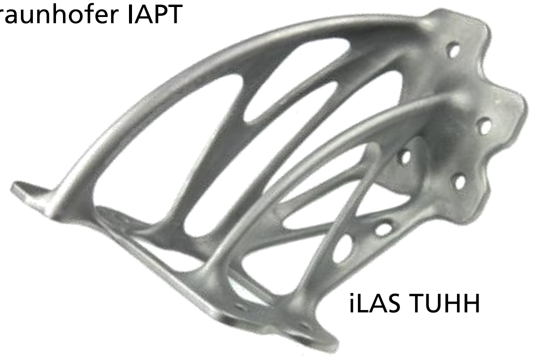

iLAS TUHH

Implantcast, Fraunhofer IAPT

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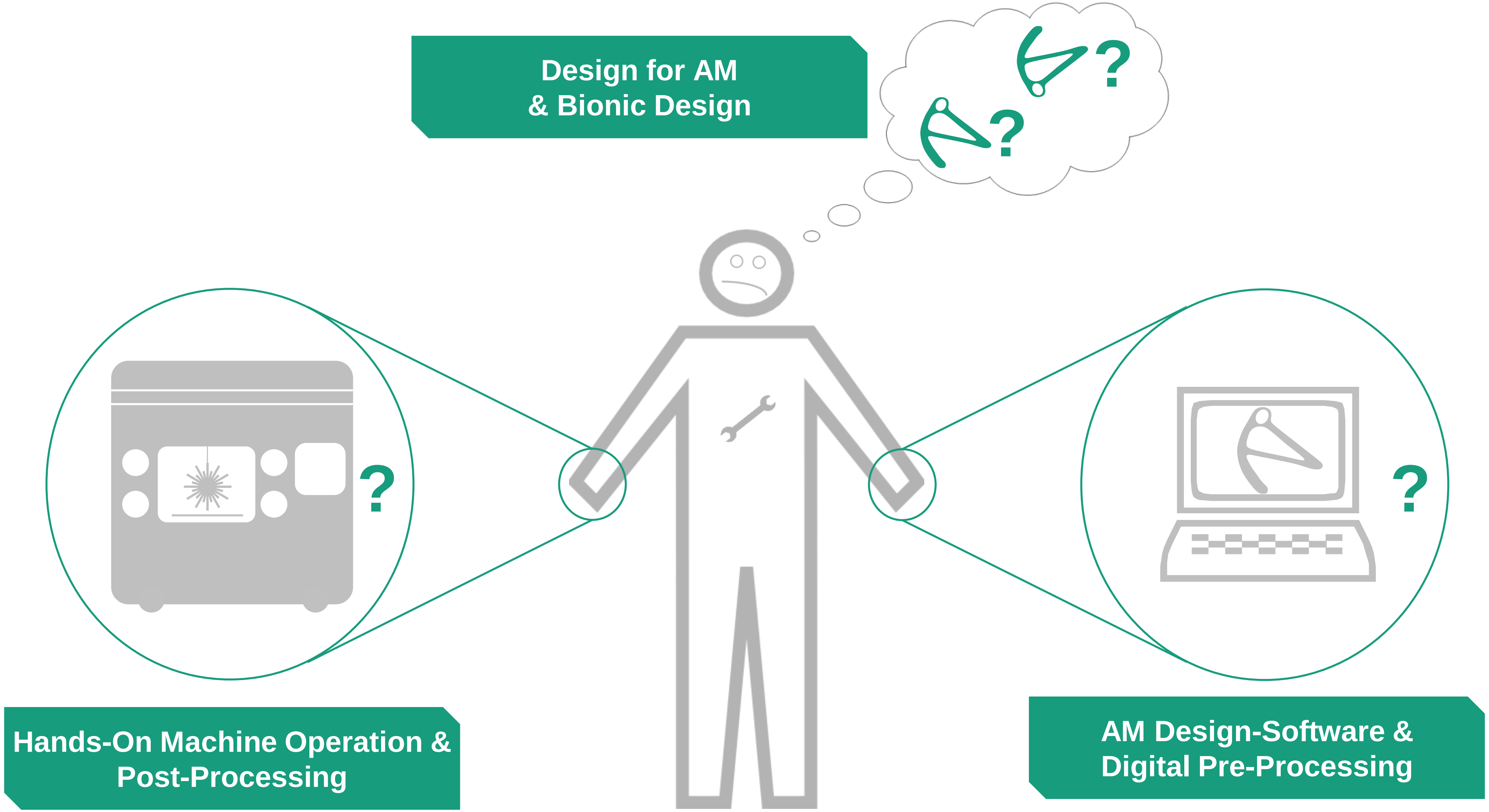
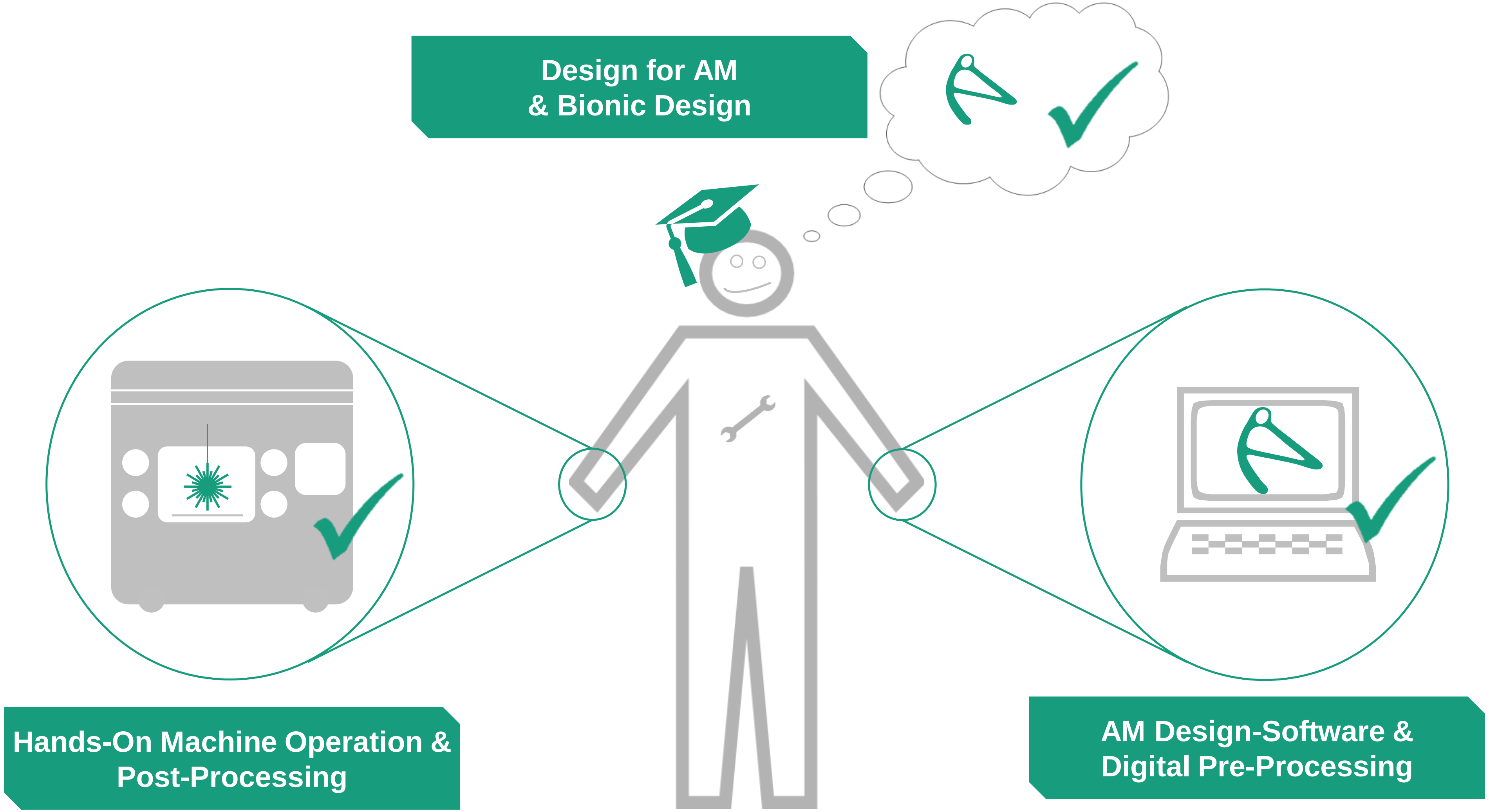
The knowledge gap in design for Additive Manufacturing



The knowledge gap in design for Additive Manufacturing



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Additive Academy – Numbers & Facts

2014 Established since	**25** Experienced trainers	**1200** Trained participants
Worldwide Trainings execution	**Excellent** Participant's feedback	**Independent** Machine park & software

Additive Academy – Worldwide leading AM-Competence-Transfer

	Design	Production	Management
Starter	Basic Training *	Basic Training *	Learning Expedition
	Design for AM Training		
Advanced	Hands-on Training *	Hands-on Training *	Management Deep Dive
	Bionic Design Training		
Expert	Bionic Design Expert Training	Data Preparation Workshop	Strategy Workshop
	Design Workshop	Powder Workshop	

* Based on metal or polymer AM technology

Implementation

- Design Challenge
- Part Feasibility Screening

Customer-specific modification of training content possible

Additive Academy – A selection of reference customers

- Our customers from SEMs and Business Consultancies to Industrial Groups

Additive Academy – Our References

„Das engagierte Trainerteam des Fraunhofer IAPT vermittelt einen tiefen Einblick in Fragestellungen rund um die Additive Fertigung.“

Florens Lichte
Leiter Konzernprojekt 3D-Druck / Head of Additive Manufacturing, DB Fahrzeuginstandhaltung GmbH

DB Mobility Networks Logistics

„Die exzellenten Schulungen des Fraunhofer IAPT zur Additiven Fertigung beschleunigen den Change-Prozess unserer Konstruktion “

Peter Sander
Head of Emerging Technologies & Concepts, Airbus Operations GmbH

AIRBUS

public

Fraunhofer IAPT

What about you and your AM Experience?

Introcution to Additive Manufacturing Technology Transfer

Contact me on LinkedIn for signing in!

Webinars & Workshops | Online-Conference Design for AM | LinkedIn Channel

Thank you for your attention!

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FUNDAMENTALS OF ADDITIVE MANUFACTURING (AM)

Unit 1

Fraunhofer
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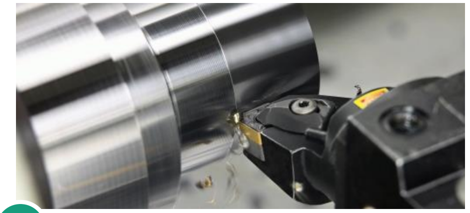
AGENDA

1. Basics of AM
2. Market Trends of AM
3. Technical Readiness Levels (TRL)

AGENDA

Classification of Manufacturing Technologies

Manufacturing Technologies



1 Subtractive Manufacturing

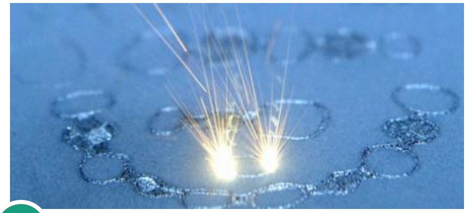
- Ablation of defined areas
- Processes: turning, milling

Photo: roemer-aschinenbau.de

2 Formative Manufacturing

- Forming of a defined volume
- Processes: forging, casting

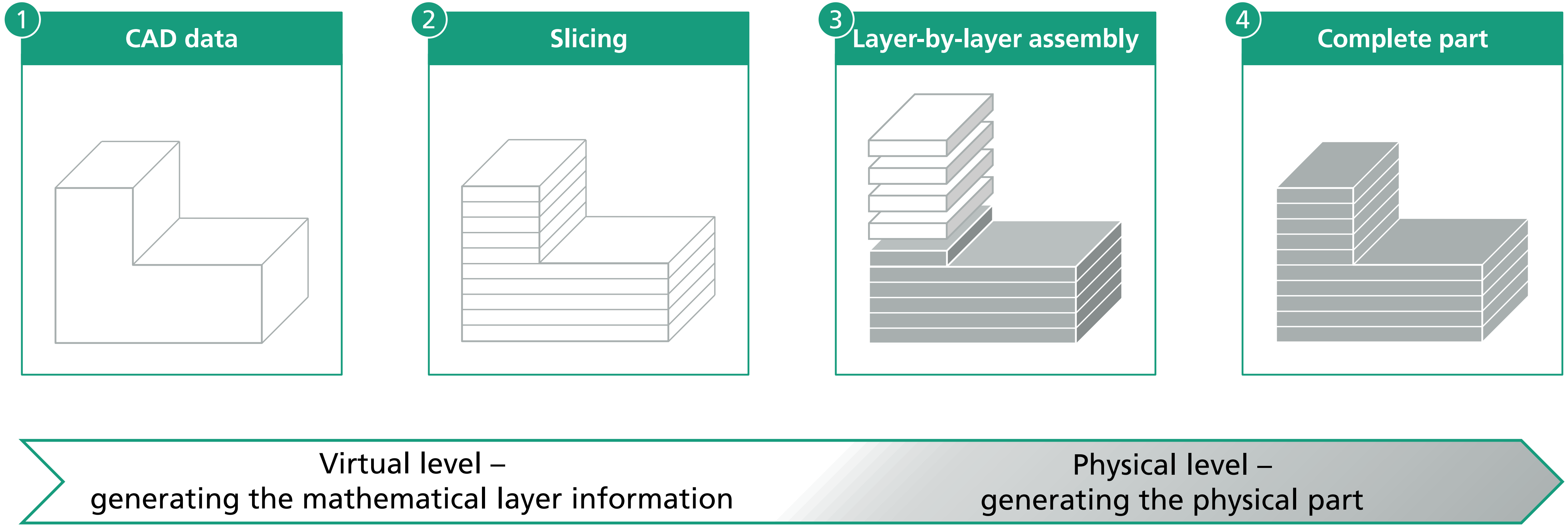
Photo: Wikioedia.de



3 Additive Manufacturing

- Joining of volume elements (voxel)
- Layerwise build up
- Processes: LBM, DED, FDM

Basic Principle of Additive Manufacturing (1/3)



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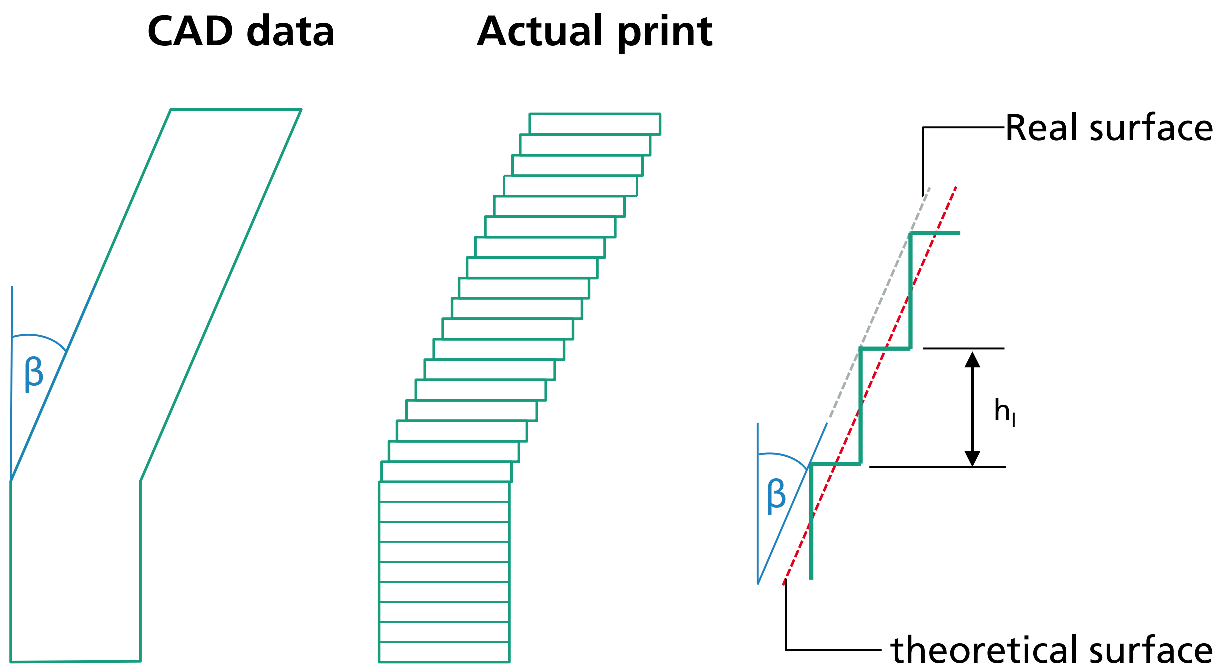
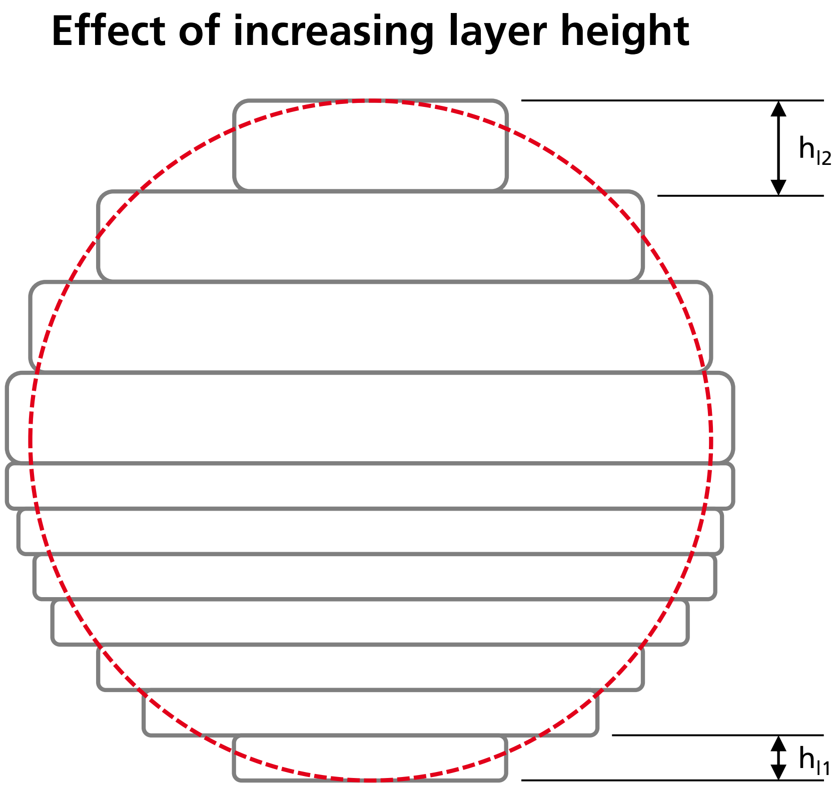
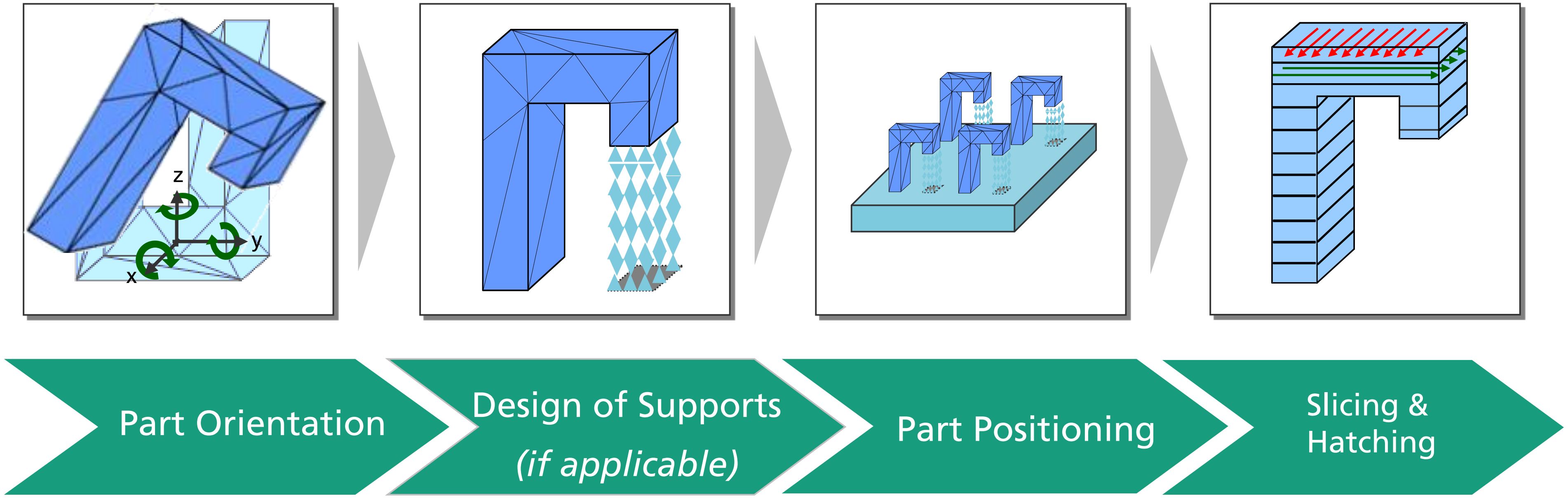
Basic Principle of Additive Manufacturing (2/3)



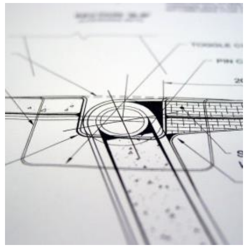


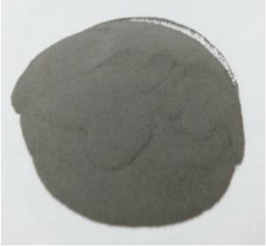
- Stair case effect caused by layer-by-layer part manufacturing
- Stair case effect increases with increasing layer height (h_l)

Basic Principle of Additive Manufacturing (3/3)



Process Chain of Additive Manufacturing





Data and Process Preparation → Additive Manufacturing Process → Finishing

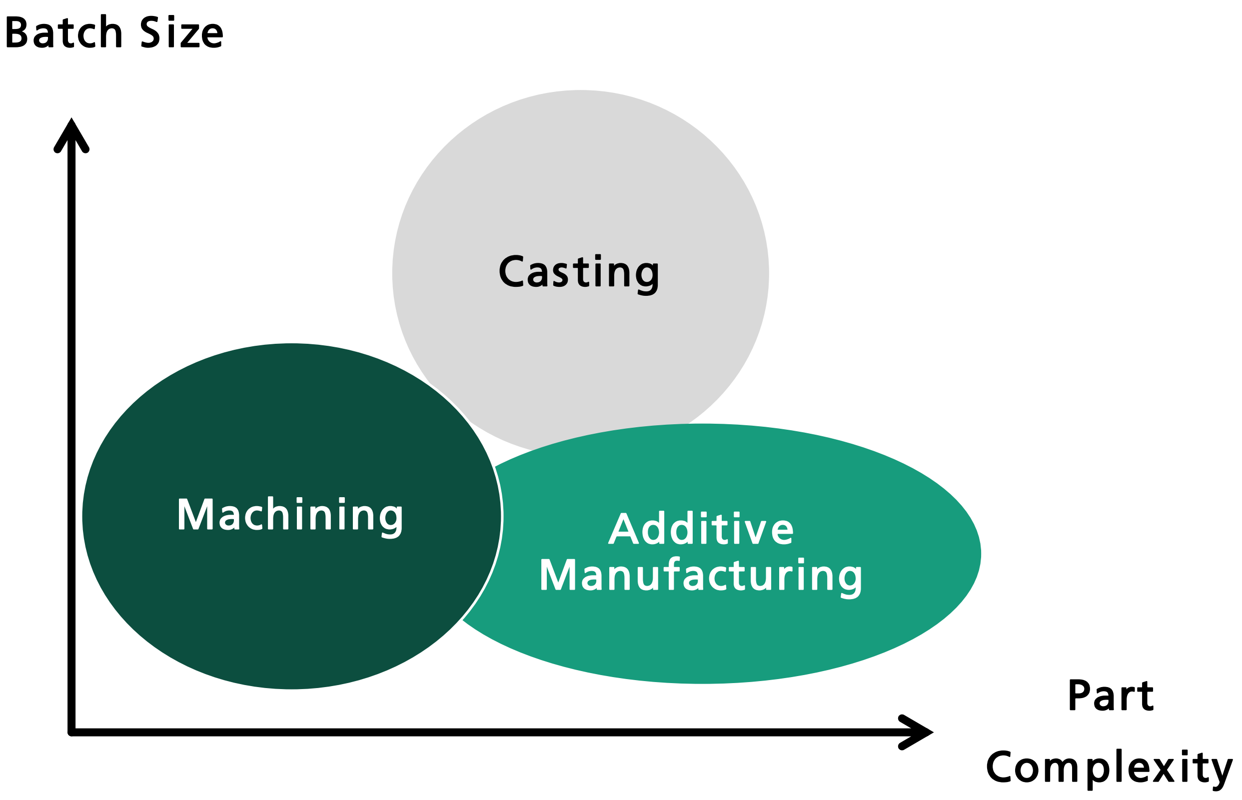
Data and Process Preparation
- Design
- Reverse Engineering
- Data optimization

Additive Manufacturing Process

Finishing
- Cleaning
- Removing of Supports
- Conv. Processing
- …

Quality Assurance

AM of Metals Compared to Conventional Manufacturing



Additive Manufacturing is filling a niche that is not covered properly by conventional manufacturing methods.

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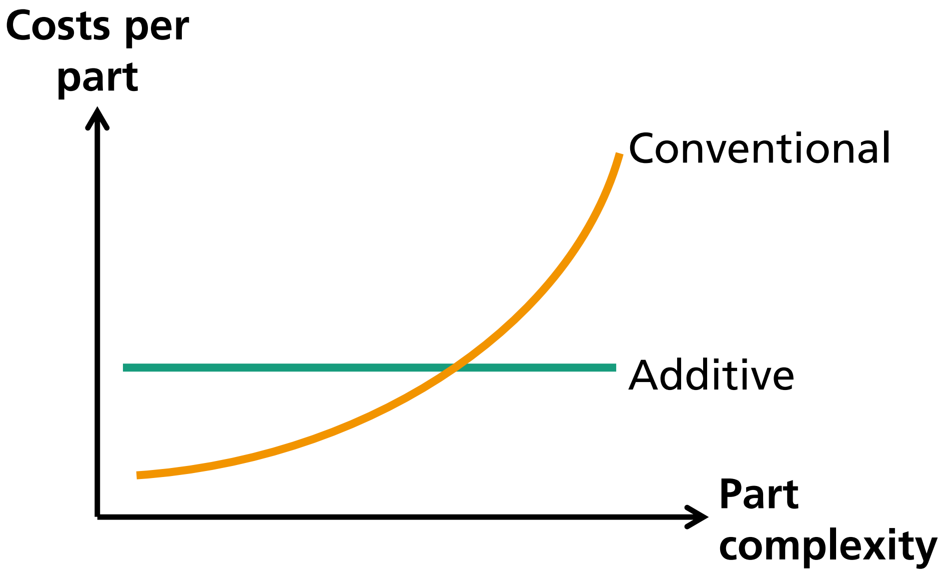
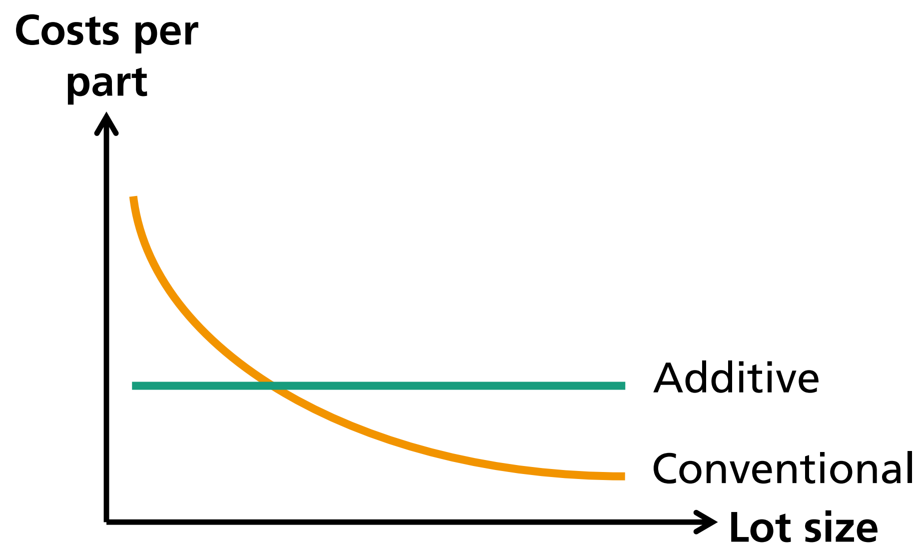
Major AM Potentials



Part complexity for free

Major AM Potentials



Mass customization

AGENDA

1 Basics of AM

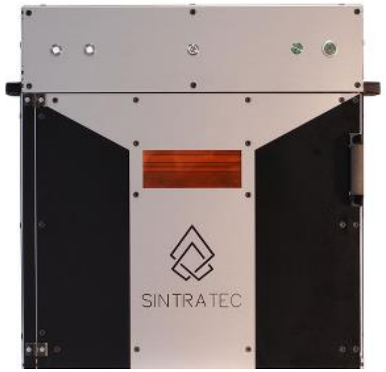
2 Market Trends of AM

3 Technical Readiness Levels (TRL)

The Industrial 3-D Printing Revolution Has Begun

Desktop 3D printer

- Desktop printer for polymer materials are conquering schools, universities, and offices.
- Pricing range: € 200 - € 10,000



Industrial 3D printer

- Powder and filament based AM technologies are shifting into production. End-use polymer and metal parts are manufactured especially for aerospace, medical, machinery and tooling applications.
- Pricing range: € 10,000 - € 1,500,000

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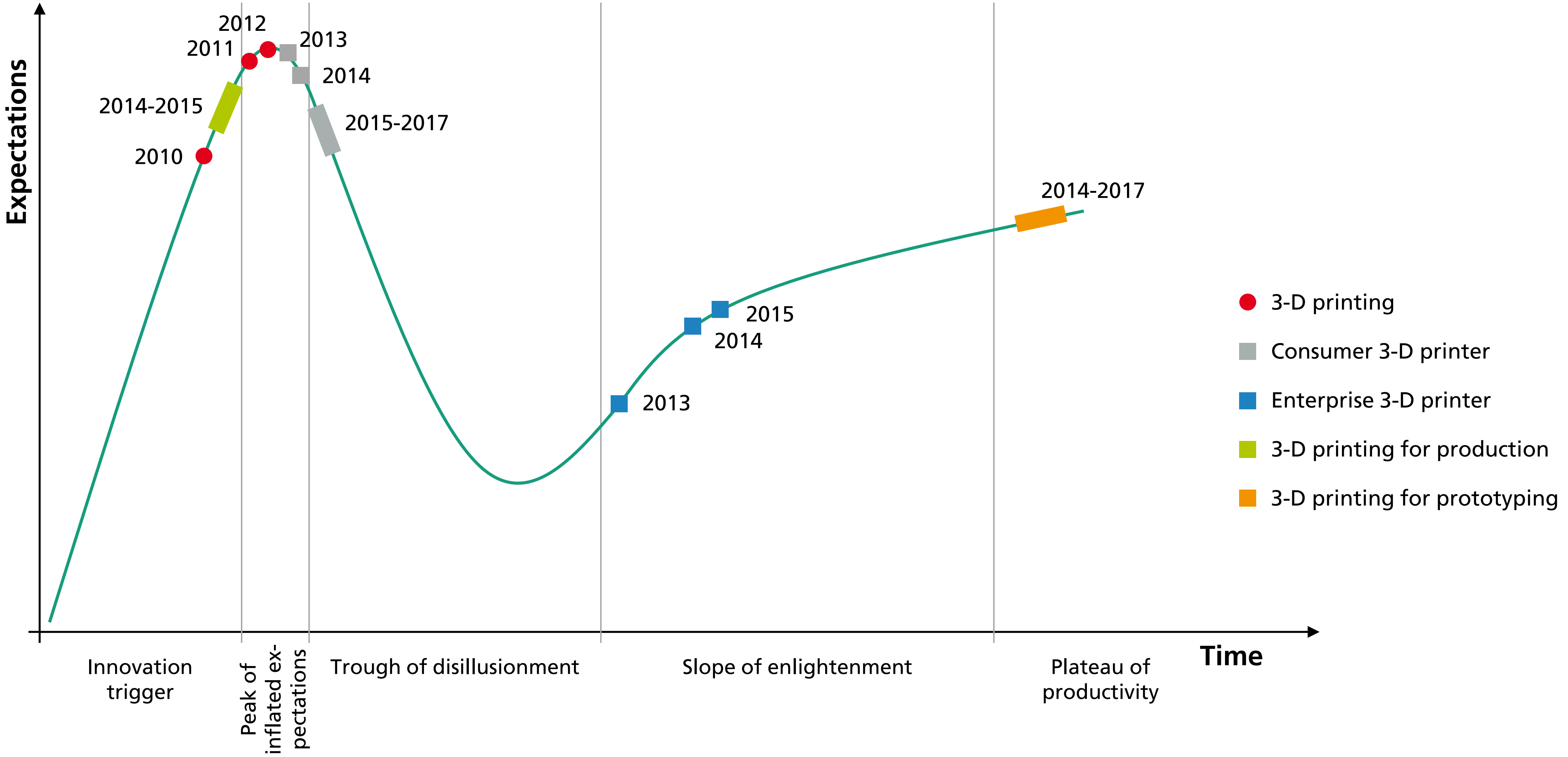
Gartner´s Hype Cycle for Emerging Technologies (2010-2017)



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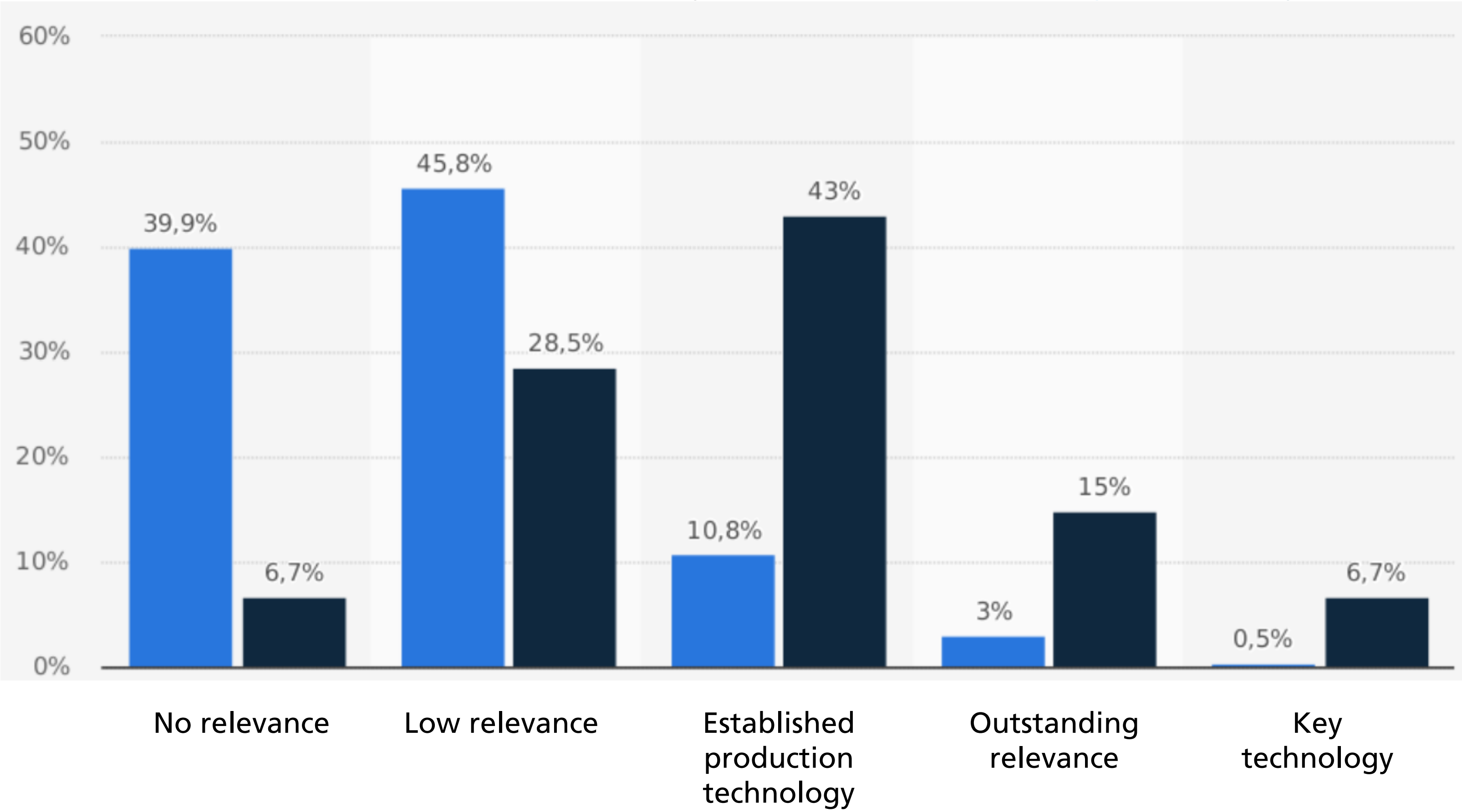
Additive Manufacturing on its Way to Production

Which relevance does AM have for your production (today / in 5 to years)?



- At the moment, it is expected that AM will not disruptively revolutionize industry completely and not ban conventional manufacturing technologies
- But AM will be established across all industries for several applications as an additional manufacturing technologies

Germany: 203 participants from different industries (2-step delphi survey)

Source: Fraunhofer IPA

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AGENDA

1. Basics of AM
2. Market Trends of AM
3. Technical Readiness Levels (TRL)

The Technology Readiness Level

	10	Full rate production
Production Implementation	9	Low rate production
	8	Pilot line capability demonstrated
	7	Production in production environment demonstrated
Pre-Production	6	Systems produced (near production environment)
	5	Basic capabilities shown (near prod. environment)
Technology Assessment & Proving	4	Technology validated in laboratory environment
	3	Manufacturing proof of concept developed
	2	Manufacturing concept identified
	1	Basic manufacturing implications identified

Technology Readiness: Aerospace Industry

TRL 6-7: Titanium (Airbus)

- First civil application are going to serial production

TRL 9: FDM Ultem (Airbus)

- Fully certified flying cabin parts in serial production and after sales + tools & customized solutions

TRL 9: Polyamide 22FR (Boeing)

- Used since years for venting & air ducts on many programs

TRL 9-10: Cobalt-Chrome (GE)

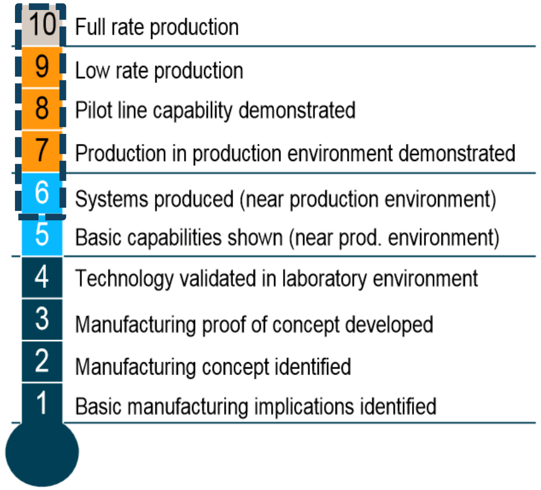
- Fuel Nozzle flight tested and in mass production

TRL 9: Inconel (MTU)

- Ramp-up of serial production for the engines

First players on the verge of (part specific) TRL 10

Technology Readiness Level (TRL)



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Technology Readiness: Medical & Dental Industry

TRL 10: Titanium

- More than 100.000 Hip Implants were manufactured using SLM & EBM technology.

TRL 10: Cobalt-Chrome

- >12.000 Crowns and Copings for dental usage are produced daily

TRL 10: Polymers

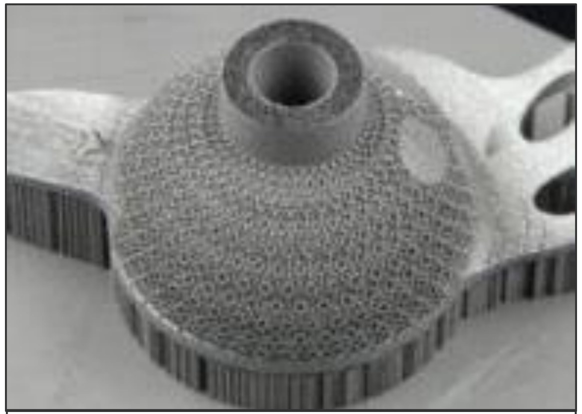
- Around 50% of all hearing aids are today manufactured

- Mass production of Surgical Guides in SLS

TRL 9: (Stainless) Steel

- Customized medical instruments for surgeons

Most advanced industry; driver → customization



Technology Readiness Level (TRL)

- 10 Full rate production
- 9 Low rate production
- 8 Pilot line capability demonstrated
- 7 Production in production environment demonstrated
- 6 Systems produced (near production environment)
- 5 Basic capabilities shown (near prod. environment)
- 4 Technology validated in laboratory environment
- 3 Manufacturing proof of concept developed
- 2 Manufacturing concept identified
- 1 Basic manufacturing implications identified

Technology Readiness: Automotive

TRL 6-8: Metals

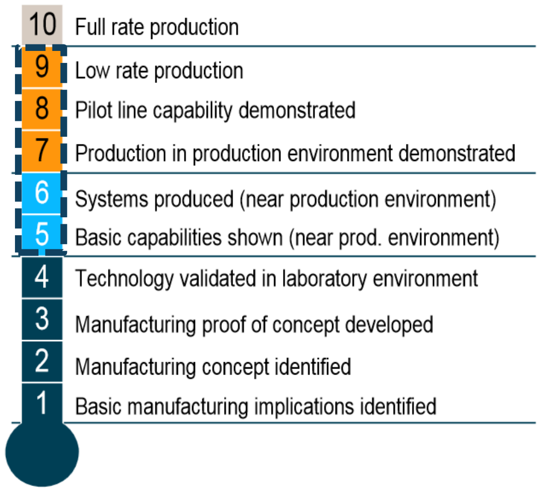
- Focus on product development (prototyping), Tooling and exotic small series
- Broader usage in motor sports & Formula 1 (e.g. gearboxes & exhaust systems)
- First application ins after-sales (esp. classic cars)
- Lightweight parts are examined for electrical cars
- First applications on luxury cars at Bugatti, Audi and BMW are on the verge to serial production

TRL 6-9: Polymers

- Rolls Royce Phantom is using 10.000 parts in small serial production (e.g. hazard flush, sockets and other polymer clips)
- Daimler is starting 2016 to use SLS for small series and repair of Trucks
- PA12 & ABS: Prototyping for interior parts (dashboard, doors,…)
- BMW is customizing e.g. interior for Mini

First automotive application are going to serial production

Technology Readiness Level (TRL)



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Technology Readiness: Tooling & Machine Building

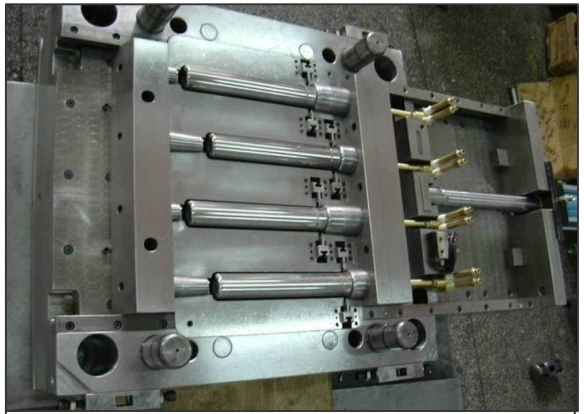
TRL 9: Steel

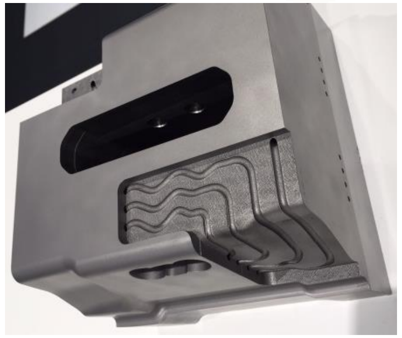
- Tool manufacturer Mapal is using steel (1.2709) for serial production of hybrid drills with optimized cooling channels
- LBM enables smaller drills (8-12mm diameter) compared to traditonal manufacturing

- Additive steel tools for deep drawing, stamping and moulding applications

TRL 9: Aluminium & Polymers

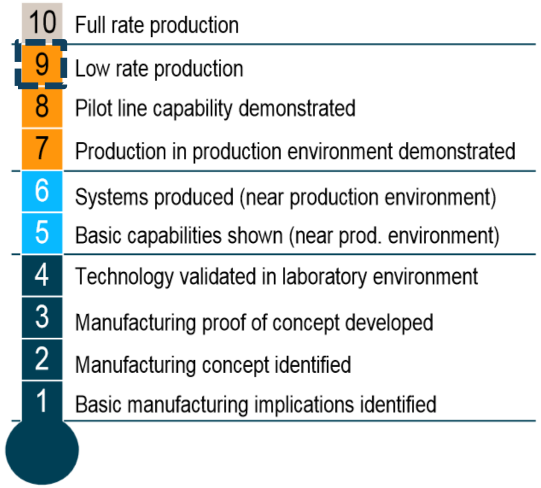
- Used for various applications in final part production





> Lower qualification burdens lead to greater adoption

Technology Readiness Level (TRL)



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Thank you for your attention!

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OVERVIEW & BENCHMARK OF DIFFERENT POLYMER AND METAL AM TECHNOLOGIES

Unit 2

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AGENDA

1 Metal based AM Technologies

2 Polymers based AM Technologies

AM Technologies – Overview

Additive Manufacturing Technologies

(Powder) Bed Systems
- Laser Beam Melting (LBM)
- Electron Beam Melting (EBM)
- Selective Laser Sintering (SLS)
- Binder Jetting (BJ)
- Multi Jet Fusion (MJF)

Nozzle Systems
- Fused Deposition Modeling (FDM)
- Metal Droplet Deposition
- Multi Jet Modeling (MJM)

Directed Energy Deposition (DED)
- Wire Feed Laser Beam Melting
- Laser Metal Deposition (LMD)
- Wire Feed Electron Beam Melting

Liquid Resin Systems
- Stereolithography (STL)
- Polyjet Process (PJP)
- Continuous Liquid Interface Production (CLIP)

Hybrid Systems
- DMG Mori Lasertec
- Matsuura Lumex

Metal

Polymers

AGENDA

1 Metal based AM Technologies

2 Polymers based AM Technologies

AM Technologies – Overview

Additive Manufacturing Technologies

(Powder) Bed Systems	Nozzle Systems	Directed Energy Deposition (DED)	Liquid Resin Systems	Hybrid Systems
Laser Beam Melting (LBM)	Fused Deposition Modeling (FDM)	Wire Feed Laser Beam Melting	Stereolithography (STL)	DMG Mori Lasertec
Electron Beam Melting (EBM)	Metal Droplet Deposition	Laser Metal Deposition (LMD)	Polyjet Process (PJP)	Matsuura Lumex
Selective Laser Sintering (SLS)	Multi Jet Modeling (MJM)	Wire Feed Electron Beam Melting	Continuous Liquid Interface Production (CLIP)	
Binder Jetting (BJ)				
Multi Jet Fusion (MJF)				

Metal

Polymers

public

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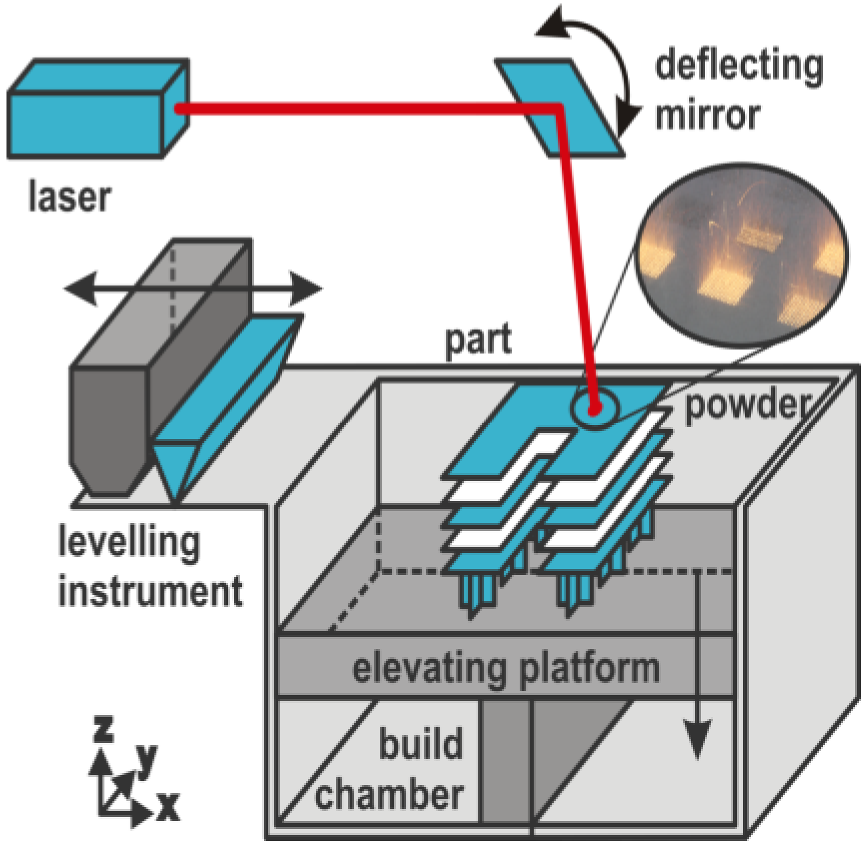
Laser Beam Melting (LBM)

(Referred to as: Selective Laser Melting (SLM); Laser Additive Manufacturing (LAM), Direct Metal Laser Sintering (DMLS), LaserCusing)



Fabrication Process:

- Powdered material selectively melted, which fuses during solidification
- Thermal radiation by laser up to 1kW
- Support structures needed

Materials:

- All weldable metal alloys
  e.g. aluminum, titanium, stainless steel, Inconel

Secondary Processes:

- Support structure removal, peening, laser-assisted material removal, conventional finishing
- Heat treatment often necessary

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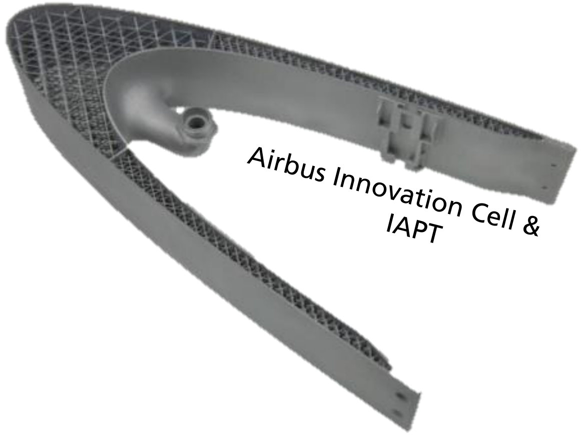
Laser Beam Melting (LBM)

Source: SolidConcepts

Laser Beam Melting (LBM) - Applications

iLAS TUHH

iLAS & IAPT (GenFLY Project)



Airbus Innovation Cell & IAPT

implantcast & IAPT

AM Technologies – Overview

Additive Manufacturing Technologies

(Powder) Bed Systems
- Laser Beam Melting (LBM)
- Electron Beam Melting (EBM)
- Selective Laser Sintering (SLS)
- Binder Jetting (BJ)
- Multi Jet Fusion (MJF)

Nozzle Systems
- Fused Deposition Modeling (FDM)
- Metal Droplet Deposition
- Multi Jet Modeling (MJM)

Directed Energy Deposition (DED)
- Wire Feed Laser Beam Melting
- Laser Metal Deposition (LMD)
- Wire Feed Electron Beam Melting

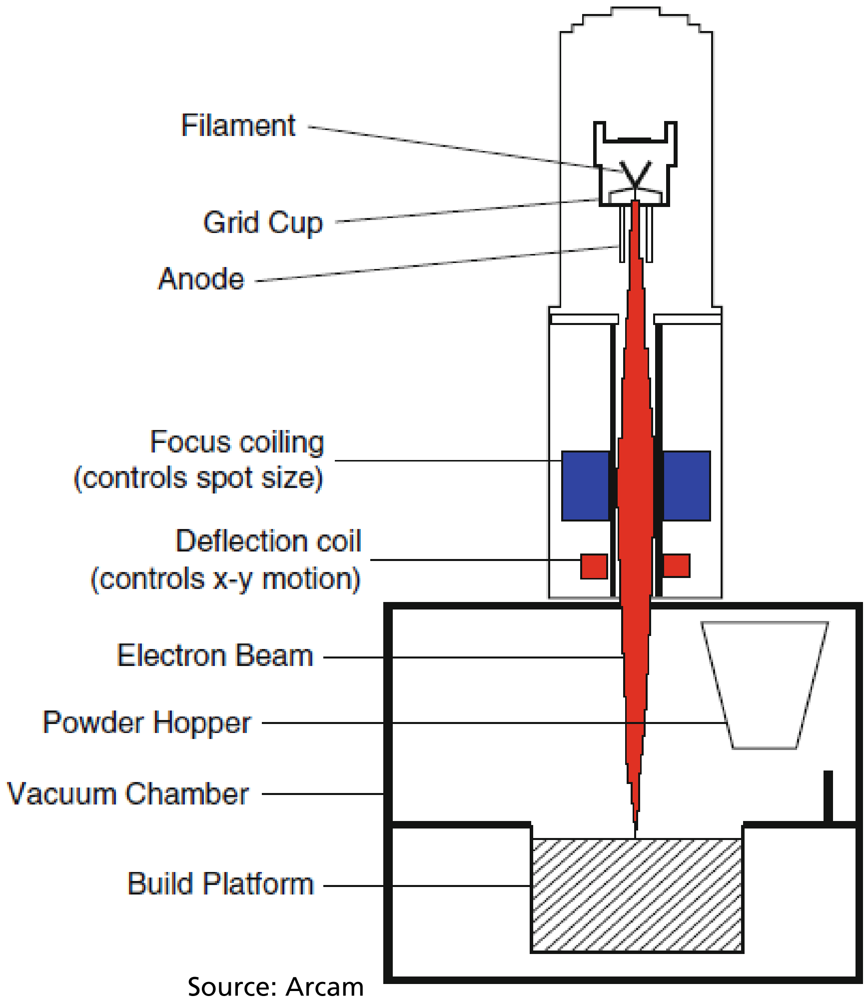
Liquid Resin Systems
- Stereolithography (STL)
- Polyjet Process (PJP)
- Continuous Liquid Interface Production (CLIP)

Hybrid Systems
- DMG Mori Lasertec
- Matsuura Lumex

Metal

Polymers

Electron Beam Melting (EBM)



Source: Arcam

Fabrication Process:

- Powdered material selectively melted, which fuses during solidification
- No Support structures needed

Materials:

- Titanium, Cobalt chrome and Inconel

Secondary Processes:

- Support structure removal, peening, laser-assisted material removal, conventional finishing

Process Characteristics

- Preheating of powder with defocussed electron beam
- Powder layers > 100 µm possible

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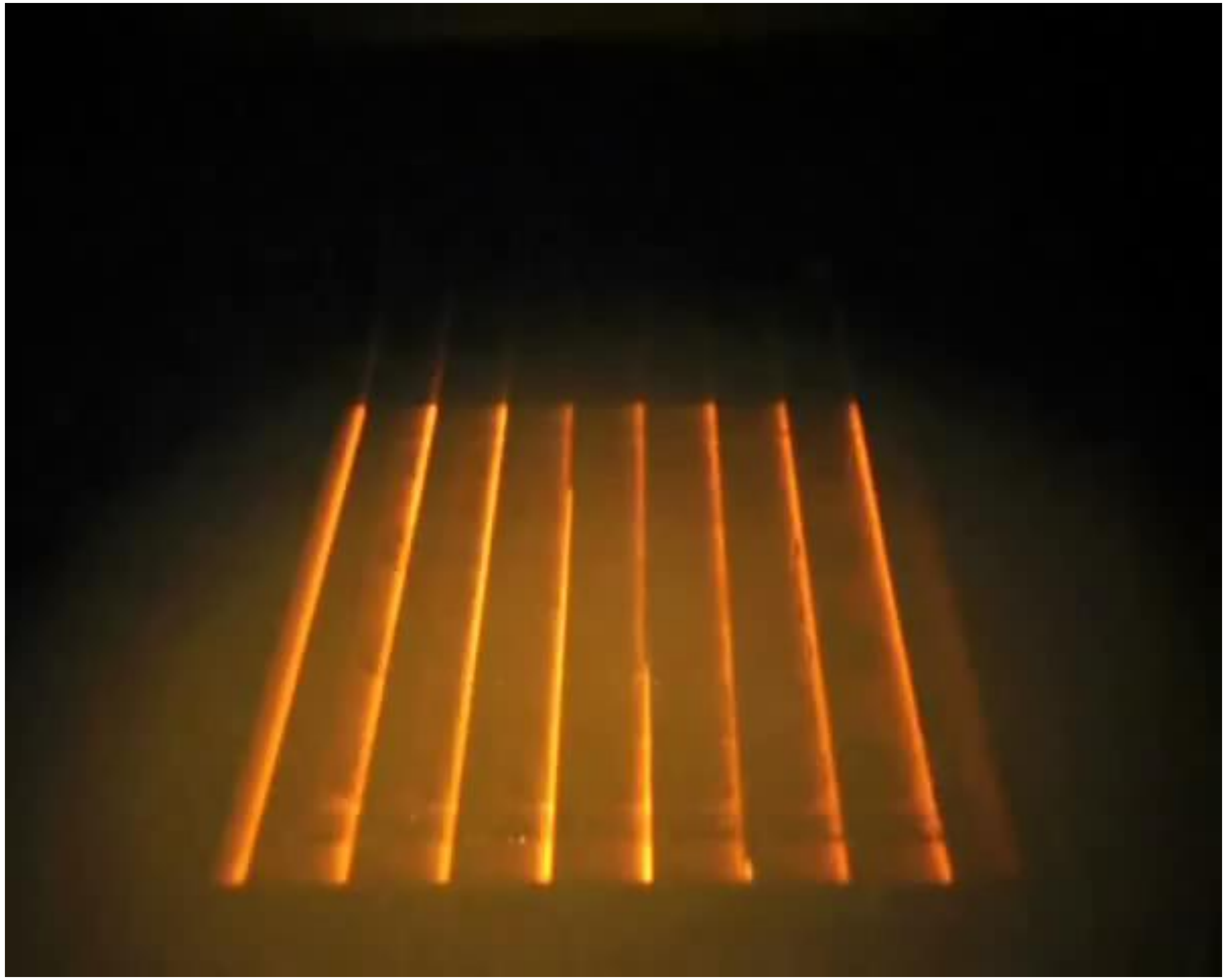
Electron Beam Melting (EBM)



Electron Beam Melting (EBM) - Applications

Source: Arcam

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AM Technologies – Overview

Additive Manufacturing Technologies

- **(Powder) Bed Systems**
  - Laser Beam Melting (LBM)
  - Electron Beam Melting (EBM)
  - Selective Laser Sintering (SLS)
  - Binder Jetting (BJ)
  - Multi Jet Fusion (MJF)
- **Nozzle Systems**
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  - Metal Droplet Deposition
  - Multi Jet Modeling (MJM)
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  - Wire Feed Laser Beam Melting
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  - Wire Feed Electron Beam Melting
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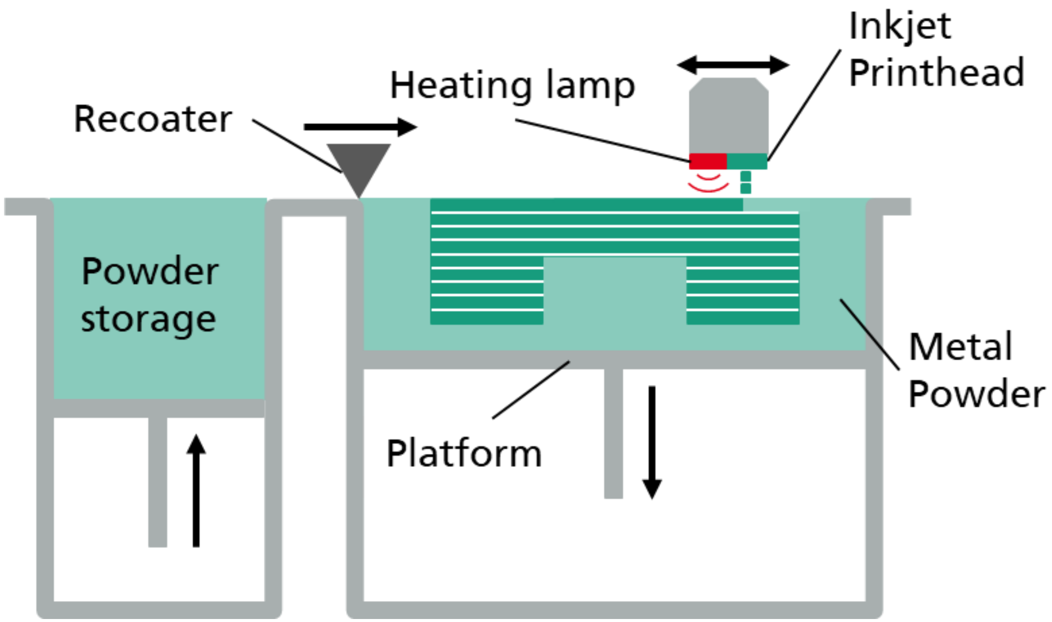
  - Stereolithography (STL)
  - Polyjet Process (PJP)
  - Continuous Liquid Interface Production (CLIP)
- **Hybrid Systems**
  - DMG Mori Lasertec
  - Matsuura Lumex

Metal
Polymers

Binder Jetting (BJ)



Source: Additive Manufacturing Technologies, Ian Gibson

Fabrication Process:

- Powdered material selectively bound by liquid binder that is jetted over the powder bed

Material:

- Steels (17-4PH, 1.4404, 1.4034), Inconel, W, WC-Cr, CoCr
- Many materials in development, main requirement is sinterability

Secondary Processes:

- Binder curing to harden the greenparts and combined thermal debinding and sintering process for final densification
- Optional post processing include peening, HIP or infiltration

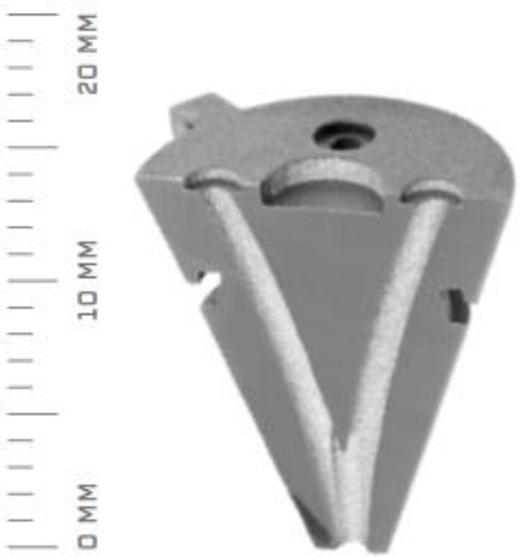
Process Characteristics

- Very fast printing process
- No heat input during printing → no support structures or building plate required and parts can be stacked
- Mechanical properties comparable to MIM or cast material

Binder Jetting (BJ)

Source: Desktop Metal

Binder Jetting (BJ) - Applications



Source: Digital Metal, ExOne

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AM Technologies – Overview

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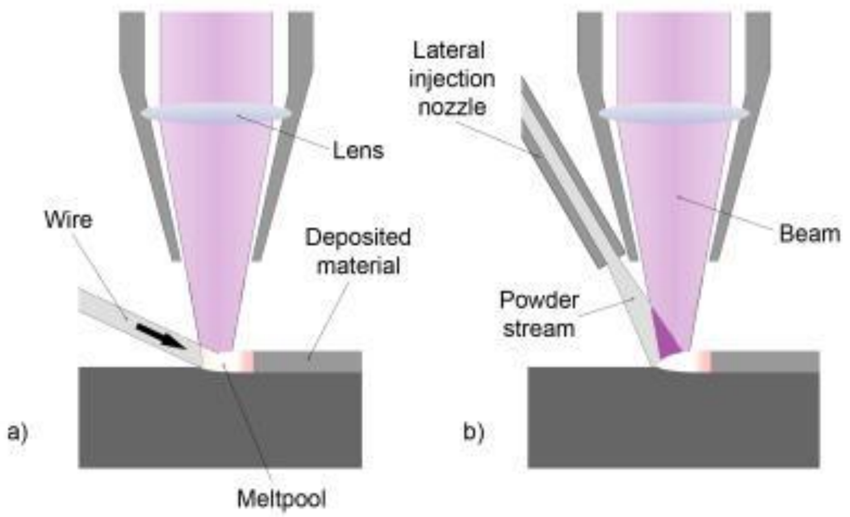
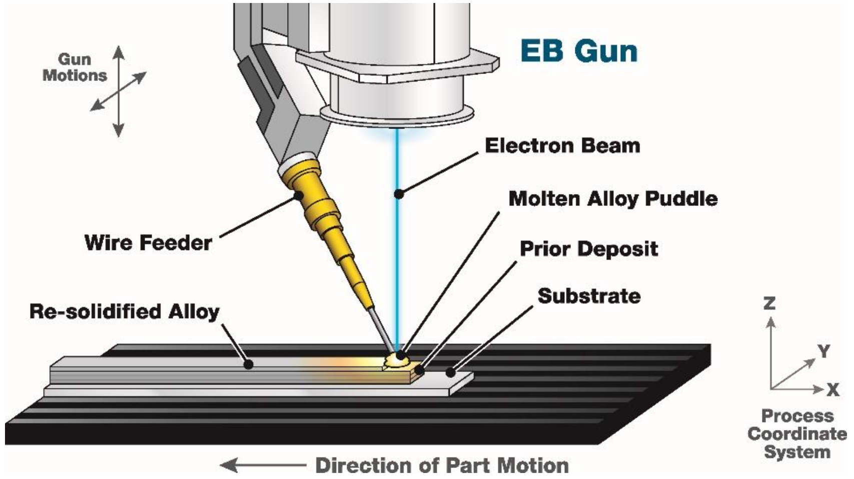
Metal

Polymers

Directed Energy Deposition (DED)

(**Referred to as:** Referred to as: Cladding, High Deposition Rate)





Source: Sciaky INC – EBAM Process

Fabrication Process:

- Selectively melted powder or wire onto substrate/structure, which fuses during solidification
- Radiation from laser or electron beam

Source Material, Binding Mechanism & Activation Energy:

- Powder or wire: weldable metal alloys

Secondary Processes:

- Conventional machining
- Heat treatment

Process Characteristics

- Layer thickness of material is varying from 0.1 mm to several cm
- Very high surface roughness as build
- Typical deposition rates: several cm² per minute @ layer thickness of around 1 mm

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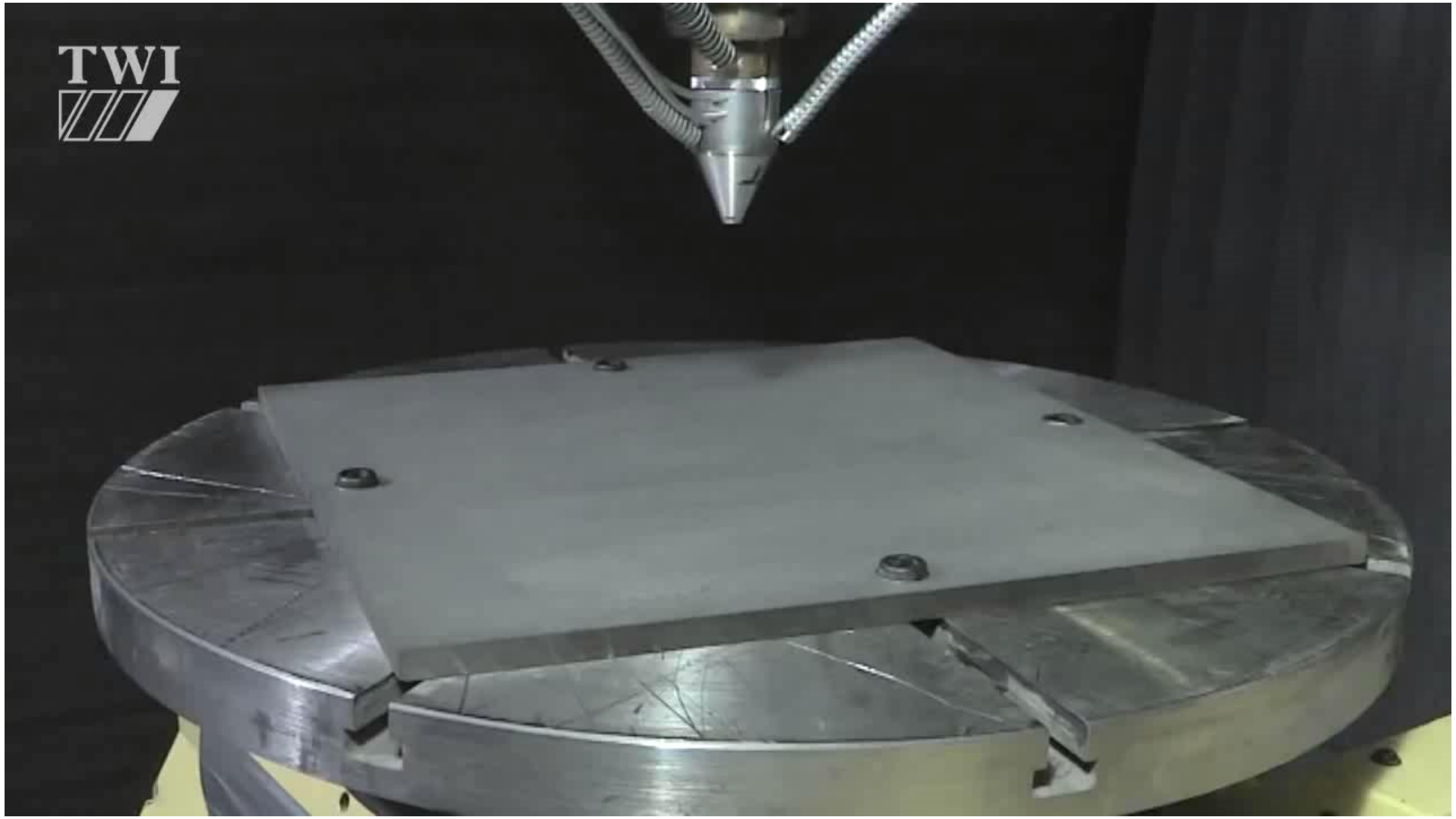
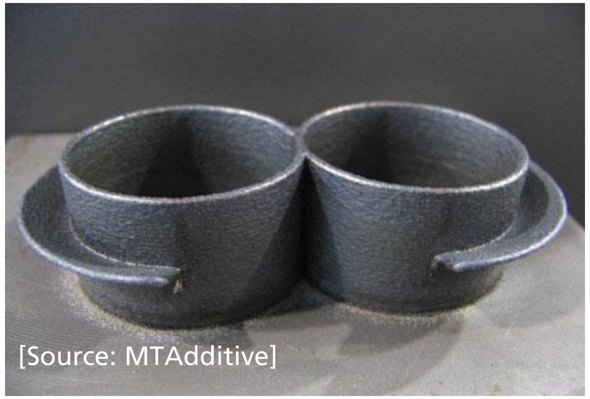
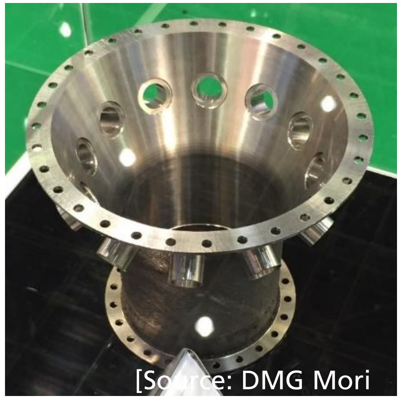
Directed Energy Deposition (DED)

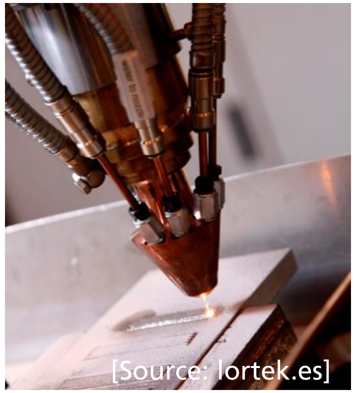


Source: Laser metal deposition manufacturing (LMD) – TWI

Directed Energy Deposition (DED) - Applications


[Source: MTAdditive]


[Source: DMG Mori


[Source: lortek.es]


[Source: RTEJournal]

[Source: Sciaky]

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Comparison – Metal AM

Good | Medium | Poor

Technology	LBM	EBM	DED	BJ
Tensile strength	Good	Good	Good	Medium
Ductility	Good	Good	Good	Medium
Long-term strength	Good	Good	Medium	Medium
Resolution	Good	Medium	Poor	Good
Surface roughness	Good	Medium	Poor	Good
Cost	Medium	Medium	Good	Good
Speed	Medium	Medium	Good	Good
Max part dimension	Medium	Medium	Good	Poor
Multi-Material	Poor	Poor	Medium	Poor

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AGENDA

1 Metal based AM Technologies

2 Polymers based AM Technologies

AM Technologies – Overview

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  - Stereolithography (STL)
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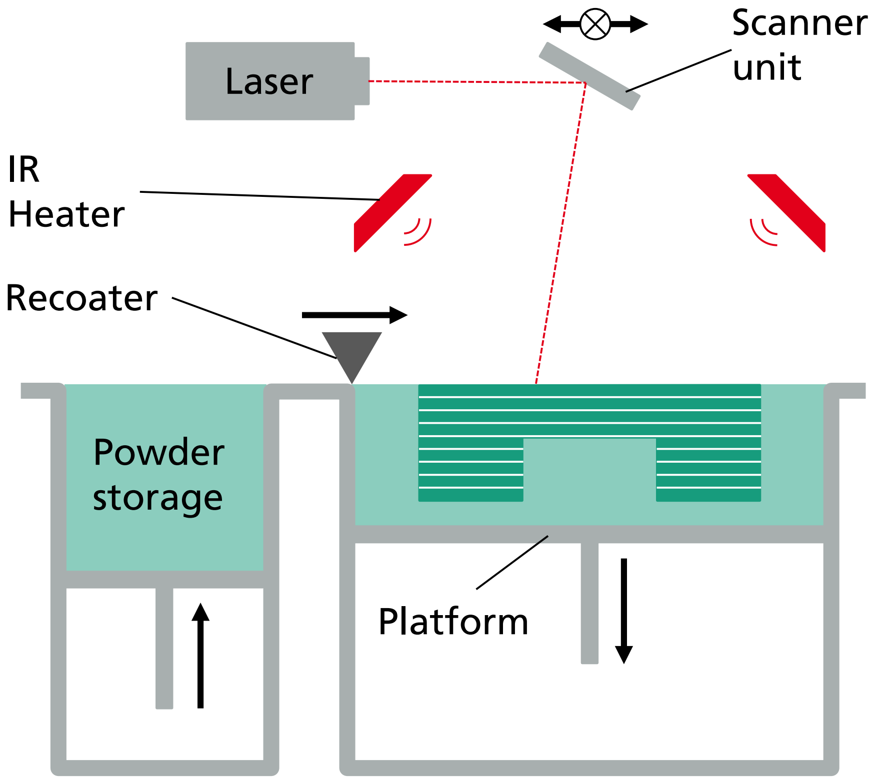
  - Continuous Liquid Interface Production (CLIP)
- **Hybrid Systems**
  - DMG Mori Lasertec
  - Matsuura Lumex

Metal

Polymers

Selective Laser Sintering (SLS)



Basic principle

- Polymeric powder bed is heated close to melting point via IR heaters
- Corresponding polymer powder is then fused by means of a short thermal activation via CO2 laser

Materials

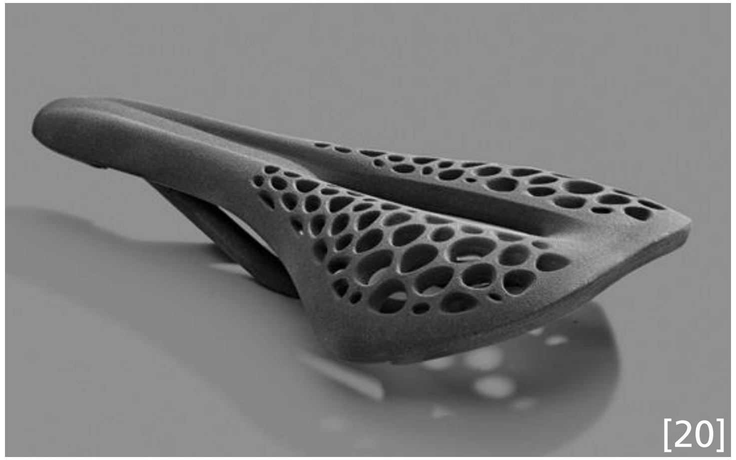
- Commodity polymers: HDPE, PP, PS
- Engineering polymers: PA 6, PA 12, TPU
- High performance polymers: PEEK, PEK

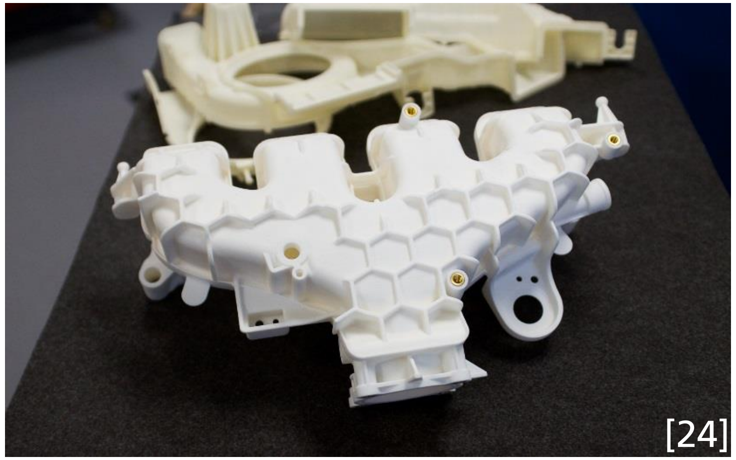
Characteristics

- Minimization of laser energy due to preheating of top layer
- No support structures needed

SLS - Selective Laser Sintering (SLS)

SLS - Selective Laser Sintering (3/3)





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AM Technologies – Overview

Additive Manufacturing Technologies

(Powder) Bed Systems	Nozzle Systems	Directed Energy Deposition (DED)	Liquid Resin Systems	Hybrid Systems
Laser Beam Melting (LBM)	Fused Deposition Modeling (FDM)	Wire Feed Laser Beam Melting	Stereolithography (STL)	DMG Mori Lasertec
Electron Beam Melting (EBM)	Metal Droplet Deposition	Laser Metal Deposition (LMD)	Polyjet Process (PJP)	Matsuura Lumex
Selective Laser Sintering (SLS)	Multi Jet Modeling (MJM)	Wire Feed Electron Beam Melting	Continuous Liquid Interface Production (CLIP)	
Binder Jetting (BJ)				
Multi Jet Fusion (MJF)				

Metal

Polymers

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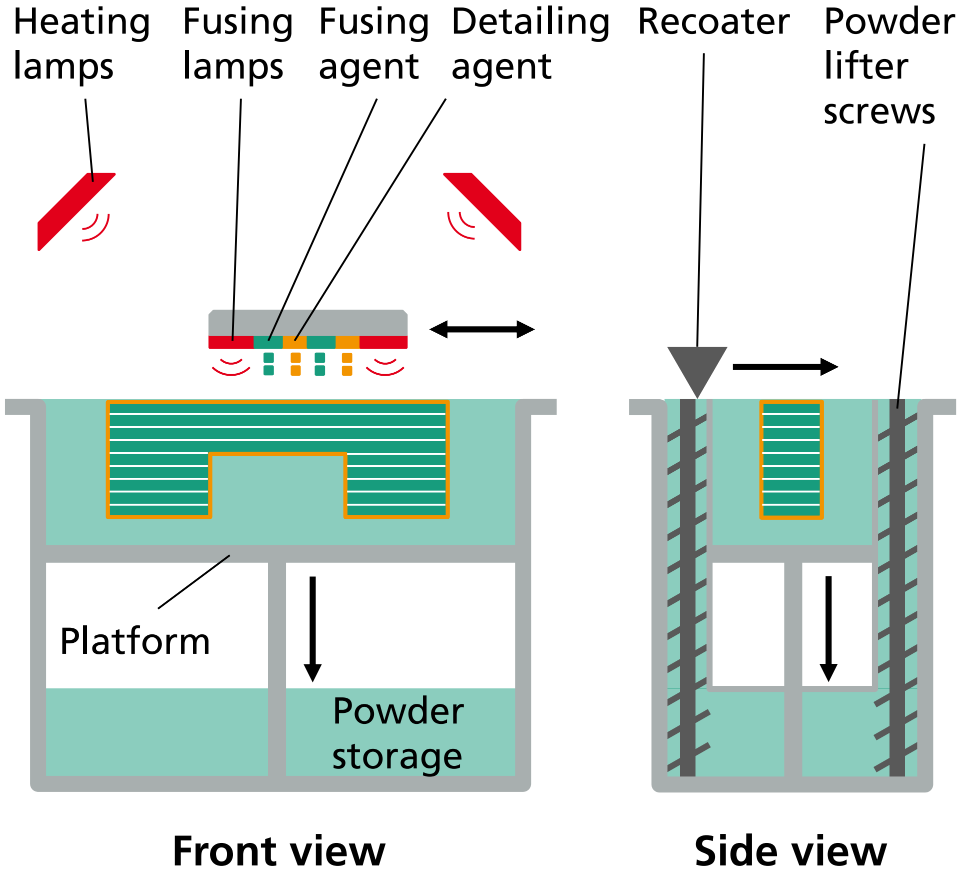
Multi Jet Fusion (MJF)



Basic principle

- Polymeric powder bed is heated close to melting point via heating lamps
- Fusing and detailing agent are deposited via inkjet nozzles
- Areas with fusing agent are melted by use of fusing lamps

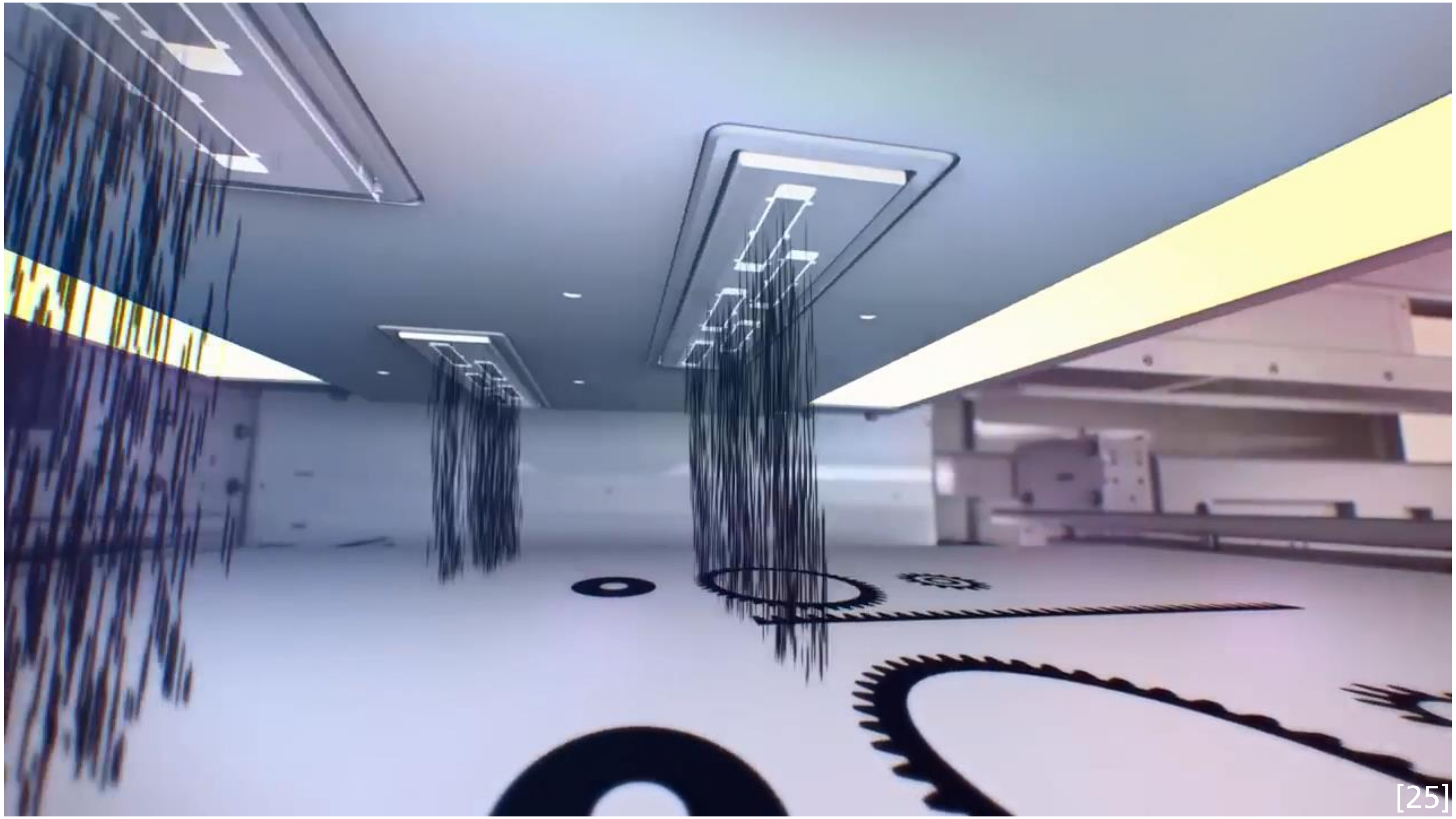
Materials

- Engineering polymers: PA 11, PA 12

Characteristics

- Similar to SLS process
- However, shorter lead times with MJF due to faster part cake cooling and post-processing

Multi Jet Fusion (MJF)



Multi Jet Fusion (MJF)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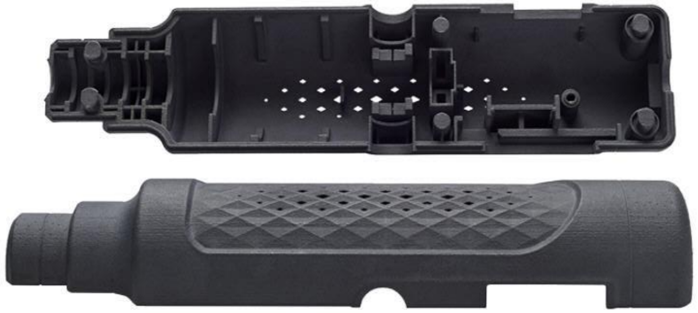
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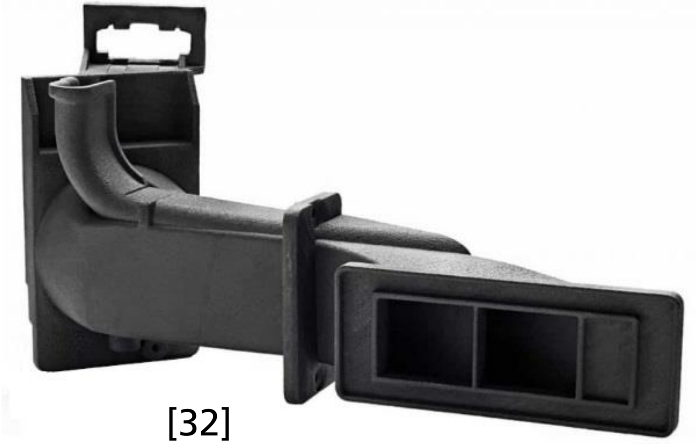
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AM Technologies – Overview

Additive Manufacturing Technologies

(Powder) Bed Systems
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- Electron Beam Melting (EBM)
- Selective Laser Sintering (SLS)
- Binder Jetting (BJ)
- Multi Jet Fusion (MJF)

Nozzle Systems
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- Metal Droplet Deposition
- Multi Jet Modeling (MJM)

Directed Energy Deposition (DED)
- Wire Feed Laser Beam Melting
- Laser Metal Deposition (LMD)
- Wire Feed Electron Beam Melting

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- Stereolithography (STL)
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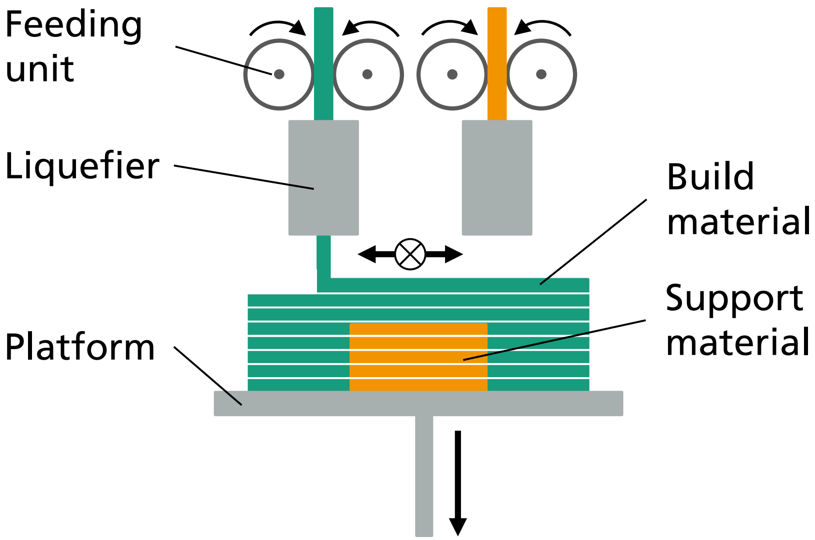
- Continuous Liquid Interface Production (CLIP)

Hybrid Systems
- DMG Mori Lasertec
- Matsuura Lumex

Metal

Polymers

FDM - Fused Deposition Modeling (FDM)



Basic principle

- Thermoplastic stock material is directed via feeding unit into a liquefier, plasticized, and applied to the previous layer in accordance with the cross section to be generated

Materials

- Commodity polymers: ABS, PLA, PVA
- Engineering polymers: ASA, PC, PETG
- High performance polymers: PEK, PEI, PEKK

Characteristics

- Cost-efficient and fast production of large parts possible
- Distinct anisotropy and high surface roughness

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Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM)


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AM Technologies – Overview

Additive Manufacturing Technologies

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Metal

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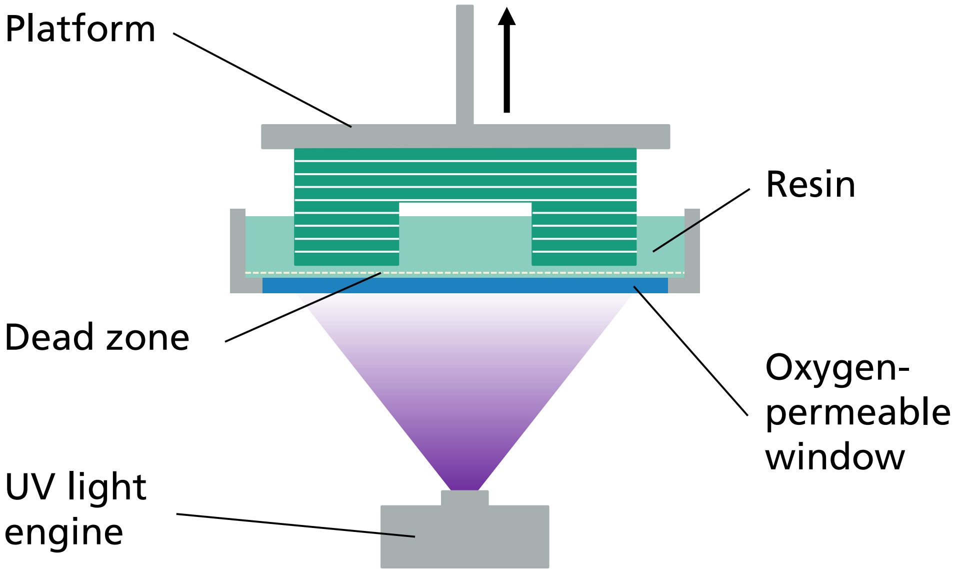
CLIP - Continuous Liquid Interface Production (CLIP)



Basic principle

- Platform is lowered into vat with reservoir of UV curable resin and gradually lifts out the part
- O_2-permeable windows lets oxygen through which creates a dead zone when it contacts the part. Dead zone separates part from resin reservoir, ensuring continuous production.

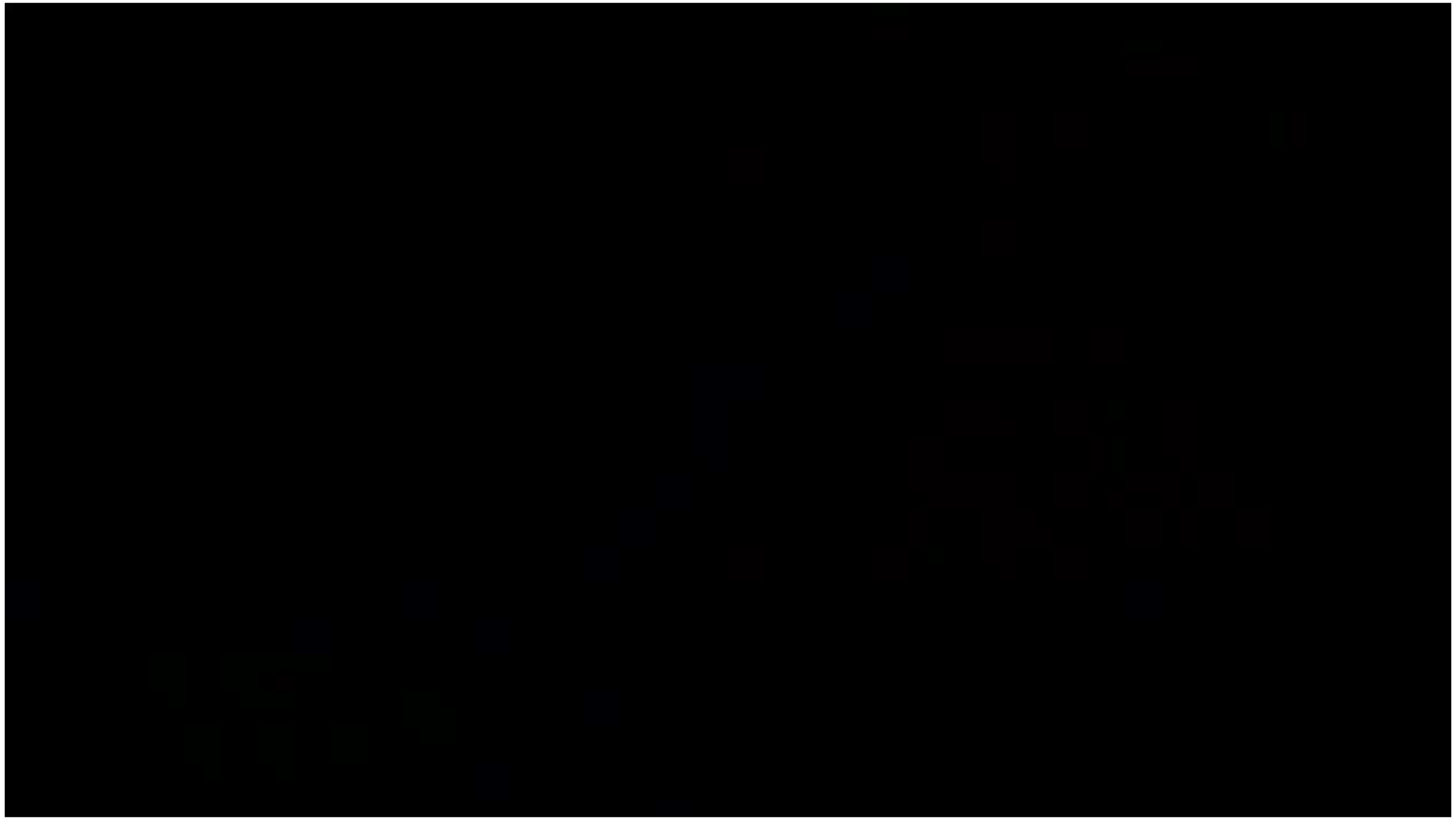
Materials

- Synthetic resins that simulate thermoplastics and elastomers mechanically, thermally and visually
- EPU, SIL, RPU, FPU, CE, EPX, UMA, Dental

Characteristics

- 25-100 times faster than SLA
- Post-curing necessary

Actual Developments in Polymer AM:
CLIP - Continuous Liquid Interface Production (CLIP)



CLIP - Continuous Liquid Interface Production (CLIP)

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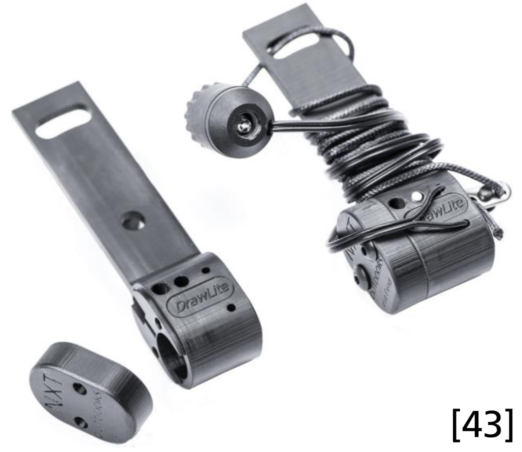

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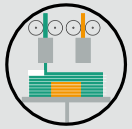
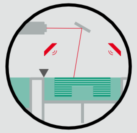
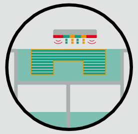
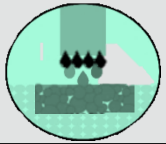
Comparison – Polymer AM

Good | Medium | Poor

Technology	 FDM	 SLS	 CLIP	 MJF
Tensile strength	Medium	Good	Good	Good
Ductility	Medium	Good	Poor	Good
Long-term strength	Medium	Good	Medium	Good
Resolution	Poor	Medium	Good	Medium
Surface roughness	Poor	Medium	Good	Medium
Cost	Good	Medium	Poor	Good
Speed	Good	Medium	Good	Good
Max part dimension	Good	Medium	Poor	Medium
Multi-Material	Good	Poor	Poor	Poor

Thank you for your attention!

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SAM

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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

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CU 34: AM Process selection

- This module is under scope of SAM project, the project funded by European Commission in the field of sector skill strategy in additive manufacturing.
- This module engages you with providing comprehensive information about “AM process selection” which is one of the dominant job activity for an AM process engineer.
- In addition, those who can pass assessment exams and complete feedback questionnaire will be awarded a certificate of attendance.

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Sequences content

- First sequence: Introduction on AM analysis from Jochen LOOCK, Head of Academy, Fraunhofer-Einrichtung für Additive Produktionstechnologien IAPT Hamburg.
- Second sequence: self learning about all the different components of the decision making process with MOOCS from AddUp Academy and with some academic papers.
- Third sequence: Analysys of case studies and guidance for process selection based on a given set of requirements.
- Fourth Sequence (over three slots): Special focus on economical issues and on costing of AM parts
- Assessment: 20 Multi-choice questions and a case study

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SAM

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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

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CU 34: AM Process selection

- This sequence is dedicated to a self investigation of most of the main aspects of why we may use additive manufacturing and what are the main issues that have to be known and controlled in order to decide if it is suitable or not to go for additive manufacturing.
- You will have to visit the 9 MOOCS of AddUp Academy: https://mooc.addup-academy.online/?lang=en
- You will have also to carefully read two papers, keynotes published within CIRP STC Design and to understand the basics and the methodology of Design for AM including process-based analysis based on the presentation of those two keynotes. The first one will be presented and read during this sequence. The second one, including the methodology will be presented during the third sequence.

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Sequences content

- At the end of these two first sequences, you may be able to describe all the different AM technologies and the main materials usable for each AM technology family.
- At the end of this second sequence, you also may be able to list the main advantages of AM and also the main aspects that have to be defined in the requirements of a part manufactured with AM.
- At the end of the third sequence, you may be able to apply the proposed methodology of Design for Additive Manufacturing and to fix the main characteristics that are relevant to the choice of AM process.

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Sequences content

- At the end of three last sequences, you will be able to calculate the cost of a AM part on the example of L-PBF technology.
- At the end of all the sequences, you will have to answer 20 questions (multiple choice questions) and to analyse a case study.
- If you are successfull to those two assessments, you will receive a certificate.

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Course:
AM Process Selection

Understanding Of Cost In ADDITIVE MANUFACTURING

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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

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Course Outline:

- Additive Manufacturing Technology Overview
- Additive Manufacturing Process Selection
- Cost Estimation Techniques
- Understanding Of Cost in Additive Manufacturing
- Different Cost Models in Additive Manufacturing Field (Academic)
- Our Cost Model

Additive Manufacturing (AM) technology Overview

What is Additive Manufacturing Technology?

Additive Manufacturing Technology Overview

Before we start with the exact definition of Additive Manufacturing lets take step back:

Additive Manufacturing; shaping objects by succussive addition of material….

Is it New Technology?

The technology may be fairly new but the principle is just is natural and ancient !!

Additive Manufacturing Technology Overview

Overview

The first modern additive manufacturing technology, which originated in the Stereo-lithography invented by Chuck Hull (US 4.575.330 priority 08.08.1984).

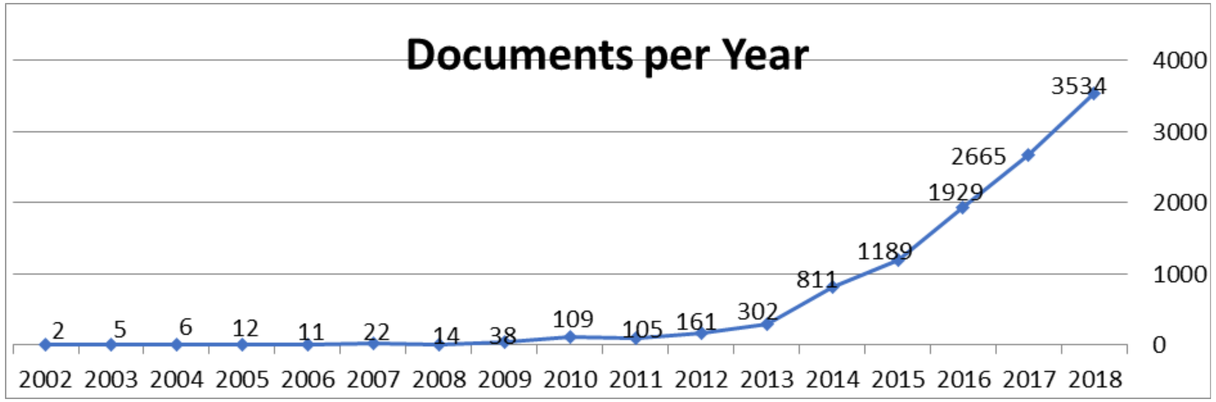
Following, Several AM technologies has been developed:

Negi et al.,2013 & Levy,2010, Gibson et al.,2015		
Typical commercial names	Year	
3DP- 3D Printing	1998	
LENS- Laser Engineered Net Shaping	1997	
FDM- Fused Deposition Modeling	1991	
PP- Polyjet Printing	2001	
SLS- Selective Laser Sintering	1991	
SLM- Selective Laser Melting	2001-2004	
DMLS- Direct Metal Laser Sintering	1998	
DMLM- Direct Metal Laser Melting		
EBM- Electron Beam Melting	2001	
LOM- Laminated Object Manufacturing	1991-1995	
SLA- Steriolithography	1987	
DLP- Digital Light Processing	2005	

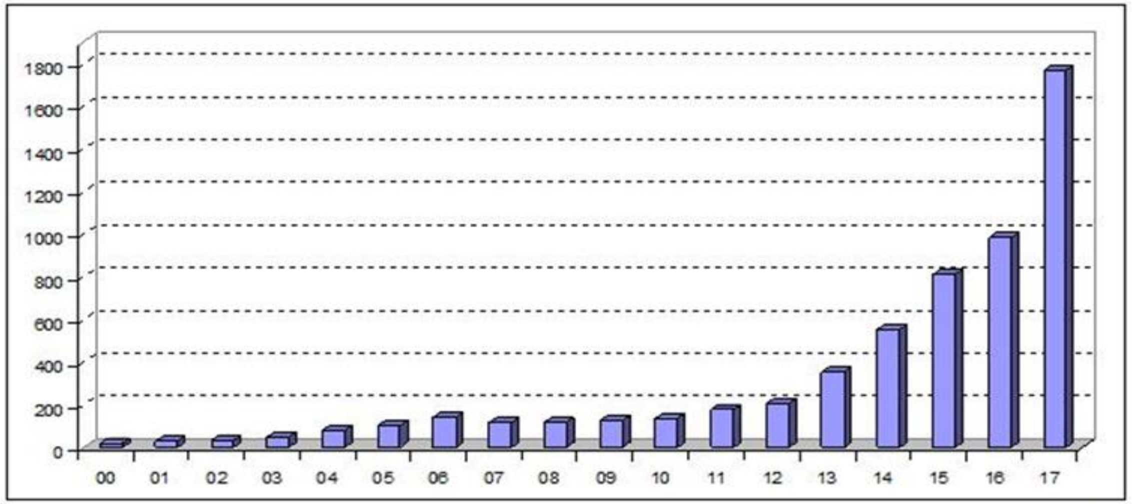
Additive Manufacturing Technology Overview

Overview

Since then, the process have inflamed high expectation and interest in research and industry.



AM Application:



Dramatic rise in metal AM system sales

Source: Wohlers Report 2018

Additive Manufacturing Technology Overview

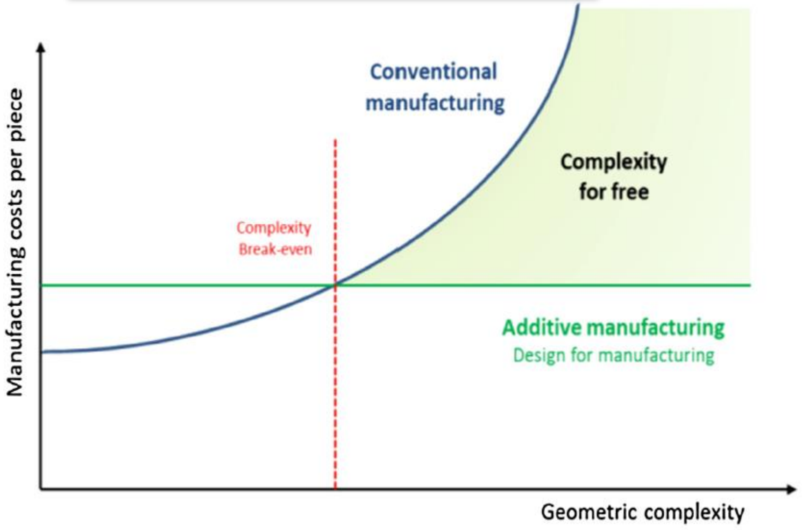
Advantages Of AM

The speed advantage

Reduces the number of processes and resources

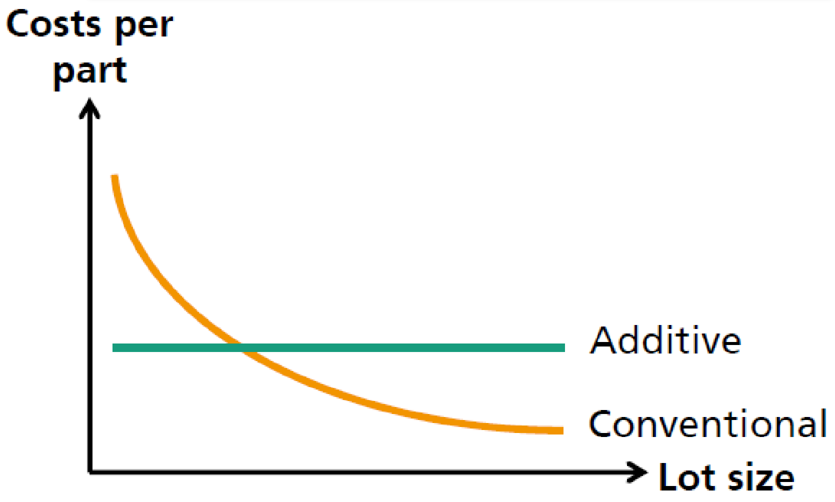
Why Additive Manufacturing Technology?

Complexity for free



It can go directly from digital design to manufacture part.

The high level of customization



Additive Manufacturing Technology Overview

The main limitation and challenges of AM

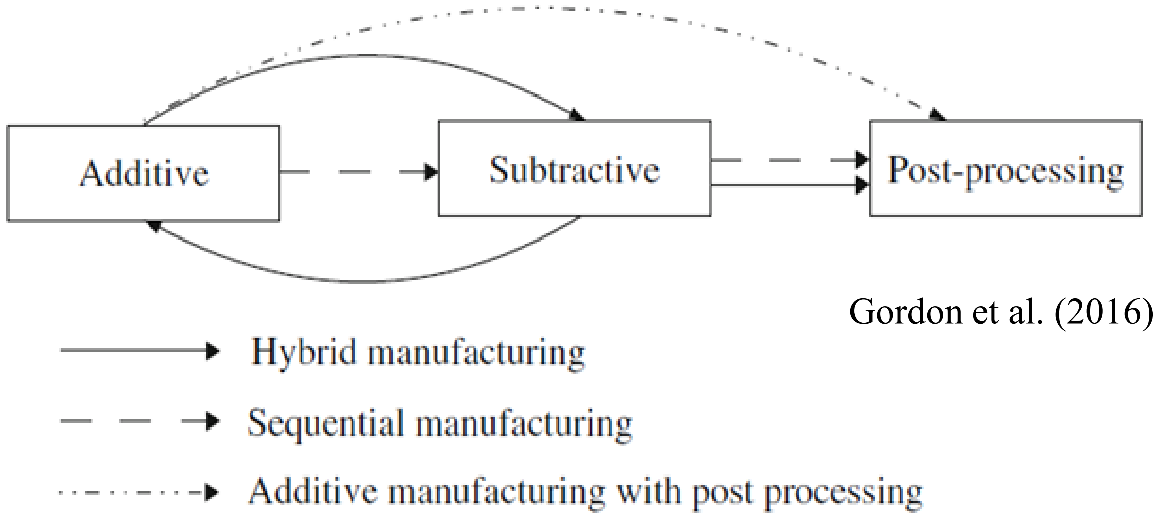
The technology has potential in terms of productivity and competitiveness but still their diffusion is still relatively limited among manufacturer and users:

- The high cost of AM equipment, and production cost
- Limited parts size
- Effort required for application design
- Not relevant to mass production
- Material choice
- Lack of deep knowledge about these technologies
- Large mass and different types of data, and heterogeneous knowledge, between stakeholders
- Large number of parameters and poor understanding of their interaction

Additive Manufacturing Technology Overview

Definition, and terms

"Process of joining materials to make object from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies", synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, and freeform fabrication [ASTM (2012)].



Gordon et al. (2016)

Often used terms:

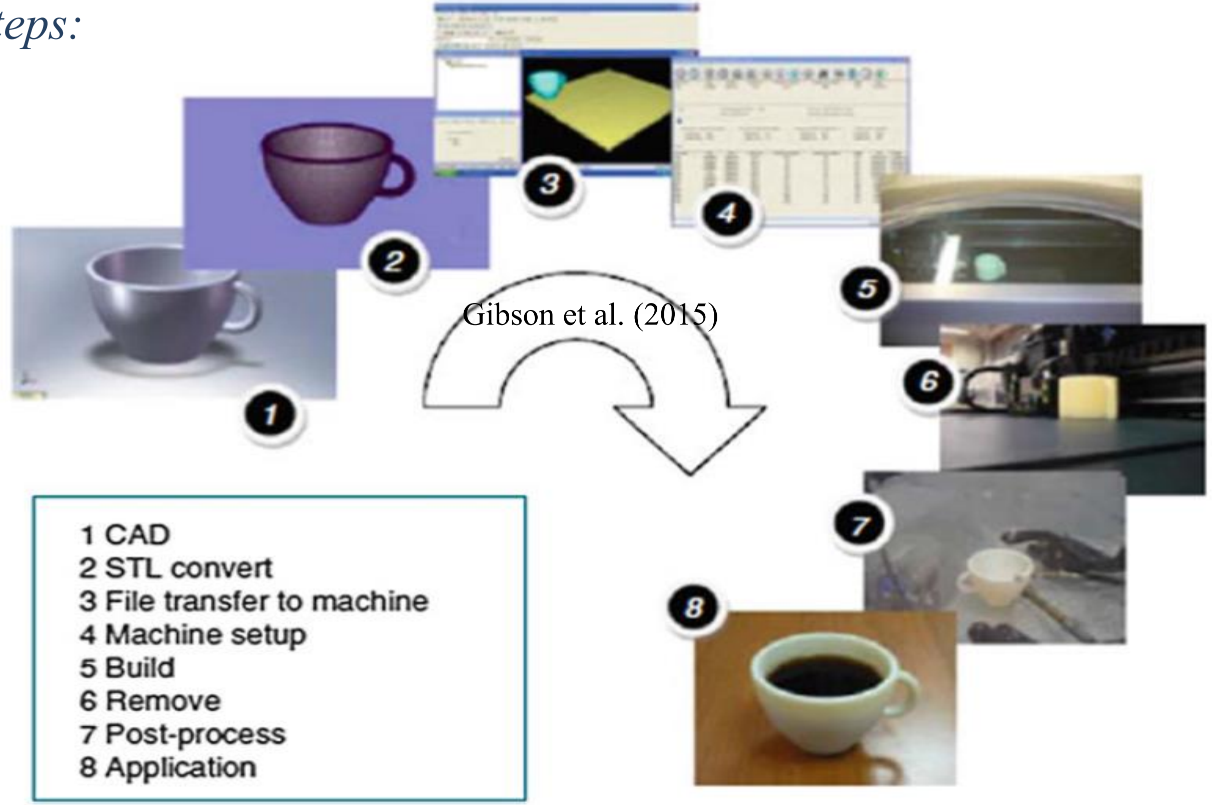
- Rapid prototyping
- Rapid tooling
- Rapid manufacturing
- Additive manufacturing
- Layer manufacturing
- …..

Additive Manufacturing Technology Overview

The main eight steps/ stages of AM

For the majority of AM processes, there is a generic sequence steps:

- Create CAD Model: to come up with an idea for how the product will look and function.
- Convert the CAD model into STL/ or another format:
  - Converts the continuous geometry in the CAD file into a header, small triangles, (x, y, z)
  - The STL file imported into specific software for pre-processing like (Magics, Viscam). For some cases the part model is oriented for building, and support structure is provided for the part.
  - Several formats have been used for a wide of variety, like: AMF file (ISO/ASTM standard), PLY, 3MF, X3D, OBJ, SLC, 3DS, DXF, SAT, STEP.
  - Also, the file is sliced after that into 2D layers with a specific thickness, as well as the laser scanning path or the deposition path is generated.



Additive Manufacturing Technology Overview

The main eight steps/ stages of AM

- Transfer the STL/or another format on AM machine: Where AM system software has a visualization tool to allow users to view and manipulate the part size, position, orientation.

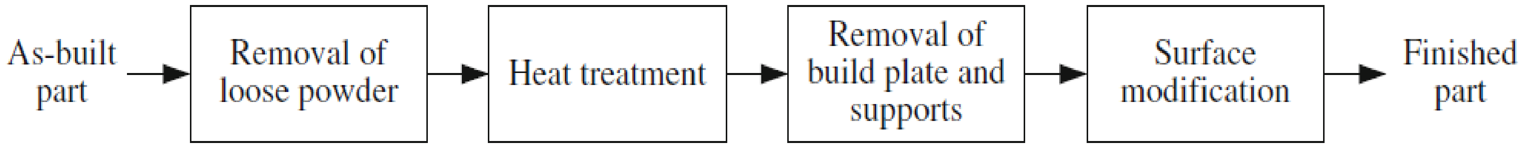
- Machine setting: AM machine has some setup parameters, require optimization to suit the type of the part to be build such setting relate to build parameters. ***In PBF machines***, the powder is often sifted, loaded, and levelled in the machine, also the platform (build plate must be inserted and levelled according to machine axes.

- Build the part by adding 2D cross section layer by layer: An automated task, where different parameters are monitored to ensure that there is no error.

- Remove from the AM machine: Removing the part when the build is completed after cooling the part down to ensure that there are no actively moving parts.

- Post Processing: Operation required to prepare parts for their use or applications by modifying existing feature. AM process can be used as the primer manufacturing process or part of a chain of process. Different post-processing may need to be undertaken following the build process based on the application of the part.

- Application : The part is ready to use.



Additive Manufacturing Technology Overview

AM process categories

AM Process Categories (ASTM)

- Binder Jetting
- Direct Energy Deposition
- Material Extrusion
- Material Jetting
- Sheet lamination
- Vat Photopolymerization
- Powder Bed Fusion

Additive Manufacturing Technology Overview

AM process categories

Binder jetting

Additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

Ex: 3DP-3D printing

Steps:

1.Powder material is spread over the build platform using a roller.

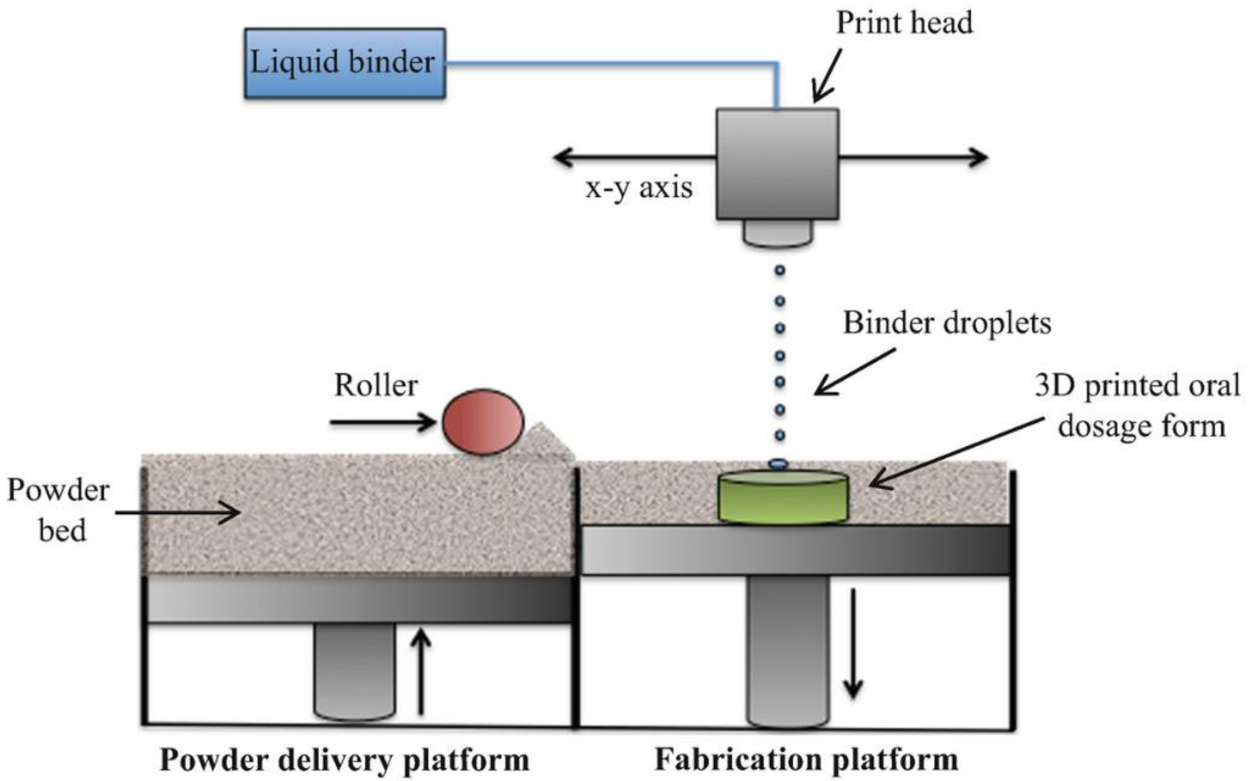
2.The print head deposits the binder adhesive on top of the powder where required.

3.The build platform is lowered by the model's layer thickness.

4.Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid.

5.Unbound powder remains in position surrounding the object.

6.The process is repeated until the entire object has been made.



Additive Manufacturing Technology Overview

AM process categories

Directed energy deposition

Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

Ex: LENS

Steps:

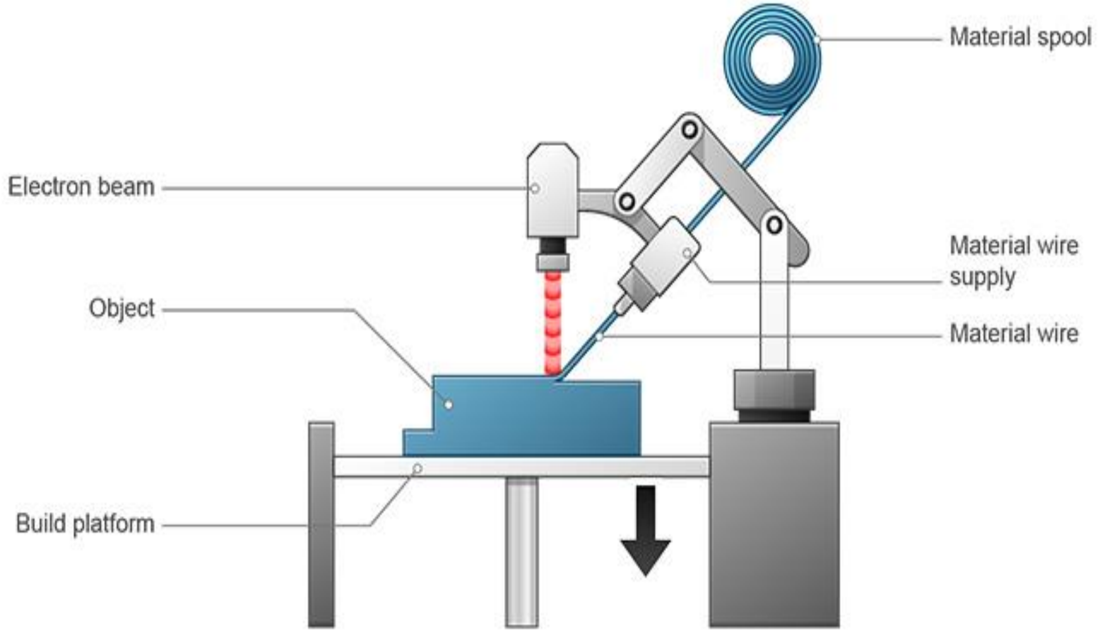
1.A4 or 5 axis arm with nozzle moves around a fixed object.

2.Material is deposited from the nozzle onto existing surfaces of the object.

3.Material is either provided in wire or powder form.

4.Material is melted using a laser, electron beam or plasma arc upon deposition.

5.Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object.



Additive Manufacturing Technology Overview

AM process categories

Material extrusion

Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

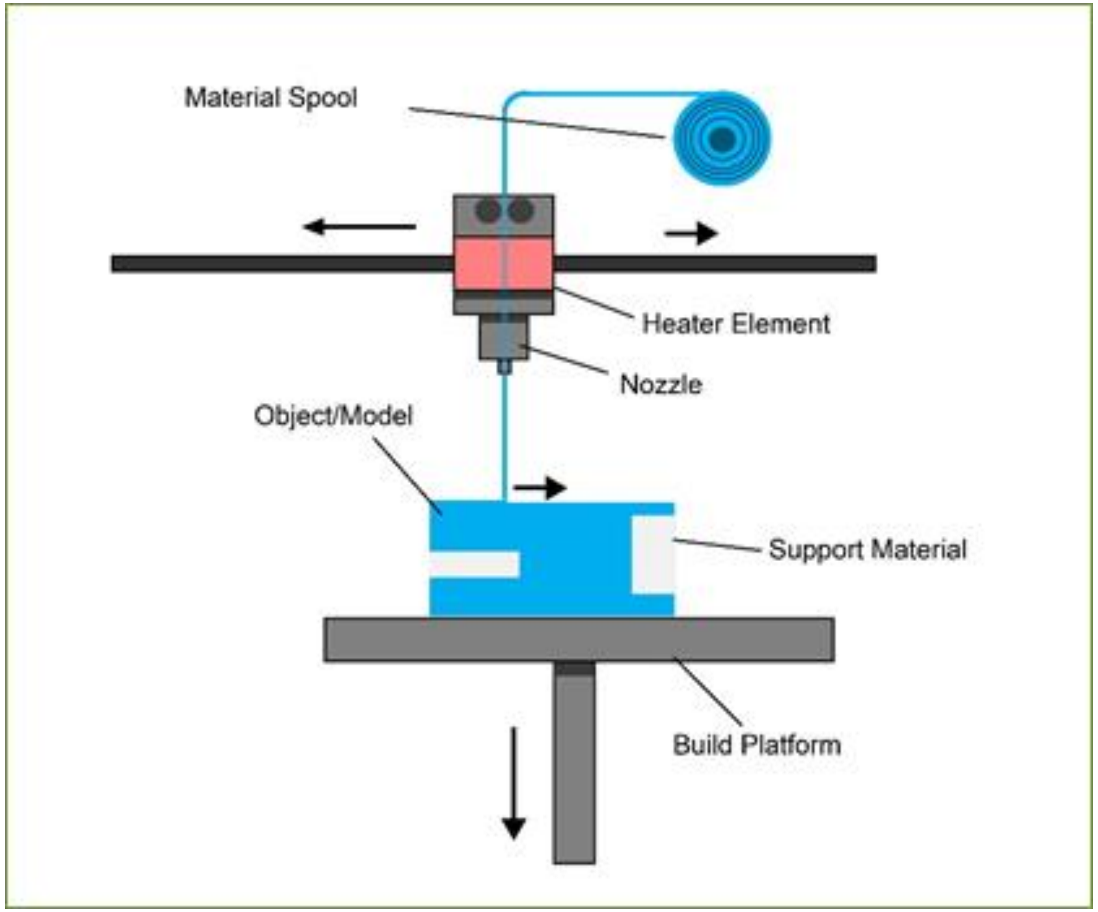
Ex: FDM

Steps:

1.First layer is built as nozzle deposits material where required onto the cross sectional area of first object slice.

2.The following layers are added on top of previous layers.

3.Layers are fused together upon deposition as the material is in a melted state



Additive Manufacturing Technology Overview

AM process categories

Material jetting,

Additive manufacturing process in which droplets of build material are selectively deposited.

Ex: PP (Polymer jetting)

Steps:

1.Powder material is spread over the build platform using a roller.

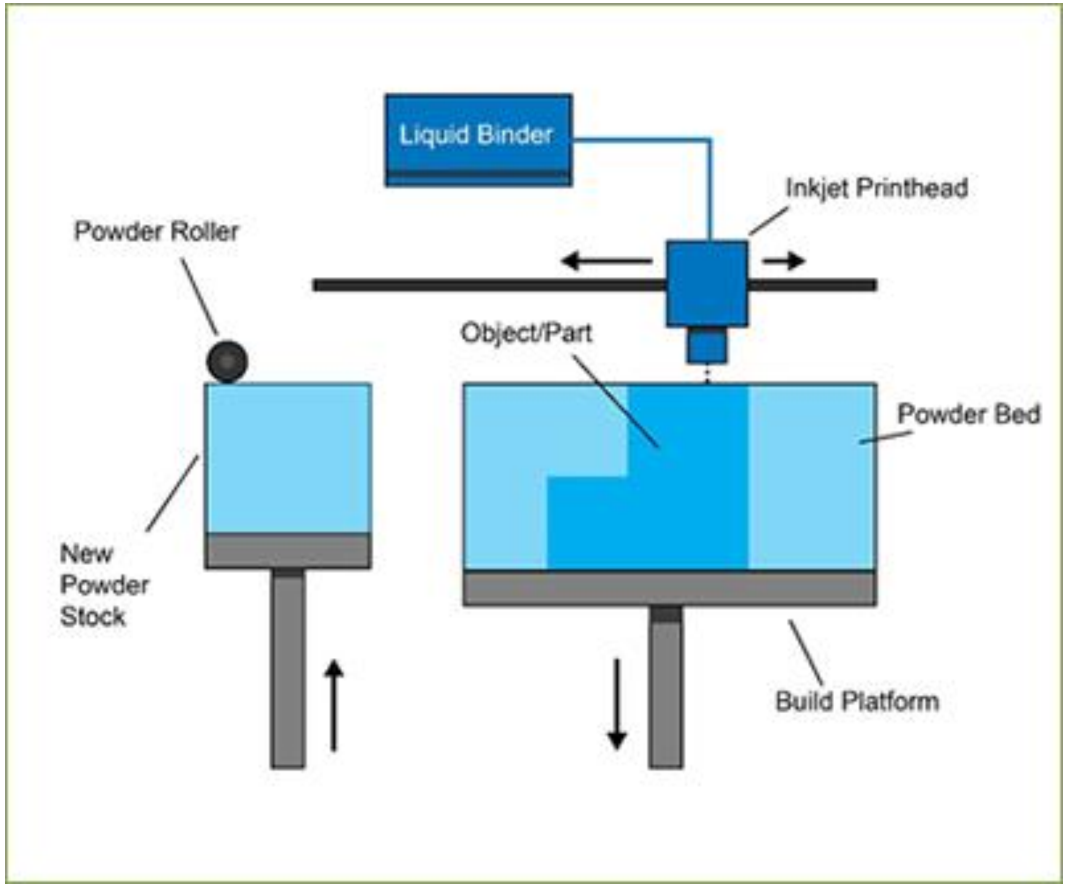
2.The print head deposits the binder adhesive on top of the powder where required.

3.The build platform is lowered by the model's layer thickness.

4.Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid.

5.Unbound powder remains in position surrounding the object.

6.The process is repeated until the entire object has been made.



Additive Manufacturing Technology Overview

AM process categories

Sheet lamination

Additive manufacturing process in which sheets of material are bonded to form an object.

Ex: LOM, SLCOM

Steps:

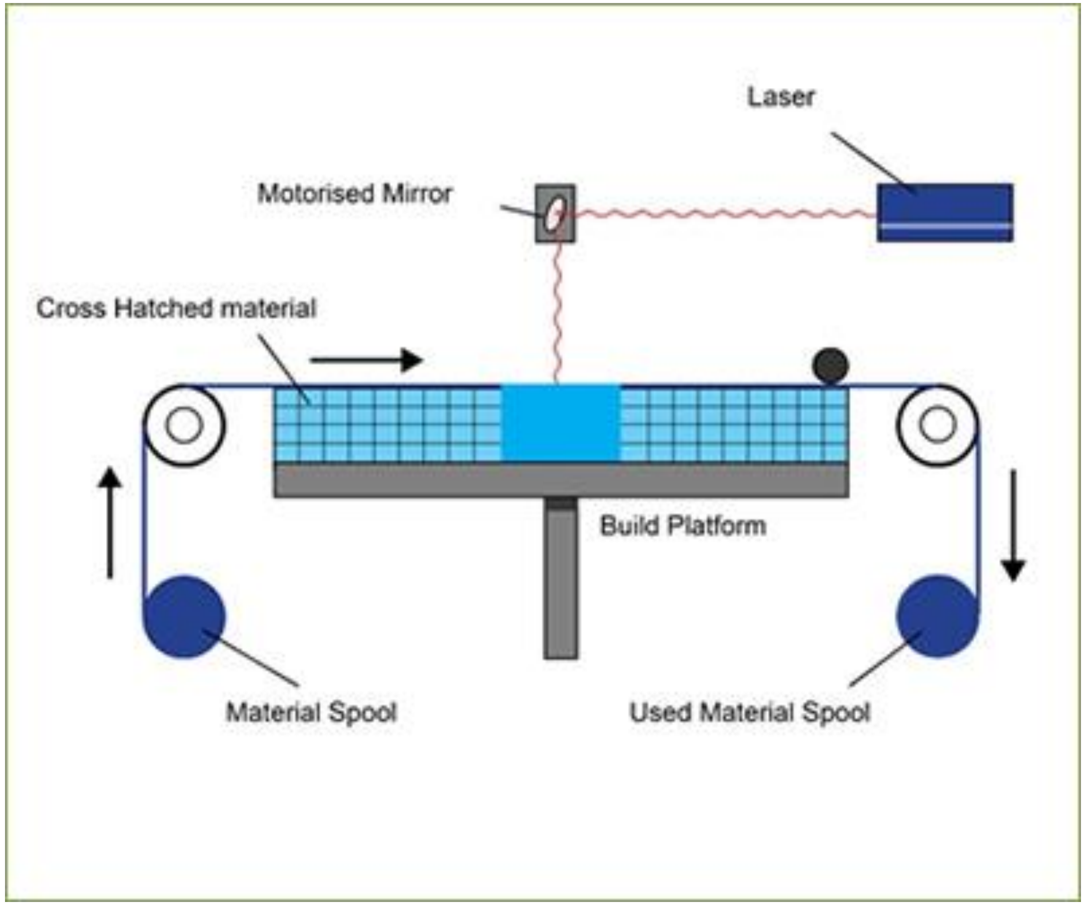
1.The material is positioned in place on the cutting bed.

2.The material is bonded in place, over the previous layer, using the adhesive.

3.The required shape is then cut from the layer, by laser or knife.

4.The next layer is added.

5.Steps two and three can be reversed and alternatively, the material can be cut before being positioned and bonded.



Additive Manufacturing Technology Overview

AM process categories

Vat photopolymerization

Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Ex: SLA, DLP

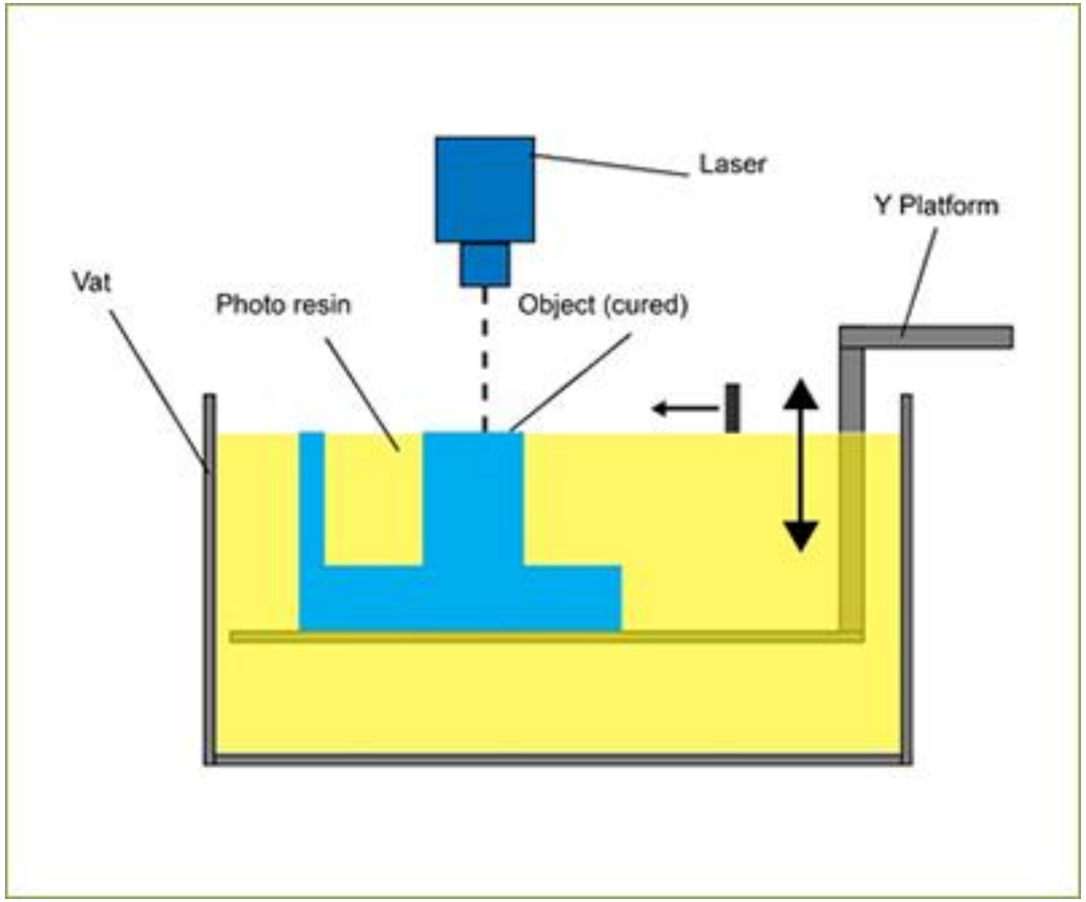
Steps:

1.The build platform is lowered from the top of the resin vat downwards by the layer thickness.

2.A UV light cures the resin layer by layer. The platform continues to move downwards and additional layers are built on top of the previous.

3.Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on.

4.After completion, the vat is drained of resin and the object removed.



Additive Manufacturing Technology Overview

AM process categories

Powder bed fusion

Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

Ex: SLS, SLM, DMLS, SMLM, EBM

Steps:

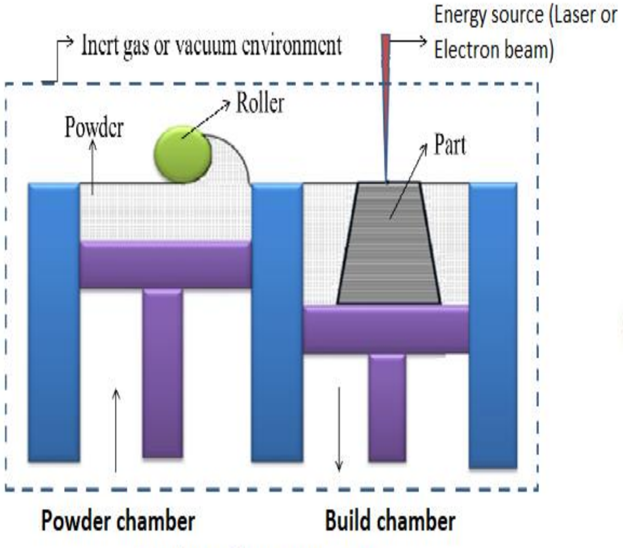
1.A layer, typically 0.1mm thick of material is spread over the build platform.

2.A laser fuses the first layer or first cross section of the model.

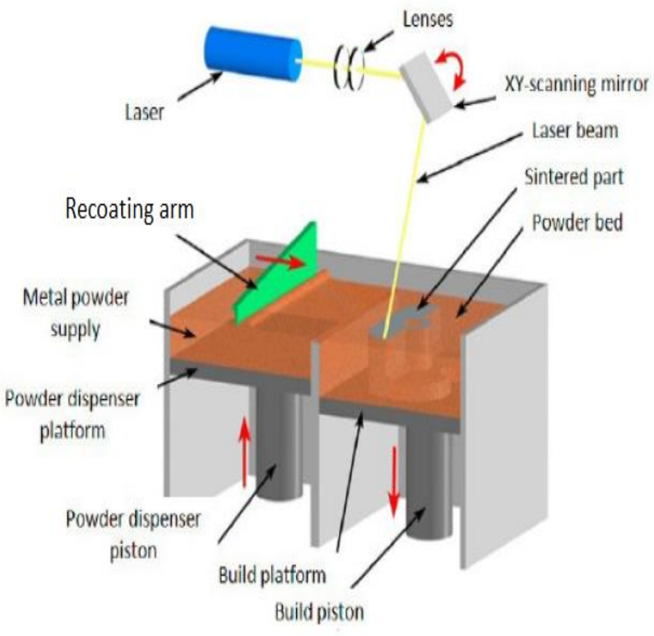
3.A new layer of powder is spread across the previous layer using a roller.

4.Further layers or cross sections are fused and added.

5.The process repeats until the entire model is created. Loose, unfused powder is remains in position but is removed during post processing.



Powder Bed Fusion process



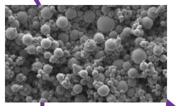
Laser based PBF technology

Additive Manufacturing Technology Overview

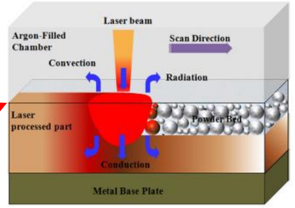
AM process categories

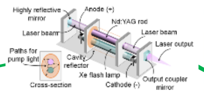
Powder bed fusion process characteristics

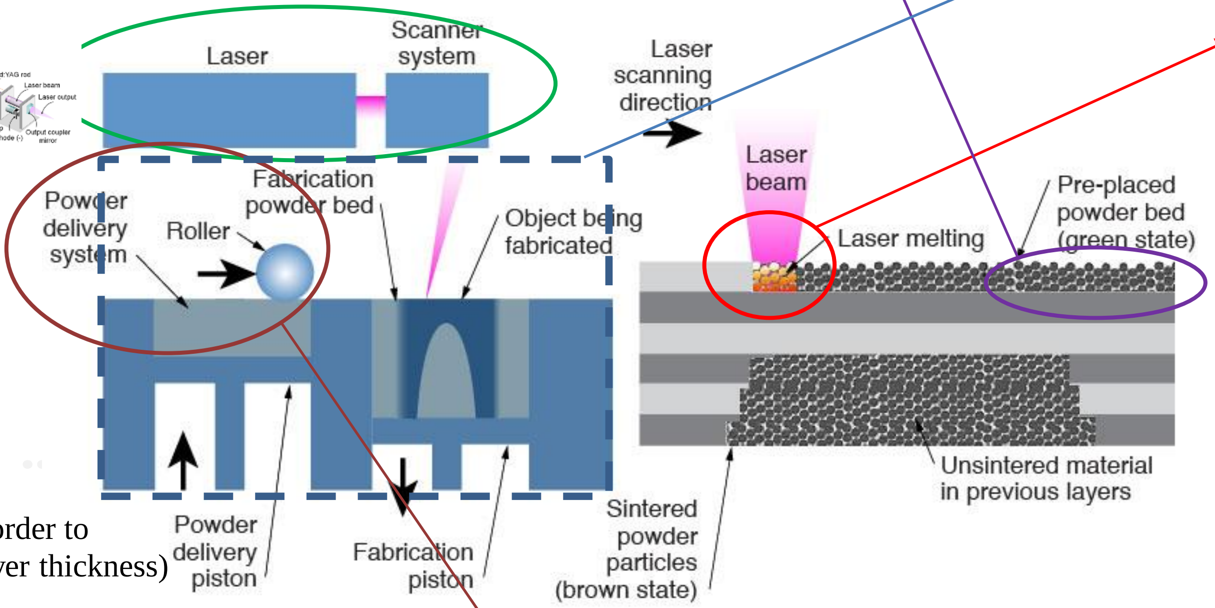
Mechanical
Optical
Chemical
Morphological
Thermal



***Enclosed Chamber*:** this is necessary to create a controlled environment free from oxygen to eliminate oxidation of the material being fused/sintered.





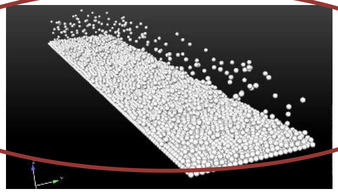


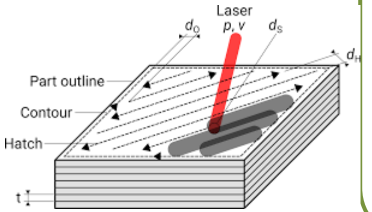
***Energy Source*:** one or more sources of heat (Laser) are necessary to induce fusion between the powder particles.
***Scanning System*:** a method to control powder fusion to a prescribed region of each layer.

A mechanism to control the lowering of the component in order to achieve growth through additional layers. (based on the layer thickness)

A mechanism for adding and smoothing powder layer.

Recoating time, Layer thickness
Particle size distribution
Powder bed preheating
Effective thermal conductivity
Relative bed density



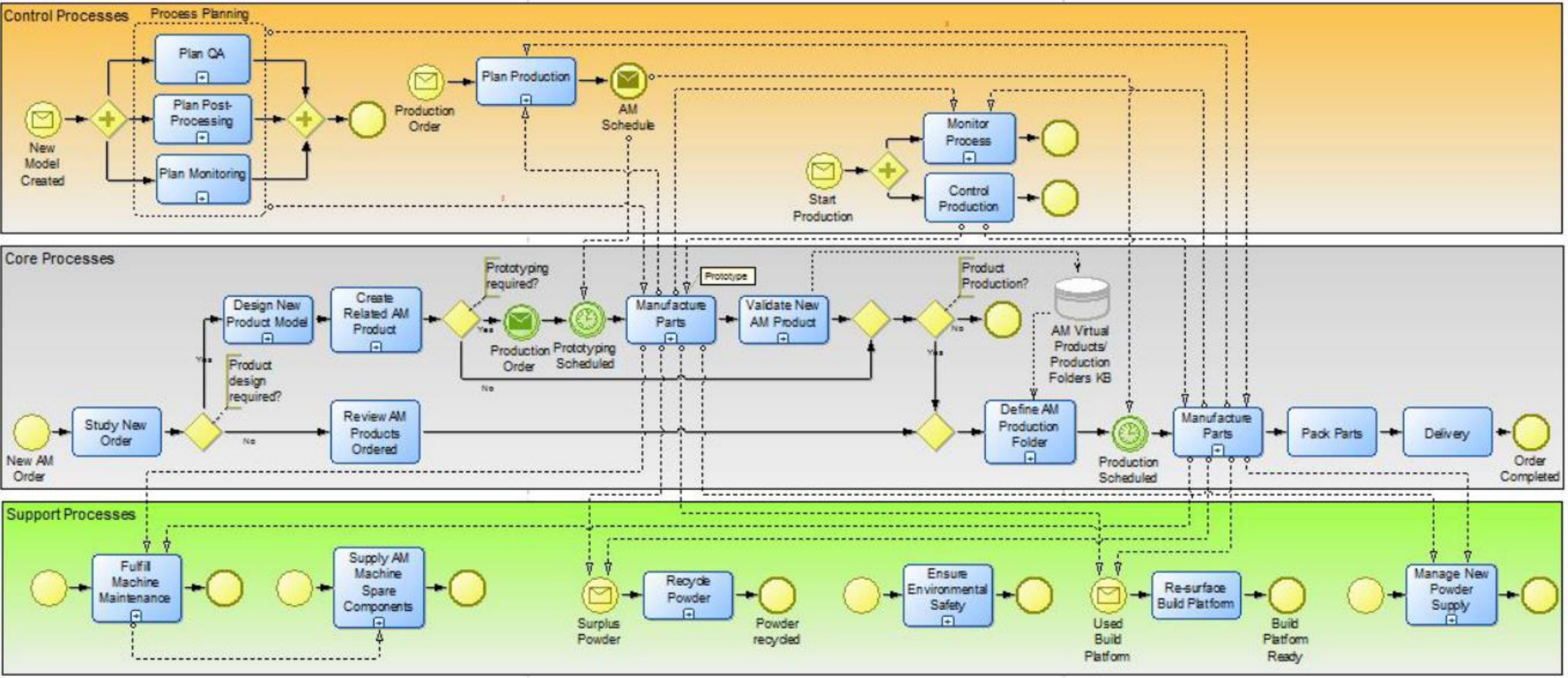


Process plan

Scan pattern
Scan speed
Hatching distance
Counter
Number of layers
Number of parts

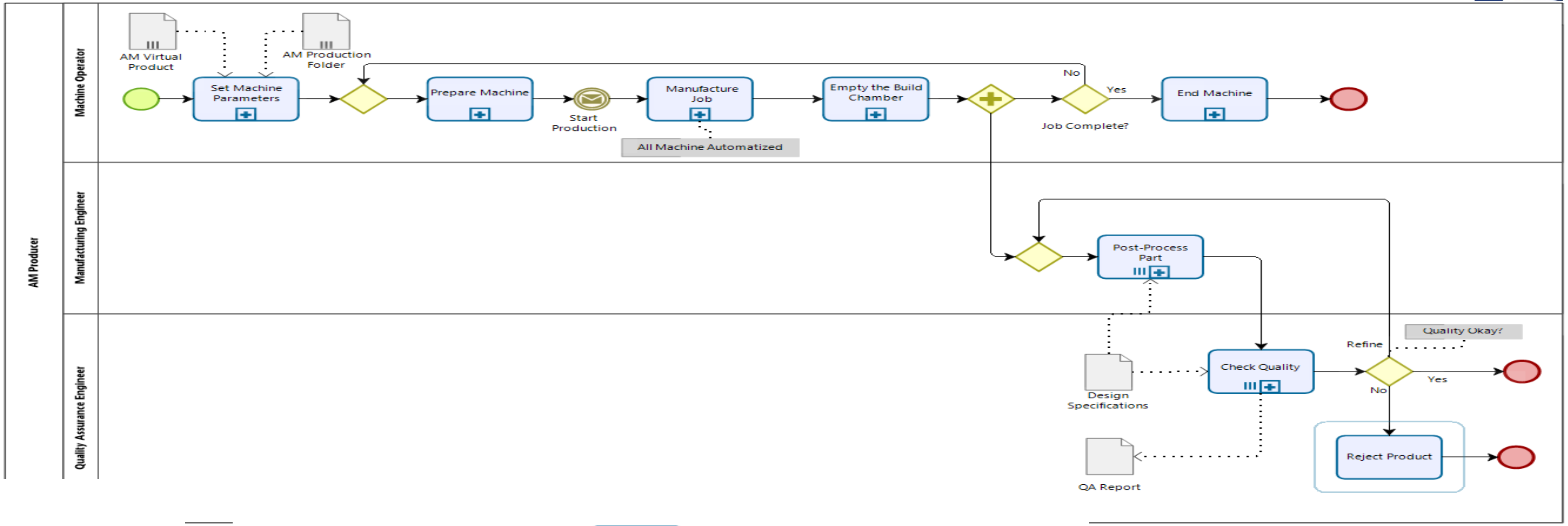
Additive Manufacturing Technology Overview

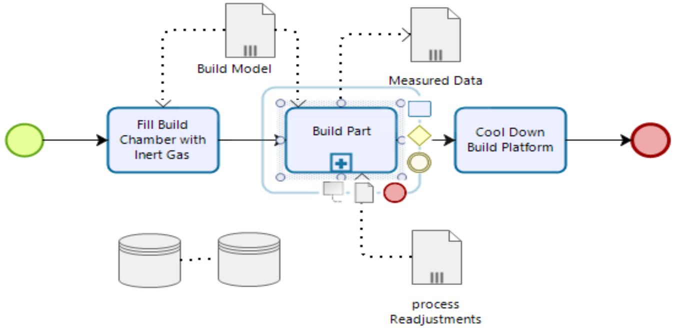
The value chain of AM

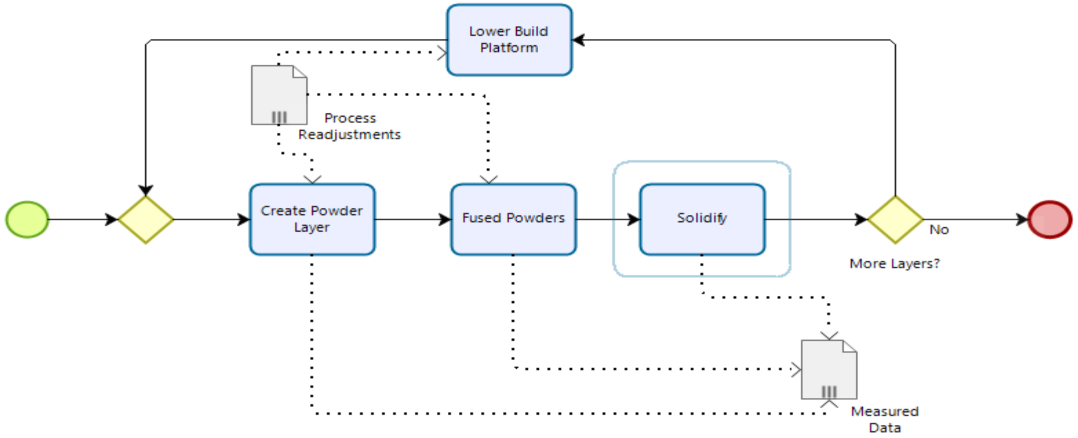


Additive Manufacturing Technology Overview

The value chain of AM







Additive Manufacturing Process selection

How to select an Additive Manufacturing technology for a production system? And How to select the right processes?

Additive Manufacturing Process Selection

Critical process Selection Problems

- **Given Design !!** Which are the best technology/ Machine to use or buy?
- **Given Part !!** Which machine and material should I use to build?
- **Given Machine, Part, and Material !!** How to set the machine up to meet different requirement, in the most efficient manner?

Solution to Selection Problems

- Capabilities and limitation of 3D printing Technologies/Machines
  - For a given designs: achievable accuracy, tolerance, layer thickness, …etc.
  - For a given materials: the compatible (Machine/ Material), the achievable mechanical properties
- Costs (Raw material cost, Machine/ technology installation price, Operation costs)
- Time to market (Velocity)

Additive Manufacturing Process Selection

Benefits beyond process selection

- Evaluate and compare different technological, or manufacturing activity choices
- what a manufacturer wants to emphasize in terms of future improvements to achieve or maintain their competitive advantage
- consistent set of criteria that the company has to value to compete in the market
- Enterprises always need to develop new sources of value.
- Support different perspectives like; financial, internal business, innovation, and defining enterprise strategies and performance management system.

Additive Manufacturing Process Selection

Major factors to consider

- **Part**
  - ❑ Size, weight
  - ❑ Geometrical complexity, accuracy, surface finish, color, …
  - ❑ Costs (Part fabrication cost)
  - ❑ Quantity requirement (certification needed??)
  - ❑ Activity sector (purpose of use; mechanical properties, demo, replacement, repair, …)
- **Machine**
  - ❑ Compatible material, allowable part size, …
  - ❑ Build speed (real productivity, cm3/hour)
  - ❑ Achievable geometry (complex geometry, with/ without support structure)
  - ❑ Costs (Machine cost)
- **Material**
  - ❑ Compatible machines
  - ❑ Cost (Raw material cost)
  - ❑ Properties (mechanical, thermal, thermal, …)

Additive Manufacturing Process Selection

Compatible materials with AM process category

	Material extrusion	Material jetting	Binder jetting	Vat photopoly-merization	Sheet lamination	Powder bed fusion	Directed energy deposition
Polymers and polymer blends	x	x	x	x	x	x	
Composites		x	x	x		x	
Metals		x	x		x	x	x
Graded/hybrid metals					x		x
Ceramics			x	x		x	
Investment casting patterns		x	x	x		x	
Sand molds and cores	x		x			x	
Paper					x		

Source: Wohlers, Terry. "Wohlers Report 2012: Additive Manufacturing and 3D Printing State of the Industry." Wohlers Associates, Inc. 2012.

Additive Manufacturing Process Selection

Material, and machine for different AM process category

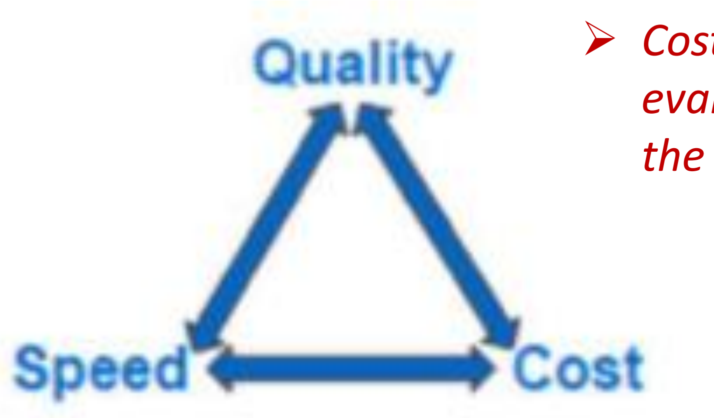
Senvol Database is the first and most comprehensive database for industrial additive manufacturing machines, and materials.

http://senvol.com/machine-search/

SENVOL®

Additive Manufacturing Process Selection

Further comparison (Major criteria)



- *Cost, Quality, and time are the most useful performance criteria that must be evaluated to give a measure of the product value and also the value provided by the value chain.*

Additive Manufacturing Process Selection

Further comparison (Major criteria)

Competitive Criteria	Definition	Characteristic of Additive Technology	Relationship
Cost	Cost for acquisition.	Acquisition value	The smaller the better
Flexibility	The company's ability to adapt its products to customer needs or to an individual customer.	Maximum size of prototypes Layer thickness	The bigger the better The smaller the better
Quality	Offer products that are produced according to pre-established standards and low defect rate.	Precision Surface Quality	The bigger the better The bigger the better
Velocity	The company's ability to deliver products in the shortest possible time.	Velocity	The bigger the better

Additive Manufacturing Process Selection

AM process categories

AM Process Categories (ASTM)

- Binder Jetting
  - Binder Jetting BJ
- Direct Energy Deposition
  - Laser Engineering Net Shape LENS
- Material Extrusion
  - Fused Deposition Modeling FDM
- Material Jetting
  - Material Jetting MJ
- Sheet lamination
  - Sheet lamination LOM
- Vat Photopolymerization
  - Stereolithography SLA
- Powder Bed Fusion
  - Electron Beam Melting EBM
  - Selective Laser Sintering SLS
  - Selective Laser Melting SLM

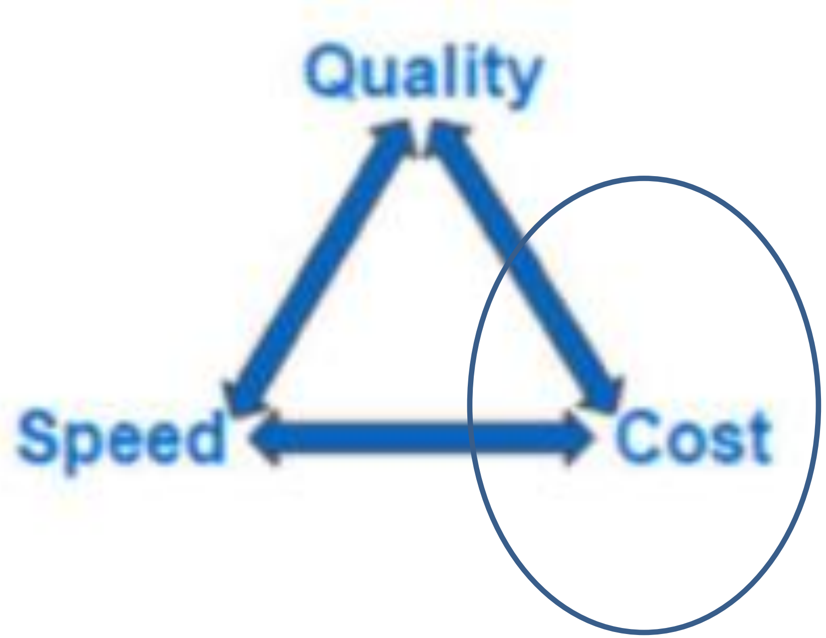
Different AM technologies " among others"

Additive Manufacturing Process Selection

Characteristics		Material Jetting (MJ)	Fused Deposition Modeling (FDM)	Binder Jetting (BJ)	Selective Laser Sintering (SLS)	Laminated Object Manufacturing (LOM)	Stereolithography (SLA)	Electron Beam Melting (EBM)	Selective Laser Melting (SLM)	Laser Engineering Net Shape (LENS)
	Velocity	34800000000 mm/h	0,00059 mm/h	16,65 mm/h	32 mm/h	1828800 mm/h	14 mm/h	28800000000 mm/h	0,0024 mm/h	76,2 mm/h
	Maximum size of prototypes	490 x 390 x 200 mm	406 x 355 x 406 mm	300 x 200 x 150 mm	340 x 340 x 600 mm	305 x 406 x 102 mm	380 x 380 x 250 mm	350 x 350 x 380 mm	420 x 420 x 400 mm	900 x 1500 x 900mm
	Precision	140,0 µm	50,0 µm	100,0 µm	175,0 µm	100,0 µm	100,0 µm	140,0 µm	150,0 µm	186,0 µm
	Layers Thickness	17,0 µm	400,0 µm	250,0 µm	400,0 µm	200,0 µm	100,0 µm	50,0 µm	100,0 µm	125,0 µm
	Price	$ 220,000.00	$ 200,000.00	$ 250,000.00	$ 250,000.00	$ 100,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00
	Surface Quality	+	-	-	-	-	+	+	-	-

Additive Manufacturing Process Selection

Cost criteria



- **Cost** is one of the major performance criteria taking into account by benefiting entities. That takes huge interest because it concerns all product life stages.
  - Operation cost
  - Material cost (Raw material cost)
  - Machine cost (Machine price, running cost €/h, .. etc.)

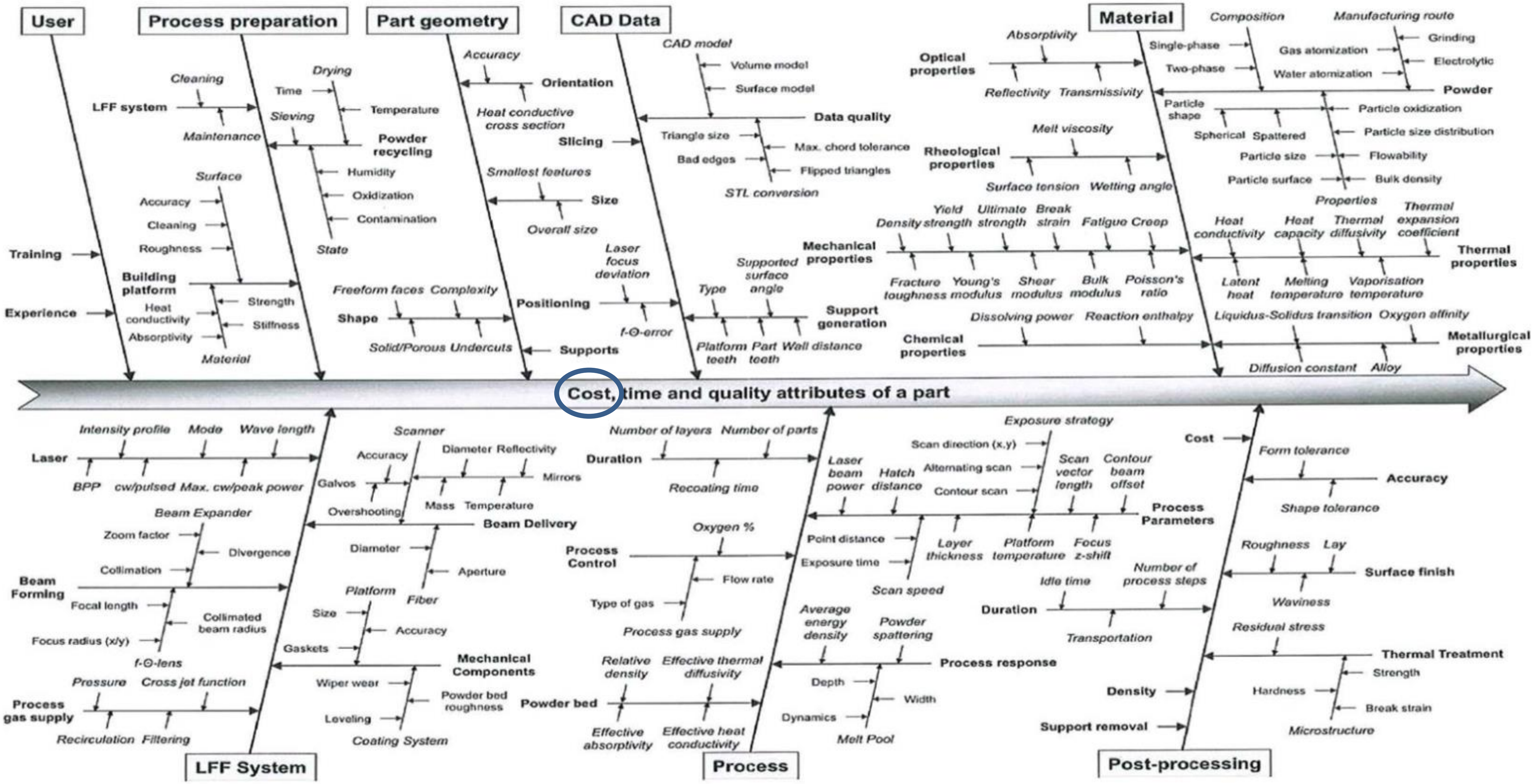
Additive Manufacturing Process Selection

Cost criteria (Cost characteristics of different AM processes)

AM Process Categories (ASTM)

Binder Jetting	Direct Energy Deposition	Material Extrusion	Material Jetting	Sheet lamination	Vat Photopolymerization	Powder Bed Fusion
Machines are less expensive than PBF, DED. Produce metal part al lower cost than PBF. But still high operation cost, and time.	High machine cost. For metal parts it is cheaper than PBF.Cost effective (for repaired industrial). For Material cost it is lower than powders material	Low cost of material. Cheap and straightforward process. Low machine cost	High machine cost. High material cost	Cost effective for full color prototype. Low material cost. Low operation, and machine cost.	Low material cost. Operation cost (relatively high, due to post process).	High material cost. High Operation cost (due to post process). Relatively low machine cost.

***Cost performance** of an AM system depends on many different variables and parameters.*



Over 200 different parameters that could potentially affect the main performance criteria of AM part, see following figure: by ("Cellular Design for Laser Freeform Fabrication", Dr. Olaf Rehme)

Cost Estimation Techniques

What is cost estimation? what are the different cost estimation technique? Which cost estimation technique to use? How to structure the product in term of costs?

Cost Estimation Techniques

Introduction in Cost Estimation

- ✓ Product cost estimation is often involved in estimating the cost of producing and selling a physical good, such as a car, which includes the costs of research and development, designing, manufacturing.

- ✓ Cost Estimation (CE) is the process of predicting the cost of a product before it is manufactured. The national estimating society has defined the cost estimation as: the art of approximating the probable cost of something based on the available information at the time.

Predicate the cost of, constructing facility, manufacturing goods, or delivering a service

Very important for any successful and effective organization

Important role internally, during the development of product

Key point for decision making

The importance of CE

Budget preparation

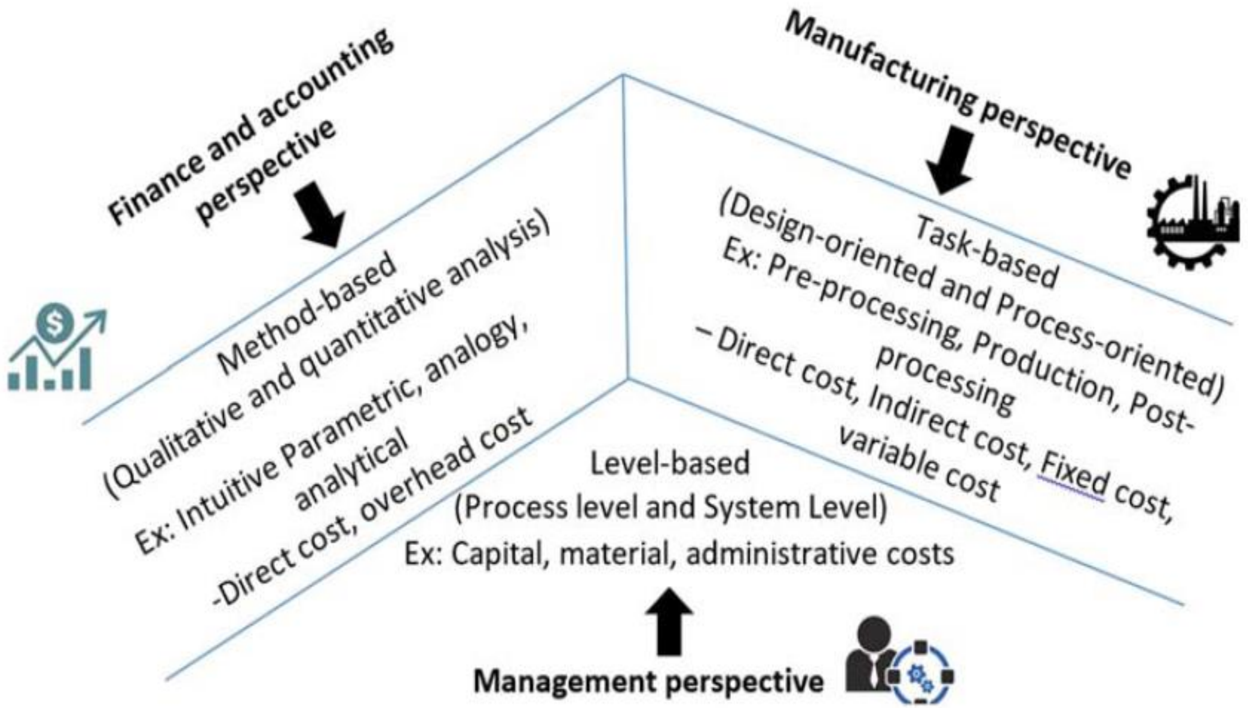
Externally when providing the quotation

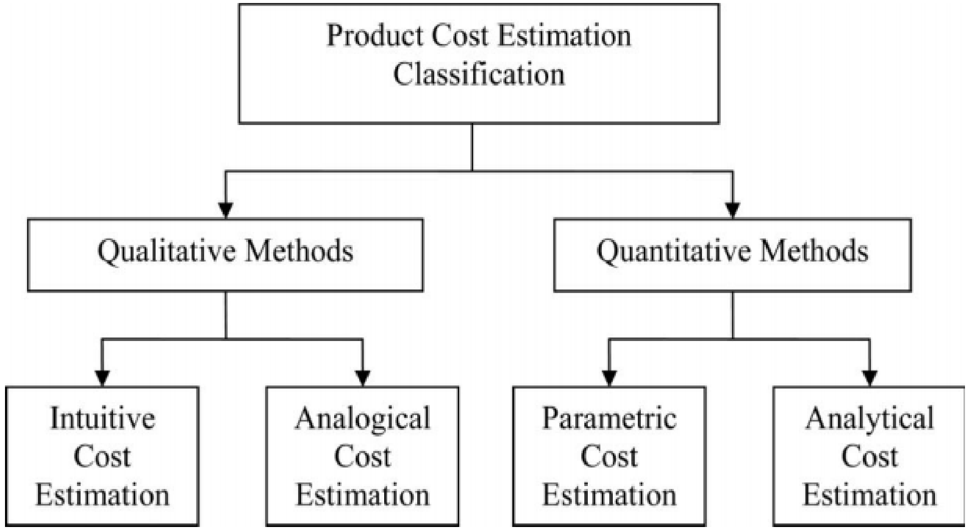
Directly linked to business performance

Cost Estimation Techniques

Different perspective of Cost classification

There are a wide range of classification regarding cost estimation, based on several aspects like; approach type, granularity level, tools used, and even the application phase.



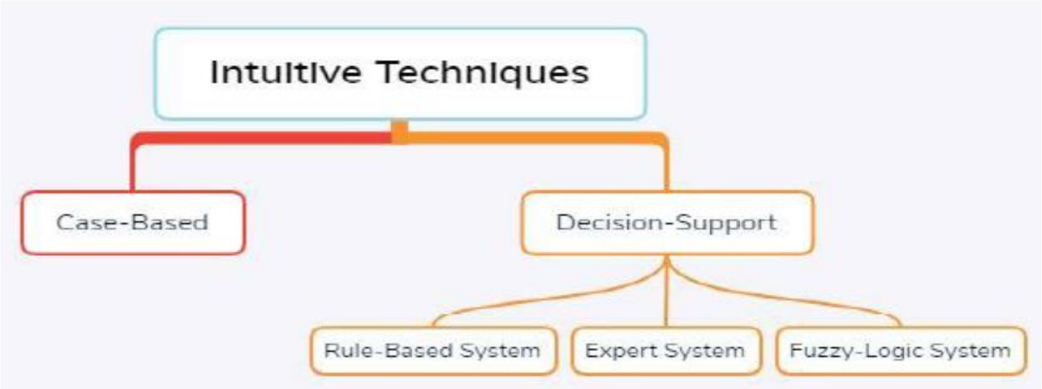


Cost Estimation Techniques

Classification of the Product cost estimation techniques

The intuitive techniques are primarily dependent on past experience, the expert knowledge is the key success of this method, where this experience can be applied either directly, or using different decision support systems:

- **Case-based reasoning**
- **Decision support technique**



Ex: “Expert opinion” “for software development”

Three software engineers are renown in the ERP software development.

- You hold interviews which each explaining the requirements, sizing level, and development process for your new system.
- Each member of the group submits their opinion of the final cost and the estimate converges to $50M.

Cost Estimation Techniques

Classification of the Product cost estimation techniques

Analogical techniques use the similarity of products by assuming similar products have similar costs, the analogical techniques have two main types:

- **Regression analysis**
- **Neural network models**

Ex: “for software development”:

Your company is developing a new IT payroll system serving 5,000 people and containing 100,000 lines of C++ code. Another company developed a similar 100,000 lines of code system for $20M for only 2,000 people. Your software engineers tell you that the new system is 25% more complicated than the other system. Other system development cost was $20M.

Estimated cost for new system = 1.25 * $20M = $25M Plus 5,000/2,000, or 2.5 * $25M = $62.5M total cost

Cost Estimation Techniques

Classification of the Product cost estimation techniques

The Parametric technique focuses on the characteristics of the product without describing it completely based on the relationship between a product’s functional or technical characteristics and the cost.

Ex: “for software development”:

You have a previously developed CER (cost estimation ratio) to estimate a new IT system based on SLOC “as number of function points”, for ex “number of code lines”.

Cost = SLOC * 25 $/SLOC

The CER is based on systems ranging from 1,000,000 to 3,000,000 SLOC.

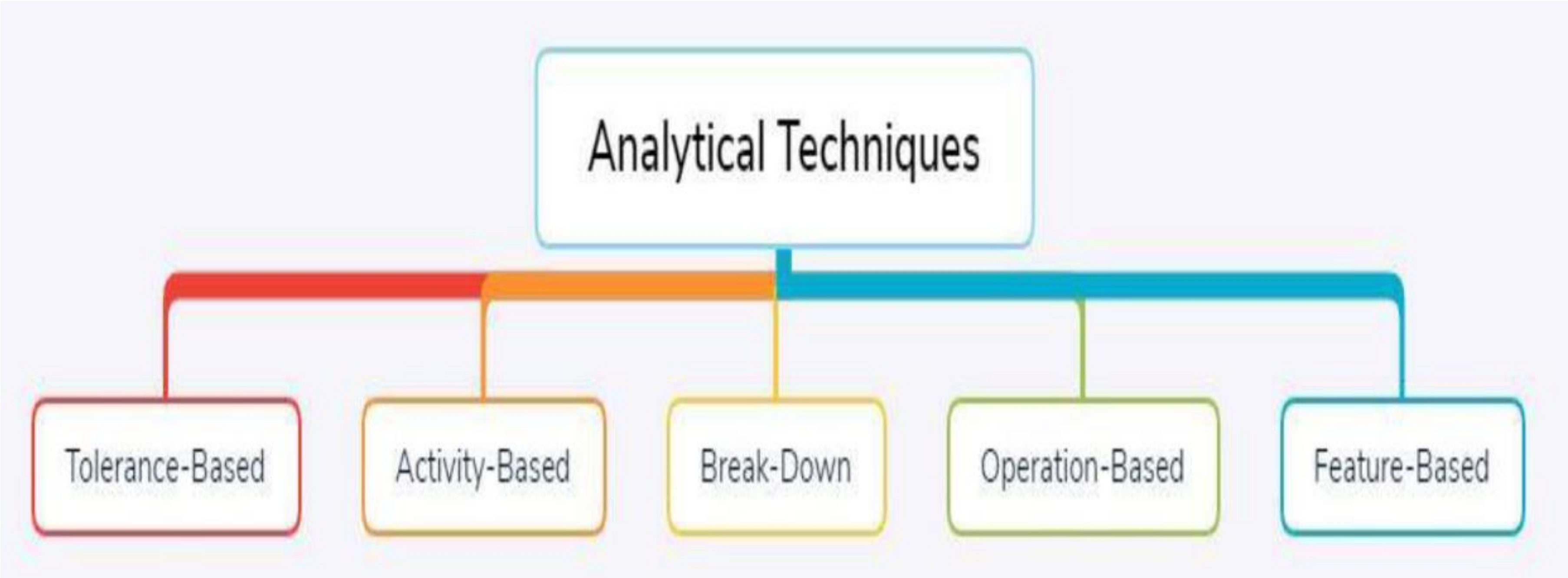
You have estimated 2,600,000 SLOC for new system

Cost = 2,600,000 * $25 = $65M

Cost Estimation Techniques

Classification of the Product cost estimation techniques

The Analytical techniques, which separate a product into several units, operations, and activities, that represent different resources consumed during the product life cycle, its further classified into:



Cost Estimation Techniques

Example of ABC

The implementation of this ABC approach follows these 7 steps, example from “Ben-Arieh et al. (2003)”:

- **Identify cost centres**: which are the resources that are used directly to produce the final product, include, human resources (designer, labour, … etc.), and equipment/ machines.
- **Analyse the indirect cost and calculate their cost drivers rate**: which are the overhead costs, the are needed to allocated to the final product, like (room rent, maintenance, … etc.). Each resource cost driver rate is determined by dividing the total annual cost of the resources by the total number of cost drivers used in one year.
- **Assign resources to each cost centre**: where the indirect cost allocated to cost centre. In this step the total cost for each cost centre is calculated, then for each cost centre one cost driver is identified.
- **Identify the activities**: The activities that take place in the product development process.
- **Analyse each activity and find the total cost of each activity**: Based on cost-centre resources for each activity. Using cost-centre drivers rate multiplied by the amount of the drivers consumed by each activity.

$$\text{RR(resource rate)} = \frac{\text{Total cost for 1 year}}{\text{Resouce drivers spent in 1 year (RD)}}. \quad (1)$$

$$\text{Total annual cost for cost center} = \sum_{i=1}^{\text{number of resources}} \text{RR} \times \text{RD} \quad (2)$$

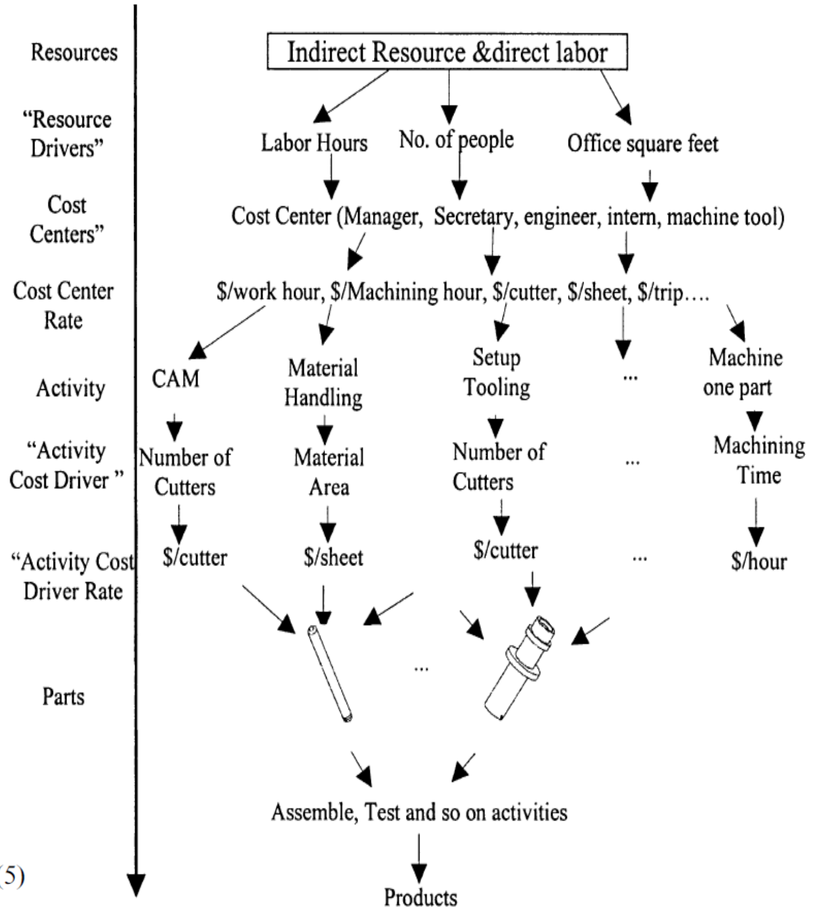
and RD is the amount if each resource driver spent by the cost center in 1 year.

$$\text{CCR(Cost centre rate)} = \frac{\text{Annual cost of center}}{\text{Cost center drivers spent in 1 year (CCD)}}. \quad (3)$$

$$\text{ACDR} = \frac{\text{Cost of one activity}}{\text{Activity cost driver spent}} = \frac{\sum_{i=1}^{\text{number of cost centers used}} (\text{CCR}_i \times \text{CCD}_i)}{\text{ACD}}, \quad (4)$$

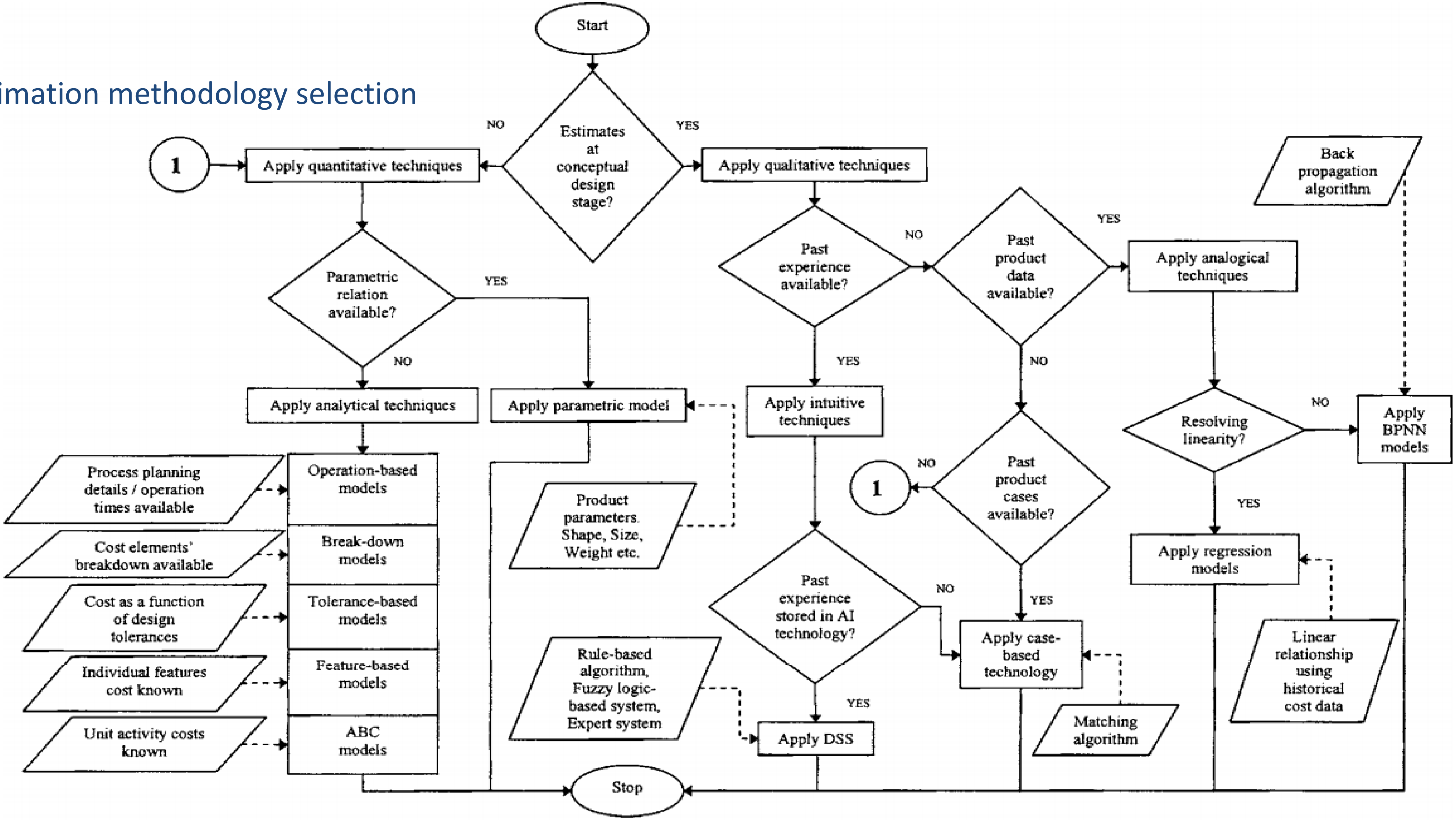
where CCD_i is the amount of the driver of center i used for the activity, and ACD is the amount of the activity's cost driver used. ACDR is the activity cost-driver rate cost.

$$\text{Total cost of one part} = \sum_{i=1}^{\text{number of activities}} (\text{ACD}_i \times \text{ACDR}_i). \quad (5)$$



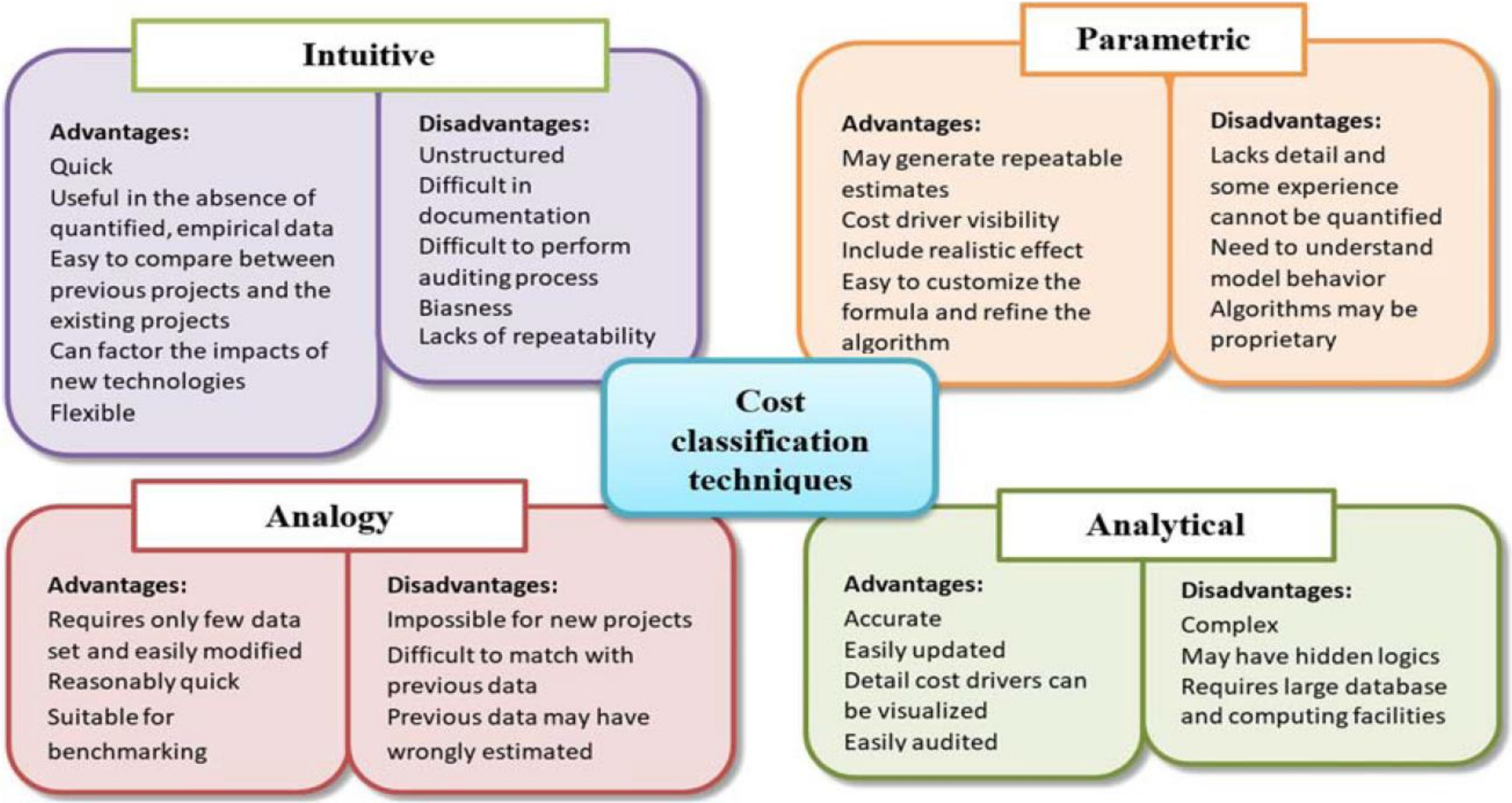
Cost Estimation Techniques

Cost estimation methodology selection



Cost Estimation Techniques

Advantages, and disadvantages of various Cost estimation techniques

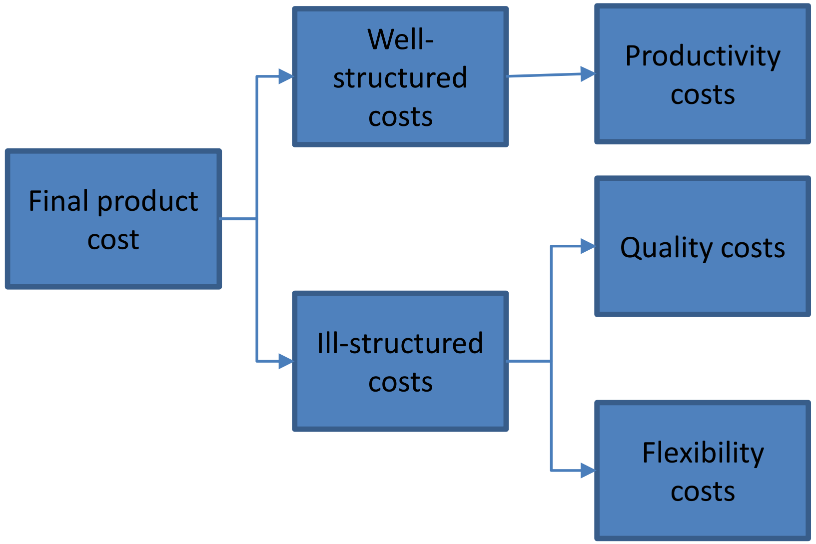


Cost Estimation Techniques

Type of costs found in product cost estimation

Additionally, it is also important, when investigating the costs of complex system, to distinguish between well-structured costs, and ill-structured costs.

- Well-structured costs which includes production costs such as labor, material, depreciation, machine, tool, overheads (administrative/production), and computer software.
- Ill-structured costs which includes the quality and the flexibility cost.
  - The quality cost included expenses incurred for inspection and prevention of defects, as well as process failure.
  - The flexibility cost was addition of the cost incurred for setup, waiting, idle time of the machine, and inventory carrying cost



Understanding Of Cost in Additive Manufacturing

Why it is important to study the cost structure and its related factors in Additive Manufacturing Technology?

Understanding of cost in Additive Manufacturing

Introduction

- The investigation of costs incurred by AM has a large interest by several parties; technology users, AM providers, software developers, technology vendor and investment community.
- Product Cost estimation play a significant role in the evaluation of AM. It represents the basis to develop the key decision variable on AM, which is the cost of product.
- Helpful to understand the cost drivers associated with the manufacturing process, which help to find innovative ways to enhance the operation efficiency from the AM facility manager perspective.
- There are two major motivational categories for examining additive manufacturing costs:
  - The first is to compare additive manufacturing processes to other traditional processes such as injection molding and machining. to determine under what circumstances additive manufacturing is cost effective.
  - The second category involves identifying resource used at various steps in the additive manufacturing process. The purpose of this type of analysis is to identify when and where resources are being consumed and whether if there can be a reduction in resource use.

Understanding of cost in Additive Manufacturing

Introduction

The analysis of AM production costs:

- ***Cost estimators***: Are specified to yield insight into the absolute cost performance within a manufacturing approach. Judged on the base on their accuracy and consistency.

- ***Cost Model***: Are designed to represent cost relationships. Not only to produce valid cost estimates, but to reflect the relationships between various relevant aspects. Judged based on their ability to capture important aspects in an appropriate ways, also the accuracy and consistency of their results.

Cost models proposed for AM mainly fall into the categories of ***Parametric Costing***, and **Analytical**, "***Activity Based Costing" .*** Fewer models may fall ***into Analogy, statistical models, or Intuitive, using different machine learning techniques.***

Understanding of cost in Additive Manufacturing

Additive Manufacturing Cost Structure/Factors

We will specify The Key cost factors/Drivers within AM in more detail:

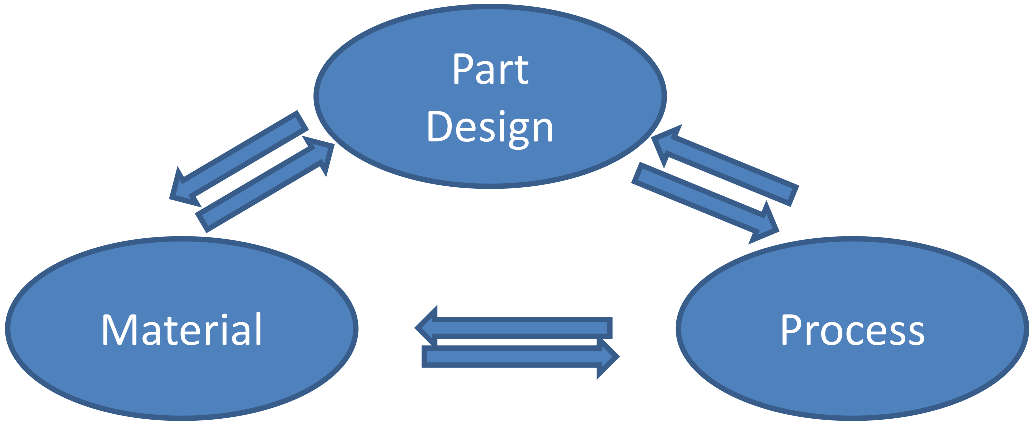
Prepare geometrical data	Machine prep	Build job	Machine output	Post-processing	Quality (Assurance/Control)
❑ Software and tools used (support structure, orientation, build composition) ❑ Designer ❑ Duration/ Time required	❑ Labor ❑ Duration/ Time required for(setup machine, clean, or material change)	❑ Build time ❑ Machine cost ❑ Material Cost ❑ Labor Cost ❑ Build platform Cost	❑ Labor ❑ Duration/ Time required for(remove part, clean, or manual powder removal)	❑ Powder removal cost ❑ Heat treatment cost ❑ Separate part from platform cost ❑ Remove the support cost ❑ Surface modification cost ❑ Equipment/ Machine (used in post-processing) cost ❑ Labor (Operate the required process) cost ❑ Duration/ Time required	❑ Quality assurance cost (3D scan, CMM) ❑ Control powder removal cost ❑ Project monitoring cost ❑ Manufacturing report cost ❑ Labor (Operate the required process) ❑ Equipment/ Machine (used) cost ❑ Duration/ Time required

- ❑ Overhead costs:
  - ❑ Production overheads
  - ❑ Administrative overheads
- ❑ Ill-structure costs:
  - ❑ Inventory cost
  - ❑ Transportation cost
  - ❑ Supply management costs
  - ❑ Quality costs (process failure)

Understanding of cost in Additive Manufacturing

Additive Manufacturing Cost Structure/Factors

In engineering domain, it is generally assumed that the choices of material, design and manufacturing process are interdependent, which means one aspect cannot be normally changes without effecting on the other two aspects. Thus, it is important to investigate these aspect and their correlation with the main cost factors/Drivers, therefore the final cost of product and AM processes. Which definitely increase the robustness of cost investigation.



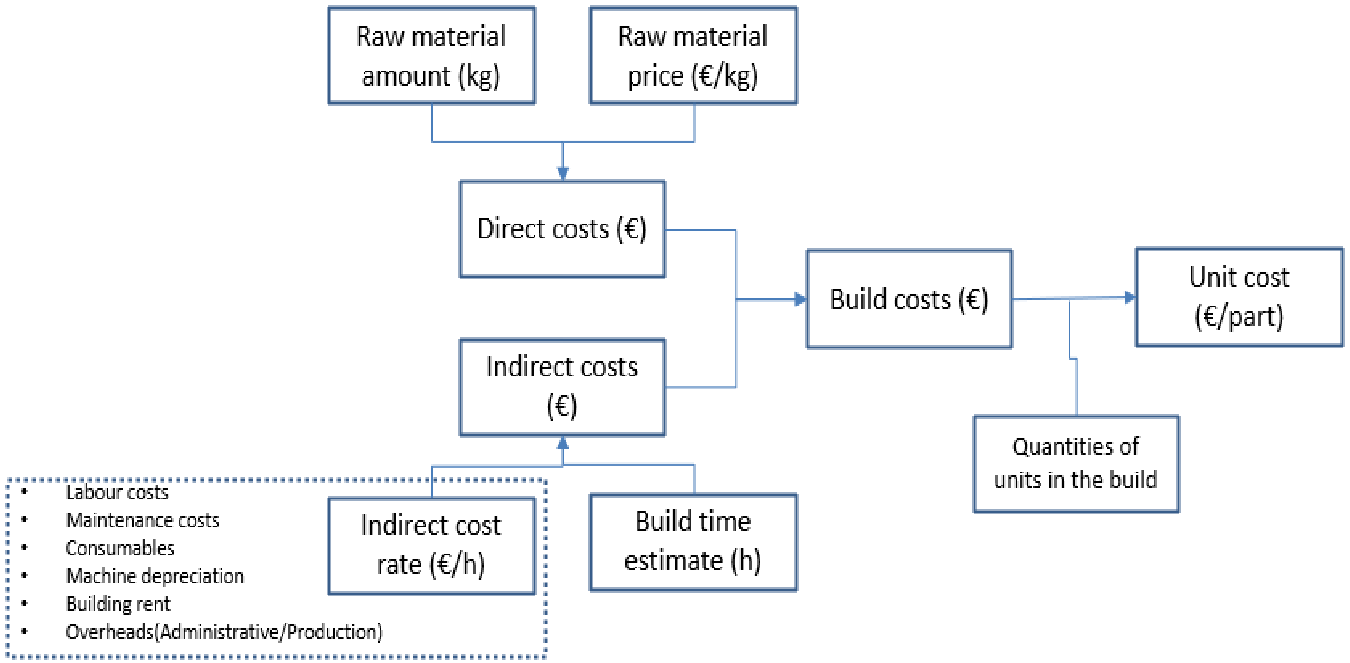
Understanding of cost in Additive Manufacturing

How to build an AM Cost Model

The influential AM cost model was published in 1998 by (Alexander et al.1998)

The activity-based costing is flexible, where it is possible to adapt individual steps depending on the scope of the cost investigation and AM technology type. To construct AM activity based-costing type, a number of steps are required:

- ✓ ***Step1: Definition of the scop of the costing model***
- ✓ ***Step2: Build time estimation***
- ✓ ***Step3: Calculation of the indirect cost rate***
- ✓ ***Step4: Estimation of direst cost***
- ✓ ***Step5: Specify the cost per build and unit cost***



Understanding of cost in Additive Manufacturing

✓ Step1: Definition of the scop of the costing model

AM processes are not stand alone systems, specially when it is adopted for Manufacturing purpose. So it is necessary to define the scop of the cost model as first step. By asking *the question of* ***what are the process of Product life cycle that will be included in the cost model***.

For example: here in this figure we can see the typical scop of AM cost model. (*scop of the cost investigation in generic AM process*)

✓ Step2: Build time estimation

Next step is to estimate the build time required by the AM system to execute the build operation. However the accurate estimation of build time can be complex and highly specific to ***product geometries*** and ***build composition*** in the operation. Also as many systems require ***significant time to warm up, and cool down***, during which no other activities take place within the machine, such durations should be included in the build time.

This factor is significant components in regard to estimate the cost of AM, build time can vary from few hours to 150 hours. . Many developed models and approaches put effort to estimate this value, also different software packages are available for estimating build time.

Understanding of cost in Additive Manufacturing

Machine specific parameters:

- Time for flooding of build chamber = t_{Fl}
- Volume related build speed = b_M (V_B)
- Build rate of basic support = b_{MGS} (V_S)
- Recoating time for one layer = t_{r1}

Parameters will be determined with the test platform

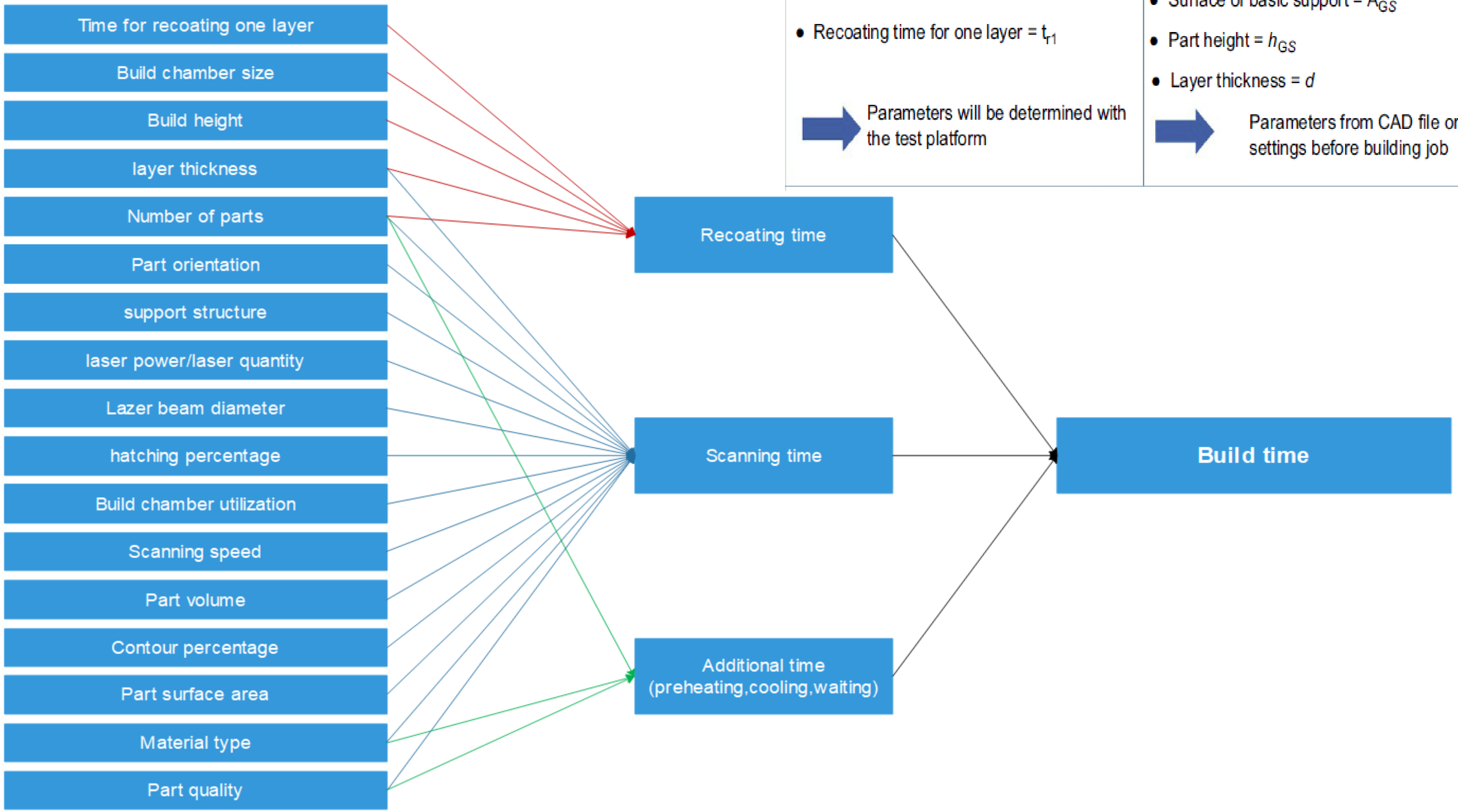
Part specific parameters:

- Part volume = V_B
- Volume of internal support = V_S
- Height of basic support = h_{GS}
- Surface of basic support = A_{GS}
- Part height = h_{GS}
- Layer thickness = d

Parameters from CAD file or settings before building job

For simple build time estimation, which rest on the assumption that ***processing speed is constant per layer***, (where in complex way it might be also based on ***other factors like: hatch, contour, laser power, scanning speed, material thermal properties, …etc.***). Making this simplification, the overall build time could approximated as follow:

Build time= Time for setup "Initialization and warm up" +(Total build volume/Building speed rate) + (Time to recoat on layer* Total number of layers) + Time for cool down



Understanding of cost in Additive Manufacturing

✓ ***Step3: Calculation of the indirect cost***

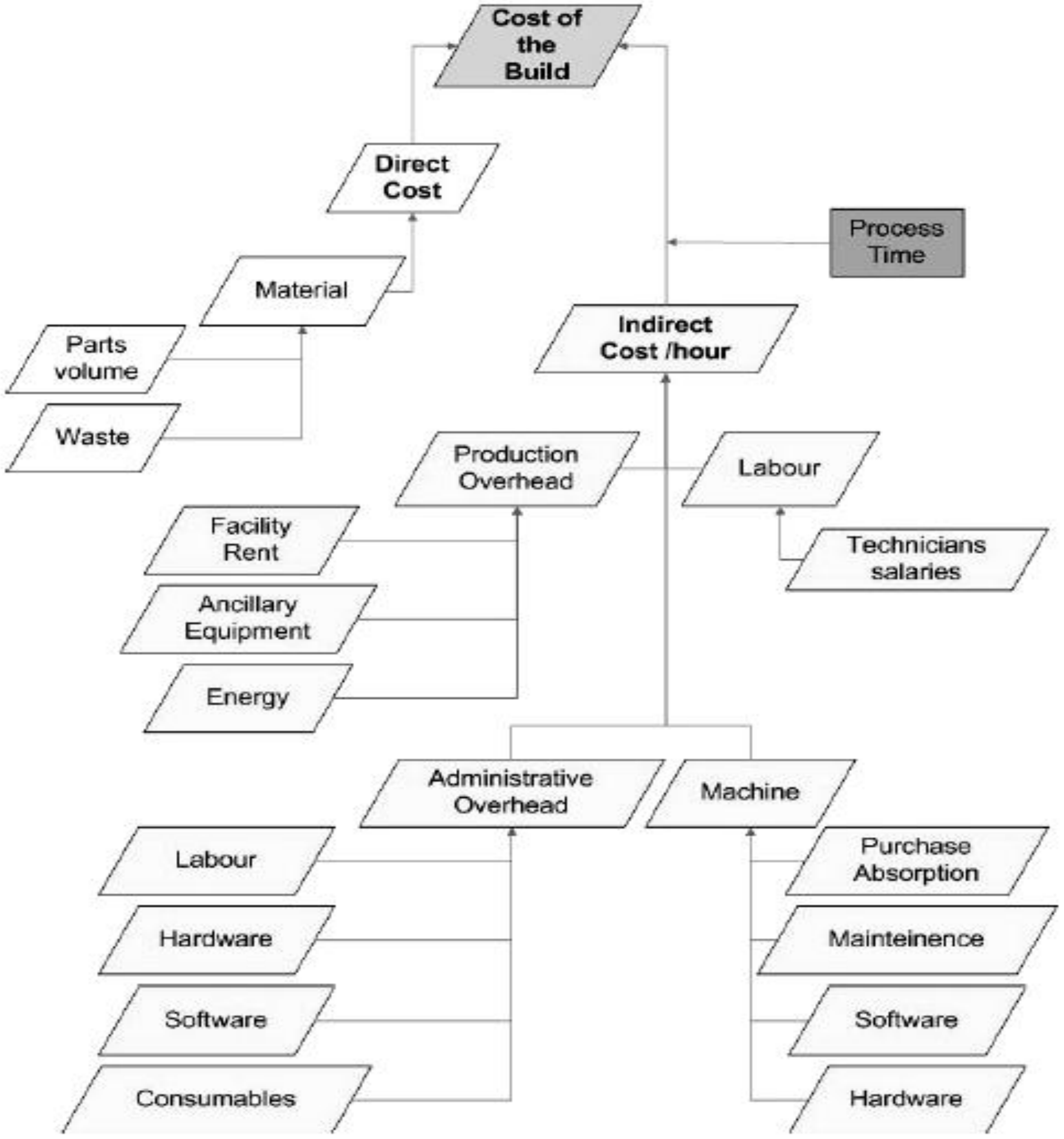
Several cost elements and activities are attributed to overall costs through build time. So this requires the calculation of an indirect costs, measured as costs incurred per unit of operating time (€/h). The elements of indirect costs are normally obtained on an annualised biases, then these costs are broken down into hourly rate, by dividing the annual cost through the number of operating hours per year ("***the capacity utilisation over time WH***", which relies on the share of operating hours of overall times, where in most models the operating time is assumed to lie between **50% and 90%** of total time.

Understanding of cost in Additive Manufacturing

✓ Step3: Calculation of the indirect cost

The most important elements that are included in in indirect costs:

- ***Machine cost***:
  - ***The purchase cost of AM system and ancillary systems***
  - ***Maintenance expenses and costs of consumables***
- ***Labour cost***:
- ***Overheads***: which are allocated to the operation of the AM system
  - ***Overheads from production***
  - Additional overheads ***are administrative***

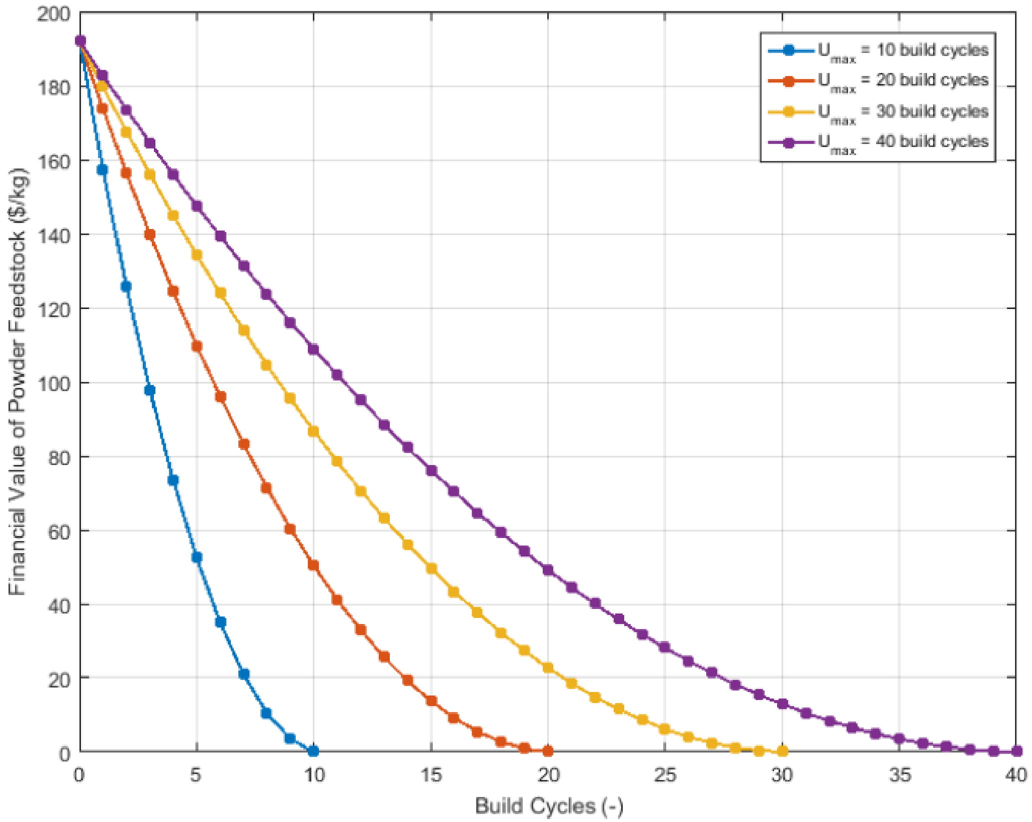


Understanding of cost in Additive Manufacturing

✓ Step4: Estimation of direct cost

Direct costs are the costs associated with physical inputs required for the operation of an AM system. The most important direct cost arises through the ***raw materials used*** in the process, including one or more build material. **Material cost:** is one of the major cost factor for AM technology. It is quite high, when compared to traditional manufacturing. It Based on:

- ***Build volume*** (including part, support, and other test parts if required)
- **Material type** (the density of the material, and the material price/kg)
- **Material waste** (loss) “based on the manufacturer, and machine type” or waste powder inside the build part
- **Capacity utilization (packing ratio),** number of parts inside the build)
- In some project some quality test for the powder has to be done, where, it important to include the **quantity of powder for the test**
- ***Raw material refreshing or state***



Understanding of cost in Additive Manufacturing

✓ ***Step5: Specify the cost per build and unit cost***

After obtaining the required data and computing the elements described above, it is possible to specify the cost model for the build (C build), including ***pre-processing, and post-processing costs***.

$$C\ build = C\ pre + (C\ indirect * T\ build + C\ direct) + C\ post$$

However, If ***multiple parts*** are contained in the build volume, it will be important to break down the build cost for the level of induvial part contained. The volume of part i divided by the volume of all j parts in the build:

$$\text{C unit (for i geometry)} = C\ build * (Vi/\textstyle\sum_j\ Vj)$$

If all part have the same geometry then:

$$C\ unit = C\ build\ /\ number\ of\ parts$$

Understanding of cost in Additive Manufacturing

Why such models are important:

- ***Reliable and used for different purposes (inter process comparison to evaluate cost performance of different AM systems against each other, or cost performance of conventional manufacturing technologies***

- ***Explore the cost effects of changes to product design***

- ***How unit costs relate to the quantity of products manufactured***

Understanding of cost in Additive Manufacturing

Example1.1: “see the excel file”

The scope: Activity involved in the Cost Estimation	
Material	Cost of material purchase
Machine cost	(Machine purchase, support equipment and (hardware, Sofware), Maintenance, Machine utilization rate, Depreciation)
Labour	Labour cost for machine set-up and machine output)
Production overhead	Costs incurred due to production, energy, and floor rent
Adminstration overhead	Costs incurred due to running the enterprise, adminstrative staff, office space, and consumables

Assumption:	It supposed that the Operator is only working on AM system.
	The total Indirect cost rate of Operating AM machine

Data:

Production overhead	
Yearly rent /m2	130,5
Building area (m2)	168,5
Energy consumption/h	1,5
(Rent/ y)/WH	4,4
Administration overhead	
Hardware purchase €	2175
Software purchase €	2175
Consumbles (€/year	1450
Software cost/year	435
Hardware cost/year	435
Production labour	
Operator annual salary + employer contribution €/y	39894
Machine costs	
Machine purchace	362500
Support machine	24360
Maintenance /year	21750
Hardware and software	11600
Software upgrades/ year	1450
Purchase cost/year	48357,5
Hardware and software cost/y	2320

EOSINT M280	
Utilization rate	57,08%
Depreciation time (y)	8
Machine WH/year (365*24*Utilization%	5000
Hardware&Software Depreciation (y)	5

The Ruffo et al.,2006 Model

$$\text{Indirect cost rate}= \frac{\sum Indirect\ costs}{Working\ time\ (WH)}$$

$$Macinhe\ working\ time\ (WH)= 365 \times 24 \times \text{ Utilization rate \%}$$

$$Prod.overhead\ rate\ = (Rent \times building\ area/WH) + Energy\ consu.$$

$$Admin.overhead\ rate\ = (\frac{Hard\ \&\ Soft}{Depretation for\ Hard\ \&\ Soft} + Consu\ per\ year)\ /\ \text{WH}$$

$$\text{Machine costs rate}= ((\frac{Hard\ \&\ Soft}{Depretation for\ Hard\ \&\ Soft} + \text{Soft. Upgrad per year} + \text{Maintenance per year} + (\frac{Machine{+}support\ machine\ purchase}{Depretation for\ Machine}))/\ \text{WH}$$

$$Labour\ cost\ rate\ = Annual\ salary\ and\ employer\ contribution/WH$$

Result:

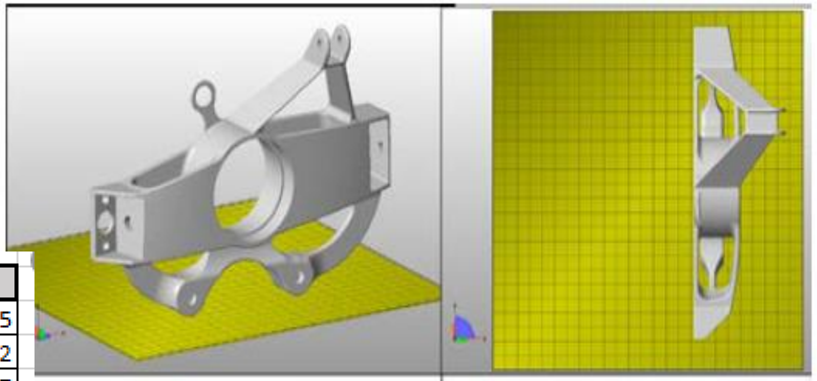
Indirect hourly rate €/h	
Production overhead	5,90
Admin. overhead	0,46
Labour/ machine hour	7,98
Machine costs	14,78
Total rate (indirect)	29,12

$$\boldsymbol{The\ total\ cost = Indirect\ cost\ rate \times Build\ time + Material\ used \times Material\ price}$$

Understanding of cost in Additive Manufacturing

Example1.1: "see the excel file"

Estimate the cost of the following part:



Part Geometry	
V part (cm3)	175
V support (cm3)	412
V total (cm3)	587
Bounding Box (mm)	74 x 218 x 172
Number of layers	3360

time for racoting one layer (sec)	9
time for cooling and pre heating (h)	3,2
Material waste (kg)	1,3

Materal	
Type	Ti64 (Titanium)
Density(g/cm3)	4,41
Material price (€/kg)	680
Build speed (cm3/h)	13,5

$$\text{Build time} = \text{Time for cooling and preheating} + \left(\frac{Vtotal}{\text{build speed}}\right) + (\text{time for coating one layer} \times \text{Number of layers}$$

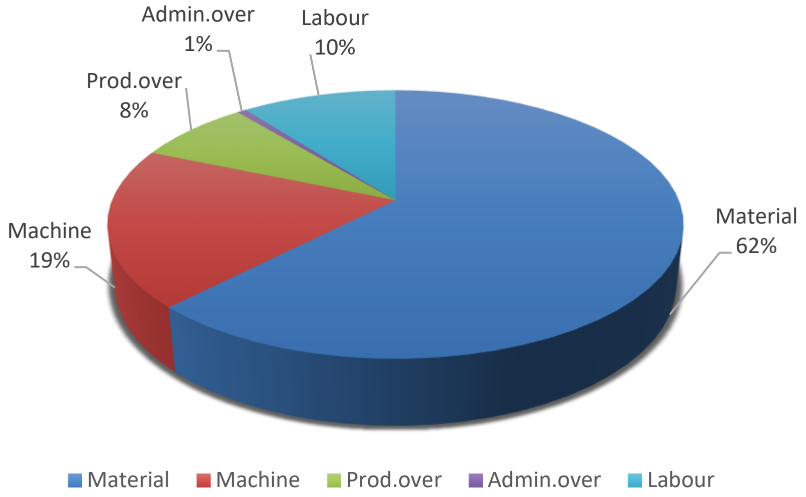
Build time(h)	55

$$\text{Material used} = Vtotal \times Density + \text{Material waste}$$

Matrial used(kg)	3,9

Simplified from Lindeman et al.,2017

Cost structure(€)	
Material	2644,3
Machine	813,9
Prod.over	324,9
Admin.over	25,6
Labour	439,5
Total(€)	4248,06



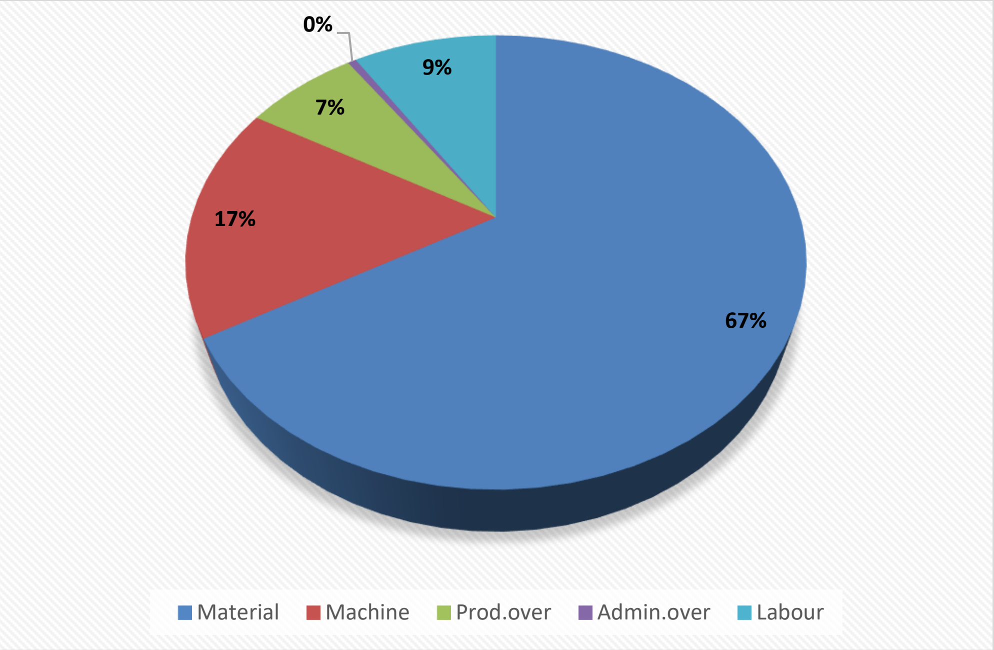
What if we change the machine utilization rate % to (70%) ??

Understanding of cost in Additive Manufacturing

Example1.2: “see the excel file”

Solution

What if we change the machine utilization rate % to (70%) ??



Machine utilization rate 70% (6132 h/year)

Cost structure(€)	
Material	2644,3
Machine	663,6
Prod.over	280,1
Admin.over	20,8
Labour	358,4
Total(€)	3967,246

Compare

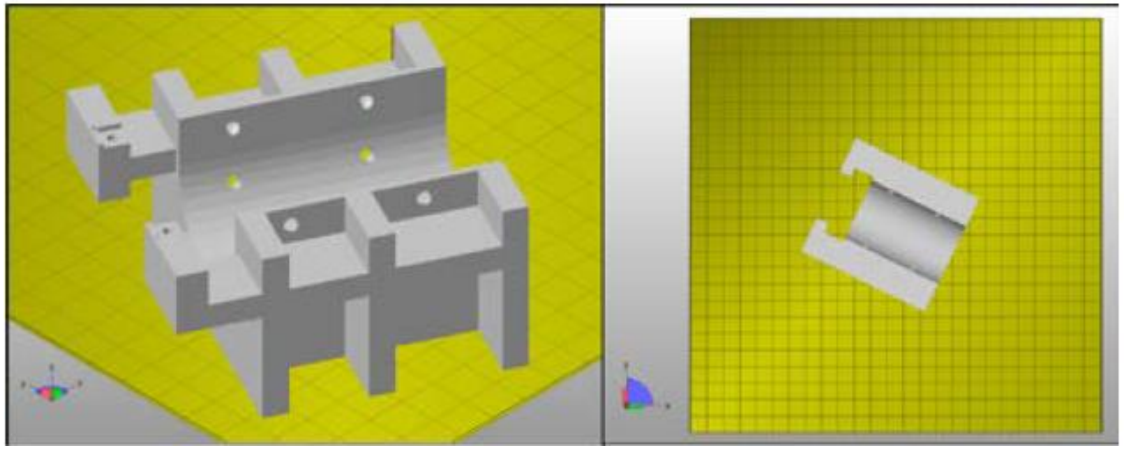
Machine utilization rate 57% (5000 h/year)

Cost structure(€)	
Material	2644,3
Machine	813,9
Prod.over	324,9
Admin.over	25,6
Labour	439,5
Total(€)	4248,06

Understanding of cost in Additive Manufacturing

Example1.3: "see the excel file"

Estimate Using the data from Ex.1,1 estimate the cost for different part ??



Part Geometry	
V part (cm3)	95
V support (cm3)	97
V total (cm3)	192
Bounding Box (mm)	76 x 84 x 47
Number of layers	1058

time for racoting one layer (sec)	9
time for cooling and pre heating (h)	1,8
Material waste (kg)	0,7

Materal	
Type	GP1 (StainlessSteel)
Density(g/cm3)	7,8
Material price (€/kg)	100
Build speed (cm3/h)	7,2

Use the data from the previous ex??

Result:

Indirect hourly rate €/h	
Production overhead	5,90
Admin. overhead	0,46
Labour/ machine hour	7,98
Machine costs	14,78
Total rate (indirect)	29,12

$$\textbf{The total cost} = \textbf{Indirct cost rate} \times \textbf{Build time} + \textbf{Material used} \times \textbf{Material price}$$

$$Build\ time = Time\ for\ cooling\ and\ preheating + \left(\frac{Vtotal}{build\ speed}\right) + (time\ for\ coating\ one\ layer \times Number\ of\ layers$$

$$Material\ used = Vtotal \times Density + Material\ waste$$

Understanding of cost in Additive Manufacturing

Example 2 : "see the excel file"

*For this example different way to estimate the cost, include the cost of electrical consumption and protective gas consumption **as a direct costs** related to the build job activity, because PBF "SLM", is involved in high power and protective gas consumption*

- **Machine set-up/Machine output:** labor work for AM operator. For **machine set-up**, several tasks like uploading the digital file, selecting process parameters, and changing material if required. For **machine output**, in order to remove the entire build and manually removing the powder from the build. The cost of these activity based on the cost of **AM operator, and the duration required for these activity** which highly based on the Machine type, material type, also If other tasks are required (e.g. Material change).

$$Total\ cost = Setup\ cost + Build\ cost + Machine\ output\ cost$$

$$Machine\ output\ cost = Labour\ hourly\ rate \times time\ for\ remove\ part, remove\ powder$$

$$Setup\ cost = Labour\ hourly\ rate\ \times time\ for\ setup$$

$$Build\ job\ cost = (C\ machine\ hourly\ rate + C\ protective\ gas\ hourly\ rate + C\ electricity\ hourly\ rate) \times Build\ time + Material\ price \times Material\ used$$

Setup machine → Build job → Machine output

$$Build\ time = \frac{Total\ Volume}{Build\ Rate}$$

$$C\ machine = (Machine\ purchase\ per\ year + Maintenance\ per\ year + Room\ rent\ per\ year + Interst\ per\ year)/WH$$

Yi al.,2019

Understanding of cost in Additive Manufacturing

Example 2.1 : "see the excel file"

Utilization rate= (90%) for both machine, WH= 7884h

Machine, Gas, Electricity Data		
Machine	M290	M400-4
Manufacturer	EOS	EOS
Size of build (mm)	250 x 250 x 250	400 x 400 x 400
Space Required (m2)	17	39
Purchase price (€)	480000	1420000
Depreciation (year)	6	6
Maintenance (per year)	48000	142000
Room Rent (€/m2)	130	130
Interest (€/year)	24000	71000
Working time (WH) (h)	7884	7884
Avg. Power (KW)	2,4	22
Electricity cost (€/h)	0,2	1,76
Gas cost (€/h) (Argon)	60	60
Gas cost (€/h) (Nitrogen)	0,228	0,228
Labour cost (€/h)	39	39

Case no.1	
Machine	M290
Material Type	316L (stainless steel)
Material price (€/kg)	40
Density (g/cm3)	7,9
Build rate (cm3/h)	13,3
Number of part per build	15
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm3	346,5
Protective gas	Argon
Time for set-up (h)	0,3
Time for machine out-put (h)	0,75

Results	
Setup cost (€)	11,7
Machine output cost (€)	29,25
Buit time (h)	26,1
Material cost (€)	109,49
Build job cost (kg)	2077,95
Total cost (€)	2228,40
One Part cost (€)	148,6

Understanding of cost in Additive Manufacturing

Example 2.2 : "see the excel file"

Estimate the final cost of the following different cases:

In this case we will use different machine, and different part, but we will keep the material type and protective gas (from case1)

Case no.3	
Machine	M400-4
Material Type	316L (stainless steel)
Material price (€/kg)	40
Density (g/cm3)	7,9
Build rate (cm3/h)	42,6
Number of part per build	40
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm3	924
Protective gas	Argon
Time for set-up (h)	0,8
Time for machine out-put (h)	2

In this case we will use the same machine, and part, but we change the used material type(from case1)

Case no.2	
Machine	M290
Material Type	ALSi10Mg (Alu)
Material price (€/kg)	75
Density (g/cm3)	2,7
Build rate (cm3/h)	26,6
Number of part per build	15
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm3	346,5
Protective gas	Argon
Time for set-up (h)	0,1
Time for machine out-put (h)	0,75

Case no.4	
Machine	M400-4
Material Type	316L (stainless steel)
Material price (€/kg)	40
Density (g/cm3)	7,9
Build rate (cm3/h)	42,6
Number of part per build	40
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm3	924
Protective gas	Nitrogen
Time for set-up (h)	0,8
Time for machine out-put (h)	2

In this case we change the protective gas (from case no.3)

Understanding of cost in Additive Manufacturing

- **Capacity utilization of the build chamber:** ”packing build volume”, number of part in the build job, (in order to minimise the unused space in the building chamber). (used volume/ possible build volume)

- Some cost models, allow for significant unused build volume capacity in the estimation of unit cost, where this in manufacturing configuration considered as inefficient.
- Here it comes the ability to minimise the cost by efficient configuring or packing build volume.
- As we saw before this factor has an effect on both the build time, and the material cost thus, the cost of additive manufacturing product.
- This factor is linked to the Build envelop or the bounding box (The build envelope is the maximum area for part production in an additive manufacturing system).
- The higher the packing ratio, the lower the waste in material and the production time per component, with a consequent cost saving.

Understanding of cost in Additive Manufacturing

AM as a Multi-step process: as we describe before, AM cant be a stand alone process, it is integrated into a chain of surrounding process steps. Thus, the challenge is to define the boundaries of cost investigation, which also challenging without sufficient knowledge of product characteristics, and the AM technology. (for example some AM technologies variants will require entirely different pre- or post-processing, which also the case for different product characteristics).

- **Prepare the geometrical data:**

The CAD/CAM preparation related to the initial CAD data, placement in the building chamber , orientation, and creating the support. Carried by the Design engineer, using workstation (Pc, software) using **software** packages like (CATIA, Solid Work, NetFabb, Materialize Magic, ..etc., which can support and automate these processes. The cost of this activity based on the cost rate of the design engineer, and the used workstation (pc, software). Multiplied by the duration of this task.

The time/duration of this activity based on the tasks required, (for example if topology optimization is required), also the **geometrical complexity of the product** to be produced(if it has difficult support to create, difficult orientation and build composition (number of part to be produced) build chamber utilization.

Understanding of cost in Additive Manufacturing

- **Post-processing:** This step is the sum up of all necessary post-processing, after machine output, (Powder removal, separate the part from the platform, support removal, mechanical process for surface modification, and heat treatment).

This cost can be a main part of the total part costs. Also, it is important to consider these activity at early stages of the design.

The post-process highly depend on **the costumer requirement, and customer activity sector "end user"**.

The **labour cost, and machine/Equipment Type** used cost, and duration/ time for the required process.

- **Quality Assurance/Control:** The different steps needed to evaluate and ensure accuracy, surface finish, and other feature detail to achieve part quality. Like (3D scan, CMM, Powder removal control check "tomography, Endo scoping", ..etc.).

The cost of Quality controls/assurance, can play an important role on the total part cost.

The part requirement, and customer activity sector "end user" are the main factor for this cost. Among labour, and machine running costs.

For example: for complex commercial Aerospace component like *LEAP fuel injection nozzle*, which will require extensive test process like; full traceability of each component, source material, and computer tomography(CT) scan,.

Also, If the build include test parts, several controls/test will be associated to this cost.

One needs to consider that post-processing and quality costs may take up to 50% of the final product costs.

Understanding of cost in Additive Manufacturing

Example 3: "see the excel file"

From the previous example (case no.1), the cost estimation need to be extended to include the following activity(CAD/CAM preparation, EDM, and manual post-process). Estimate the cost of one part??

From case no.1 result	
Setup cost (€)	11,7
Machine output cost (€)	29,3
Material cost (€)	109,5
Build job cost (kg)	2077,95
Number of part (-)	15
Note:	*All parts have the same geometry*
For one part (€)	
Setup cost (€)	0,78
Machine output cost (€)	1,95
Material cost (€)	7,30
Build job cost (kg)	138,53
Operator cost(€/h)	39

CAD/CAM preparation → Set-up machine → Build job → Machine output → Separate build platform (EDM) → Manual post process

Data	
T prep (h)	0,5
C Designer (€/h)	90
C Pc (€/h)	90
C EDM (€)	150
C tool (€/h)	40
T post (one part) (h)	0,1

$$C_{Prep}(P_i) = (C_{Oper} + C_{PC}) * \frac{T_{Prep}(G_i)}{N_i}$$

$$C_{Substrate}(P_i) = \frac{C_{EDM}}{\sum_i A_{Con}(G_i)} * A_{Con}(G_i)$$

Simplified from Rickenbacher et al.,2013

$$C\ Substrate = \frac{C\ EDM}{Numbe\ of\ part}$$

$$C_{Postp}(P_i) = T_{Postp}(G_i) * (C_{Oper} + C_{Tools})$$

Understanding of cost in Additive Manufacturing

Inventory cost

This inventory is for products that are unused or undelivered yet. They occupy physical space, buildings, and land while requiring rent, utility costs, insurance, and taxes. Thus, the products are becoming obsolete. Additive manufacturing provides the ability to manufacture parts on demand, which reduces the need for maintaining large inventory and eliminates the associated costs.

Transportation cost

Additive manufacturing allows for the production of multiple parts simultaneously in the same build, making it possible to produce an entire product. which reduces the transportation of parts produced at varying locations

Understanding of cost in Additive Manufacturing

The supply management cost

includes purchasing, operations, distribution, and integration. Purchasing involves sourcing product suppliers. Operations involve demand planning, forecasting, and inventory. Distribution involves the movement of products and integration involves creating an efficient supply chain. Additive manufacturing may have significant impacts on the manufacturing supply chain, reducing the need for supply chain management.

Quality cost (process failure)

During machine operation This type of process failure is associated with significant costs for repeating the build and also disruption to the production schedule.

Rejection of induvial parts after completion of the build The nature of the cost models changes in a subtle way if the risk of failure is included, so the model become "probabilistic"

Different Cost Models in Additive Manufacturing Field (Academic)

Cost Models in AM

Cost Estimation models in Additive Manufacturing

In this section we will present some of the existing costing model in additive manufacturing:

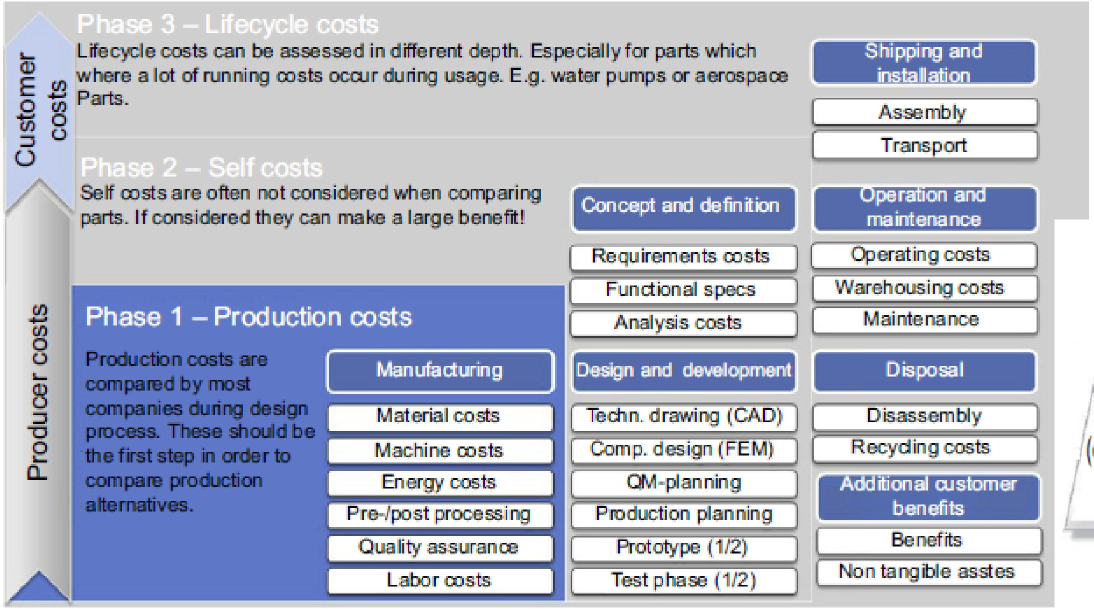
Author	Main Cost Drivers	System-level	Process /task-level	Used method/technique
Schroder et al. (2015	CAD preparation cost, Operating cost (preparation process), material cost, machine cost, Labour cost (production), post-processing cost, quality control process, administrative cost		✓	ABC
Rudolph et al. (2017)	CAD preparation cost, set-up cost, operating cost, labour cost (production), production overhead, pricing mode cost, material cost, part removal cost, treatment cost, post-processing overhead		✓	Analytical
Chan et al. (2018)	Material cost, machine cost, labour cost (production), production cost, production overhead		✓	(Analogical) ML algorithms, Net regression
Barclift et al. (2017)	Material cost, machine cost, depreciation cost (powder feedstock)		✓	CAD-based software
Lindemann et al. (2017)	Inventory cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, post-processing cost, part removal cost, Production overhead, logistic cost	✓	✓	ABC (time-driven)
Facchini et al. (2018)	CAD preparation cost, Operating cost (preparation process), setup cost, labour cost (preparation process), material cost, labour cost (production), part removal cost		✓	Parametric
Kamps et al. (2018)	CAD preparation cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, maintenance cost, electrical cost, gas cost, energy cost, production overhead, post-processing cost, part removal cost	✓	✓	Intuitive, Analogical LCA life cycle assessment
Tosello et al. (2019)	Operating cost (preparation process), setup cost, labour cost (preparation process), material cost, machine cost, labour cost (production), depreciation cost, maintenance cost electrical cost, production overhead, labour cost (post processing), part removal cost, finishing cost, curing cost		✓	ABC
Cunningham et al. (2017)	Operating cost (preparation process), setup cost, material cost, machine cost, labour cost (production), part removal cost, post-processing cost, quality control cost, tooling cost, treatment cost		✓	ABC
Ruffo et al. (2006)	Material cost (direct costs), Machine cost (indirect costs) "only build job cost"		✓	parametric model, and the engineering approach

Note: The main factors affecting the cost during various processes of AM are called "Cost Drivers".

Cost Models in AM

Lindemann et al. (2017)

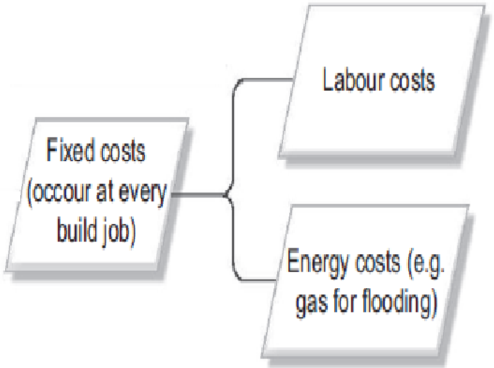
Represent the costs generated by product during the whole lifecycle. Which exceed the price the customer will pay for the final product. That cover all expenditures during the different phases of the lifecycle, from the perspective of the manufacturer and user. ***Production costs, Self costs, and Life-Cycle Costs***.



Production costs: using ***Time driven activity-based costing***, where process factors are replaced by time consumption. Considering the main processes:

- Preparation of the part: Designer cost, duration of this task (which affected by part complexity, build composition)
- Production of the part:

$$\text{Costs}_{\text{Build}} = \text{Costs}_{\text{Fixed}} + \text{Machine hourly rate} \times \text{Build time} + \text{Material costs}$$



Method for build time estimation: $T = t_{Fl} + t_B + t_{GS} + t_r$

Expected build time $= T$; additional processing times (e.g. pre-heating)$= t_{Fl}$; scanning time part$= t_B$; Scanning time basic support$= t_{GS}$; recoating time $= t_r$

Scanning time of the part: $t_B = \frac{V_B}{b_M(V_B) * K_S(V_S)}$

Volume of the part$= V_B$;

Volume related production speed$= b_M(V_B)$(*compare Fig* 11.7);

support based correctional factor$= K_S(V_S)$

Recoating time: $t_r = t_{r1} * \left(\frac{h_B + h_{GS}}{d}\right) * K_r(A_{GS})$

Recoating time for one layer $= t_{r1}$; max part height$= h_B$; height of basic support$=h_{GS}$; layer thickness $= d$

Correctional factor for basic support$= K_r(A_{GS})$

Cost Models in AM

Lindemann et al. (2017)

- Post-processing: (sum up all the necessary; mechanical post-processing steps :support removal, sand blasting or milling , drilling, ..etc.). Which has to be considered during the design phase.

- Adjustment of mechanical properties: as an optional process that aims to change the microstructure of the material to obtain different characteristics. (for example: hot isostatic, heat treatment.

- Quality control costs: Manly based on the part requirements. Test like; (initial set-up costs, cost for ensuring process stability, and tests for ensuring the part quality (ex: tomography), the test methods has also to be considered during the design phase.

Self costs: costs accrued directly at the begging of product development (product development process, product optimization), practically, they include all costs to produce and distribute a product. These phases have a high fluence on the later parts costs.

Lifecycle costs: are the costs associated with the product users as the sum of all costs due to purchase and during the period of use of a product

$$LCC = C_{CD} + C_{DD} + C_{Pro} + C_I + C_U + C_D$$

The variables have the following meanings:

C_{CD} = costs in the concept and definition phase (conception & definition)

C_{DD} = costs in the design and development phase (design & development)

C_{Prod} = costs at the manufacturing phase (production)

C_{INST} = costs in the installation phase (installation)

C_U = costs in the operation and maintenance phase (usage & maintenance)

C_{DIS} = costs in the disposal phase (disposal)

Cost Models in AM

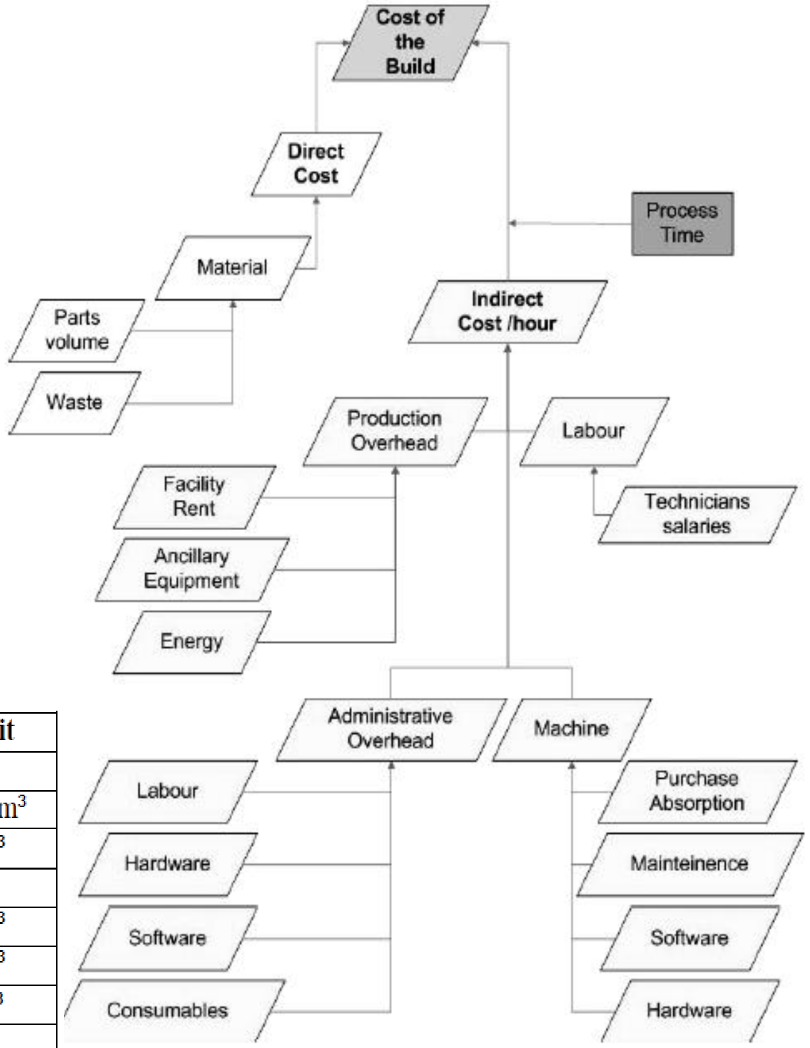
Ruffo et al. (2006)

This model is placed between ***parametric model, and the engineering approach "analogy"***, as the relationships found are approximation based on statistics.

The model assumed, that the material used and time required are the main variables of the cost model.

The indirect costs as cost rate €/h, the Sum of (indirect costs annualized) over the total working time per year

The equation for times are estimated using empirical time estimator based on simulation results obtained with build ***Setup ver3,4***. Based upon object geometry (height, volume, bounding box volume) and, therefore, to estimate the (scan time, cooling/preheating time, and doating times)



Build Cost = Indirect Costs * $(t_{XY} + t_Z + t_{HC})$ + Material Cost in Euros per unit mass * (p * $((Vp * n_p) + (V_{beds} - V_b) * \alpha))$

Variable	Description
t_{XY}	Laser on and actively sintering time
t_Z	Recoating time
t_{HC}	Temperature stabilization time.
direct costs	Material cost and waste material.
indirect costs	Costs associated with labor/hour, machine costs/hour, as well as production and administrative overhead/hour

Variable	Description	Unit
m_B	Material mass	g
p	Material density	g/cm^3
V_b	Volume of build	cm^3
n_p	Total number of parts	N
V_{beds}	Total Beds Volume	cm^3
W_b	Volume material wasted	cm^3
Vp	Volume of the part	cm^3
α	Waste Factor	

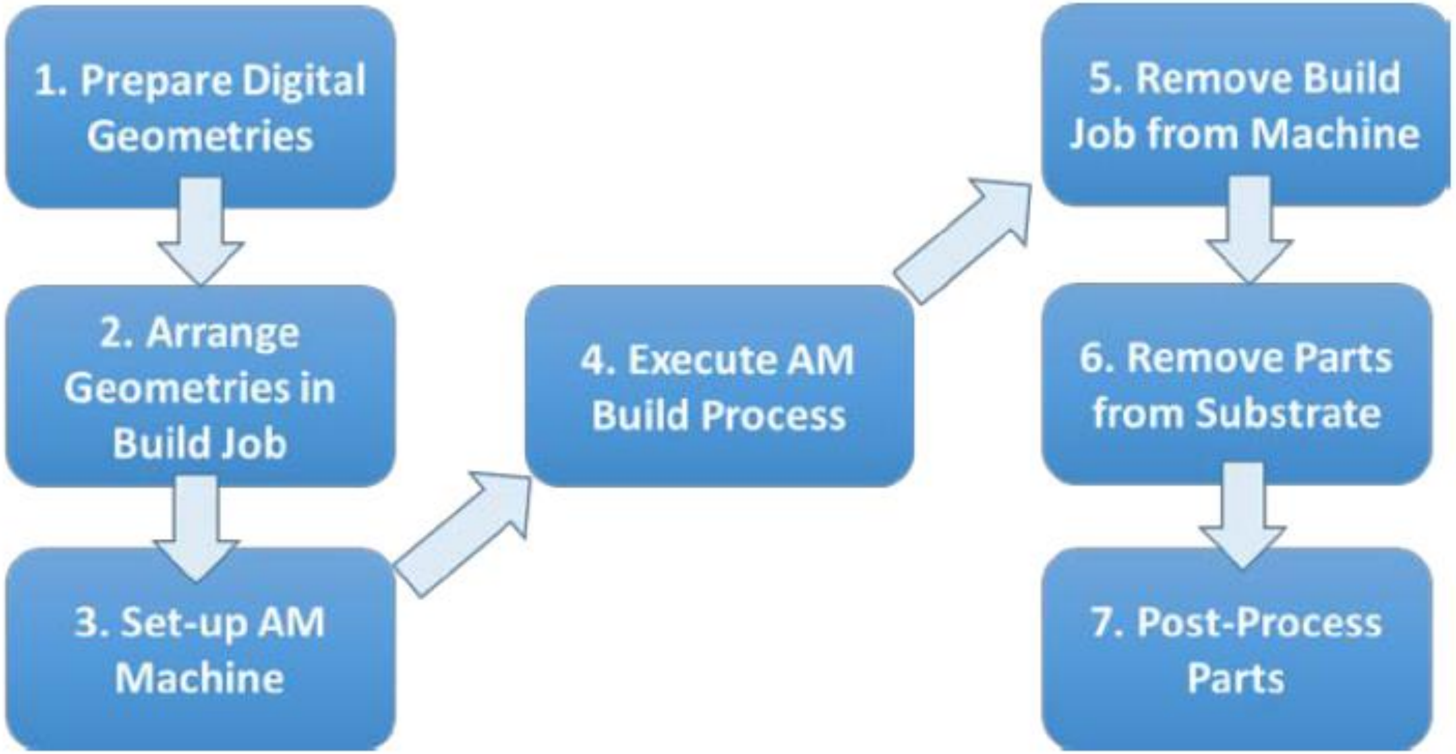
Cost Models in AM

Barclift et al.,2016

A cost model was created for reused metal powder feedstocks using SOYD depreciation to account for costs pertaining to the diminishing and depletion of a metal powder feedstock's properties in PBF.

This depreciation model was implemented in a generic ***activity-based costing*** model for PBF.

$$C_{Total}(P_i) = C_{prep}(P_i) + C_{buildjob}(P_i) + C_{Setup}(P_i) + C_{Build}(P_i) + C_{Removal}(P_i) + C_{Substrate}(P_i) + C_{Postp}(P_i) \quad (12)$$



Cost Models in AM

Barclift et al.,2016

$$C_{setup}(P_i) = (C_{op} + C_{Mach}) \cdot \frac{(T_{setup} + T_{mat.change})}{\sum_i N_i}$$

where:
C_{setup} is the cost per part for setting up the AM machine ($),
P_i is the built-up AM part corresponding to ith geometry (-),
C_{Mach} is the AM machine's hourly rate ($/h),
C_{oper} is the operator's hourly rate ($/hour),
T_{setup} is the time for setting up the machine (h),
$T_{mat.change}$ is the total time for changing the material, including corresponding activities (h),
N_i is the quantity of parts with ith geometry (-).

$$C_{build}(P_i) = C_{build-Machine}(P_i) + C_{build-Material}(P_i) + C_{build-Depreciation}(P_i) \quad (4)$$

where:
C_{build} is the cost per part for building up a part using the AM machine ($),

P_i is the built-up AM part corresponding to ith geometry (-),
$C_{build-machine}$ is the cost per part for operating the AM machine during a build job ($),
$C_{build-material}$ is the cost per part for the melted powder feedstock in the AM process ($),
$C_{build-Depreciation}$ is the cost per part for the un-melted feedstock used in the AM process ($).

$$C_{build-machine}(P_i) = T_{build} \cdot (C_{mach} + C_{gas}) \quad (5)$$

where:
$C_{machine}$ is the cost per part for producing a build job in the AM process ($),
P_i is the built-up AM part corresponding to ith geometry (-),
T_{build} is the time for building up the entire job in the AM process (h),
C_{mach} is the AM machine's hourly operating cost ($/h),
C_{gas} is the cost for inert gas consumption during the build ($/h),
N_i is the quantity of parts with ith geometry (-).

$$T_{build}(P_i) = \frac{T_{idle}}{\sum_i N_i} + T_{build\ speed} \cdot \sum_i (N_i \cdot V_{total_i}) + T_{recoat}(P_i) \quad (3)$$

where:
T_{build} is the total time required for building up a single part in a given build job (h),
P_i is the built-up AM part corresponding to ith geometry (-),
T_{idle} is the time when the AM machine is inactive (e.g., heating, cooling) (h),
$T_{build\ speed}$ is the average time for the AM machine to consolidate a voxel of powder (h/cm^3),
N_i is the quantity of parts with ith geometry (-),
V_{total_i} is the total volume of the part and support structures for ith geometry (cm^3),
T_{recoat} is the total recoating time allocated to a single part (h).

$$C_{build-material}(P_i) = M_i \cdot Cm_u \quad (6)$$

where:
$C_{build-material}$ is the cost per part for the powder feedstock melted in the AM process ($),
P_i is the built-up AM part corresponding to ith geometry (-),
M_i is the mass of a part with ith geometry (kg),
Cm_u is the cost of the powder feedstock that has been used in u build cycles ($/kg).

$$M_i = (1+\alpha) \cdot \rho_w \cdot (V_{part_i} + V_{supports_i}) + \gamma \cdot \rho_t \cdot V_{supports_i} \quad (7)$$

where:
M_i is the mass of a part with ith geometry (kg),
α is the percentage of powder loss due to process inefficiency (%),
γ is the percentage of powder loss due to being trapped within support structures (%),
V_{part_i} is the volume of the part body for the ith geometry (cm^3),
$V_{supports_i}$ is the volume of the support structures for the ith geometry (cm^3),
ρ_w is the powder wrought density (kg/cm^3),
ρ_t is the powder tap density (kg/cm^3).

Cost Models in AM

Barclift et al.,2016

Instead of using a fixed vale for material price the model proposes a feedstock value for the used material based on cycle numbers.

$$Cm_{u+1} = Cm_u - (Cm_0 - S) \cdot \left(\frac{U_{max} - u + 1}{\frac{U_{max}(U_{max} + 1)}{2}}\right) \quad (1)$$

where:
Cm_u is the cost of the powder feedstock that has been used u times (\$/kg),
Cm_0 is the cost of a virgin powder feedstock (\$/kg),
S is the salvage value of the powder at the end of its depreciable life (\$/kg),
U_{max} is the maximum number of build cycles a powder can be used for a PBF technology (-),
u is the number of build cycles a powder has underwent in PBF (-).

$$C_{build-Depreciation}(P_i) = \frac{M_i}{\sum_i (N_i \cdot M_i)} \cdot \left(M_{FB} - \sum_i (N_i \cdot M_i)\right) \cdot (Cm_u - Cm_{u+1}) \quad (8)$$

where:
$C_{build-Depreciation}$ is the cost per part for the un-melted feedstock used in the AM process (\$),
P_i is the built-up AM part corresponding to ith geometry (-),
M_i is the mass of a part with ith geometry (kg),
N_i is the quantity of parts with ith geometry (-),
M_{FB} is the total mass of the powder loaded into the AM machine's feed bed (kg),
Cm_u is the cost of the powder feedstock that has been used in u build cycles (\$/kg).

Depreciation cost is calculated by taking the mass of the powder loaded in the feed bed and subtracting the total mass of all built-up parts, including their corresponding powder losses. This is multiplied by the difference in financial value of the feedstock at its present state to the diminished value after one additional build cycle.

Cost Models in AM

Barclift et al.,2016

$$M_{FB} = CA \cdot D_x \cdot D_y \cdot Bh(P_i) \cdot \rho_t \quad (13)$$

where:
M_{FB} is the total mass of the powder loaded into the AM machine's feed bed (kg),
CA is the vertical rise of the feed bed per layer thickness in the build (-),
D_x is the length of the dispenser platform in the feed bed (mm),
D_y is the width of the dispenser platform in the feed bed (mm),
Bh is the build height of the tallest part in the build job (mm),
ρ_t is the powder tap density (kg/cm^3).

$$C_{Substrate}(P_i) = \frac{C_{stress}}{\sum_i N_i} + C_{EDM} \cdot \frac{A_{con}(G_i)}{\sum_i N_i \cdot A_{con}(G_i)} \quad (10)$$

where:
$C_{Substrate}$ is the cost per part for separating a part from the substrate ($),
P_i is the built-up AM part corresponding to ith geometry (-),
C_{stress} is the cost for stress-relieving a build plate($),
C_{EDM} is the total cost for separating a part via EDM ($),
A_{con} is the connected area of a part to the substrate (cm^2),
N_i is the quantity of parts with ith geometry (-).

Based on Machine type (the build chamber dimensions)

$$C_{Removal}(P_i) = (C_{op} + C_{mach}) \cdot \frac{T_{Rem}}{\sum_i N_i} \quad (9)$$

where:
$C_{Removal}$ is the cost per part for removing the substrate/parts from the AM machine ($),
P_i is the built-up AM part corresponding to ith geometry (-),
T_{Rem} is the time required to remove parts, clean machine, and perform all ancillary tasks (h),
C_{oper} is the operator's hourly rate ($/hour),
C_{Mach} is the AM machine's hourly operating cost ($/h),
N_i is the quantity of parts with ith geometry (-).

$$C_{postp}(P_i) = \sum_i \left(T_{postp}(G_i) \cdot (C_{op} + C_{tools})\right)$$

where:
C_{postp} is the total cost for post-processing ($),
P_i is the built-up AM part corresponding to ith geometry (-),
T_{postp} is the time required to post-process a part geometry ($),
G_i is the ith geometry (-),
C_{op} is the operator's hourly rate ($/hour),
C_{tools} is the hourly rate of tools and machines for post-processing ($).

Cost Models in AM

Schroder at al. (2015)

- Provide business model which evaluates process cost of additive manufacturing technologies, serve as a tool to support the industrial decision makers. Using ***Time-driven activity-based costing***.

- The tool has two main areas: the ***data input area and the data output area***.

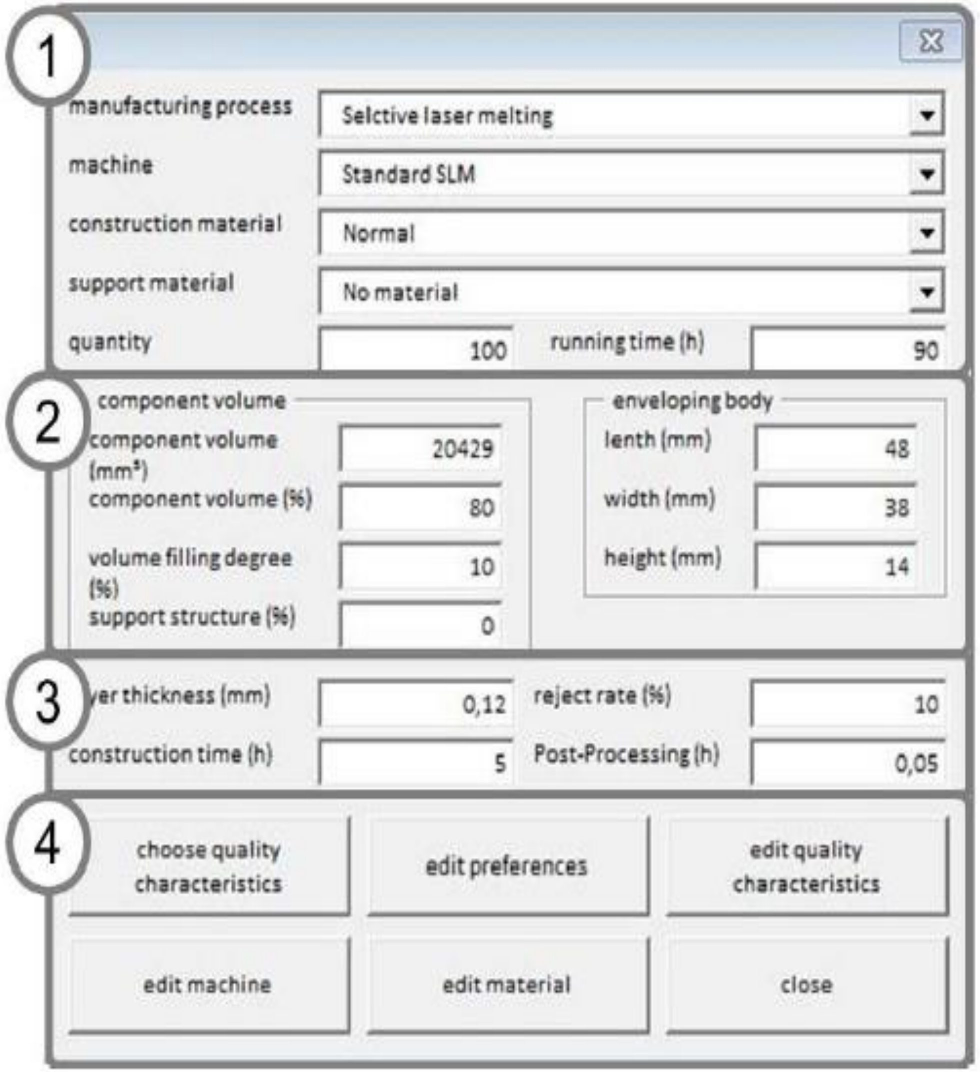
- For a detailed cost calculation, an overall of ***77 input*** values is needed.

- Because of this high amount of values ***the input area*** is divided into

  - ***process-specific information:*** Includes quality-related investments, process relevant cost rates and machine and material settings

  - ***Order-specific information***: divided into 4 sections

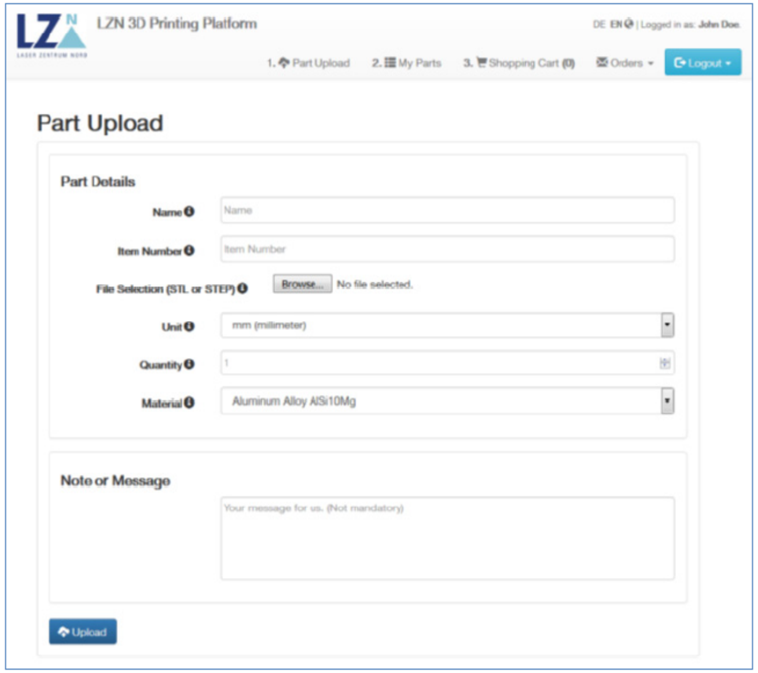
- *The **output area*** : the cost calculations for each main process step



Cost Models in AM

Rudolph et al. (2017)

- Develops an automated, self –learning calculation –Cost model- for SLM, focusing on a cost of the generation process "build processes".
- In which the customers are able to upload the part geometrical data, then converted into STL, to execute the algorithms, so the given geometry is automatically analyzed to identify the key characteristics: ***volume, surface, and dimensions***.
- The cost model uses ***analytical and "analogy" statistical based functions*** to determine the build cost for one part with SLM. Concludes that ***the capacity utilization*** depends on the ***build height***, thus two variants for more accurate cost calculation were developed, ***based on linear regression***.



$$t_{Exp} = \frac{(V_{Part}+V_{Sup})}{v_{Melt}}$$

$$u_{BJ} = \alpha_0 + \alpha_1 \cdot dim_{Part_1}$$

$$C_{Part} = t_{Part} \cdot C_{mh}$$

$$V_{Sup} = V_{Part} \cdot a_{Sup}$$

$$h_{Gen,Part} = \beta_1 \cdot dim_{Part_1} + \beta_2 \cdot dim_{Part_2}$$

$$t_{Coat} = \frac{h_{Gen,Part}}{h_{Recoat}} \cdot t_{Recoat} \cdot \frac{(V_{Part}+V_{Sup})}{u_{BJ} \cdot h_{Gen,Part} \cdot l_{BC} \cdot w_{BC}} = \frac{t_{Recoat} \cdot (V_{Part}+V_{Sup})}{h_{Recoat} \cdot u_{BJ} \cdot l_{BC} \cdot w_{BC}}$$

$$t_{Part} = t_{Exp} + t_{Coat}$$

Cost Models in AM

Some limitation Of The exist Cost Models

- ***Cost models are always discussed based on unique case study components that focus on targeted AM technologies in a specific application.***
- ***A versatile cost calculation model that can represent AM in general is still missing.***
- ***Neglecting other important characteristics, for instance, the part functional requirements, such as mechanical properties and surface roughness, may lead to a misleading decision being made. Which AM cost models should take into consideration.***
- ***There have been limited studies to utilize the AI technique.***
- ***Not many studies were found that contribute towards providing a variation of web-based cost models services.***
- ***A customer-oriented user perspective is still not widely explored, "where target costs can be obtained at front end, as well as modification can be available at every step of product development, based on target cost preference".***

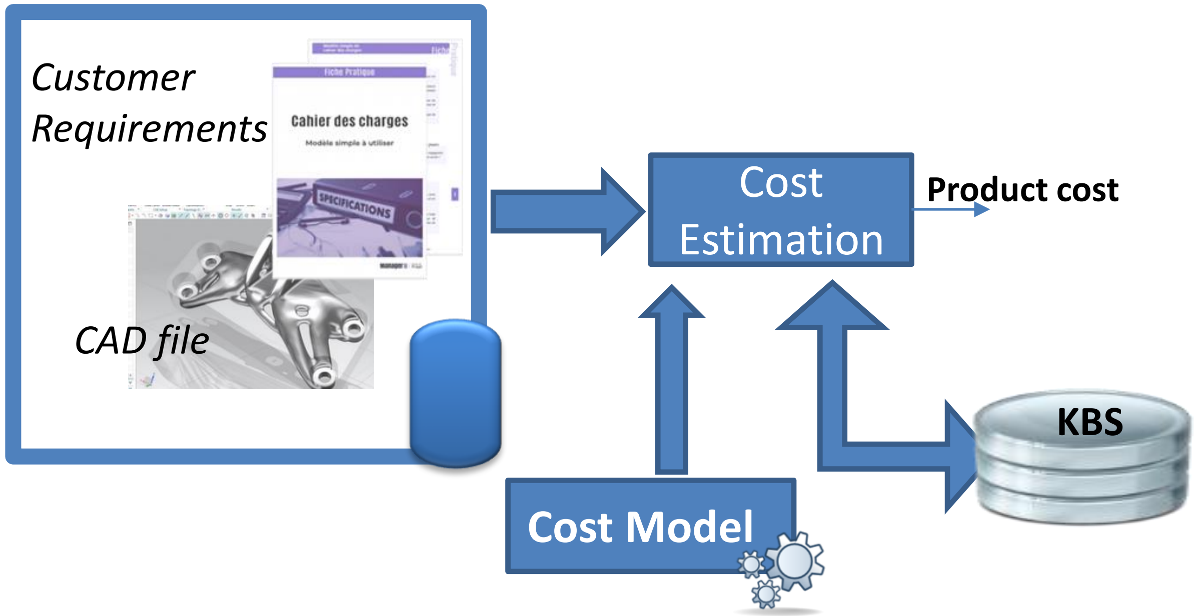
Our Cost Model

Our cost Model

The proposed cost model is part of our current work to develop decision support system, "using knowledge based approach", for estimating the additive manufacturing product cost. In order to provide a support for the AM cost estimation of products at early stages, when receiving the customer order, therefore to achieve relevant cost estimation.

However, to perform a manufacturing cost estimation it is important;

- ✓ From one side, to define the cost model that could be used to estimate the product cost. In which it could be equations, or relationship between different cost factors/ parameters.
- ✓ Where the other part is resides in the knowledge that is essential to determine the activity and the factors that generate cost, as well as the knowledge required to link the product, and customer requirement to cost factors.



Our cost Model

For the cost model we used **Activity based approach** (among other advantages we've described previously):

- ABC could provides the structuring support (the activity) to keep non financial information such as defect rates (quality), throughput rates (effectiveness of the industrial process) and delivery time.

- Better profitability measures, Better decision and control, better information for controlling capacity cost.

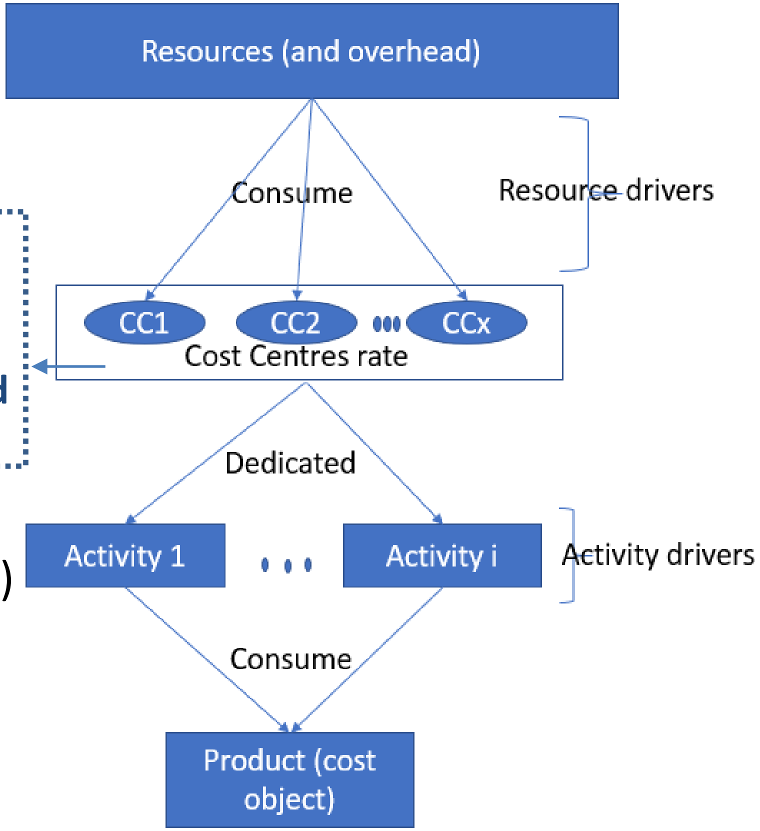
- Help the companies to improve product design and manufacturing process.

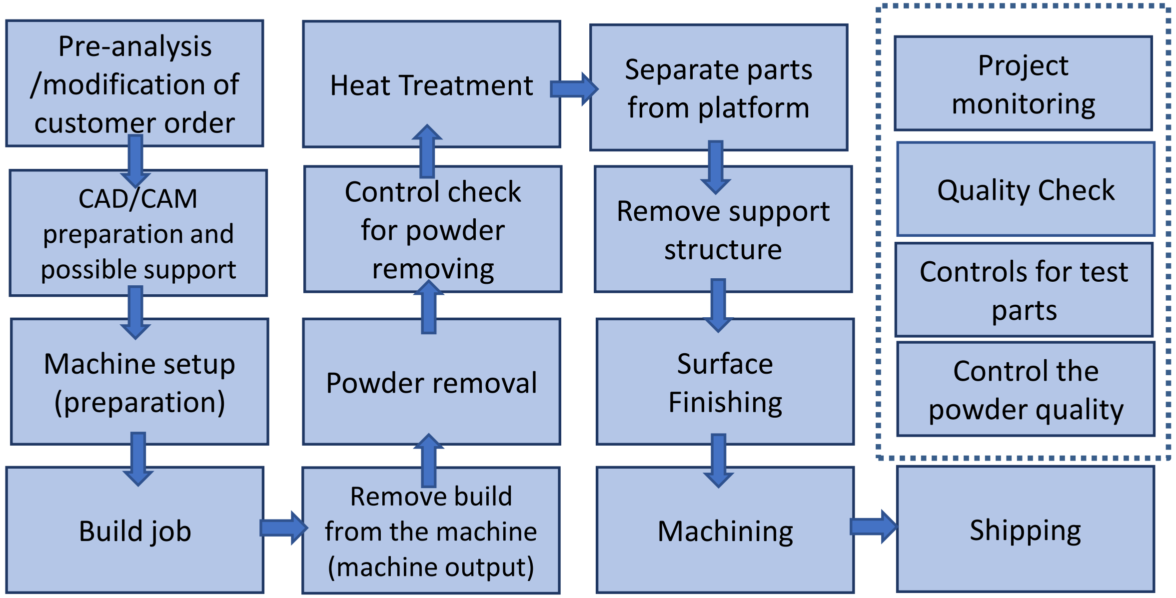
- In addition, it can lead to classifying activities as value-added and non-value added

Our cost Model

- **Machine rate**
- **Labor rate**
- **Overheads rate (Administrative/Production)**

Consumed by activity (based on the activity)





$$\textbf{Final Product Cost} = \boldsymbol{Material\ cost} + \boldsymbol{Build_{platform}\ cost} + \sum_{i=1}^{n} \textbf{Activity(i)}\boldsymbol{Cost}$$

$\boldsymbol{n}$: Number of activities (-)

$\sum_{i=1}^{n}$ Activity(i)$Cost$: the sum of all activity cost (€)

Final product cost: the cost of the final product (€)

- ❑ **Build platform:** The cost of the used platform in the build can vary based on the material type, and dimension of the platform.

Our cost Model

For the sake of example, lets assume that the product will have one activity (build job), and the final cost will be as follow:

Build job

Final product cost= Material cost + Build platform cost + Build job cost

$$C_{material} = M_{material} * C_{material}$$

Based on material type, and if it is new, or used powder.

M material: Mass of used material (Kg)

C material: The commercial price of the used powder (€/kg)

$$M_{material} = (V_{build} * P_{\text{melted density}}) + ((V_{waste} + V_{\text{powder loss}}(\textit{inside the build part})) * P_{density})$$

$$P_{\text{melted density}} = (P_{density} / 0.6)$$

The volume of the powder loss that accumulated inside the build part, (e.g. if the part has internal channel)

The volume of the powder loss within the build process (proportional to the build time)

The total build volume, is the entire build inside the machine, including the product volume, and the support structure, also if the project is require test part for some control analysis, the volume of the required test part is included.

V build: The total build volume (mm^3)

V waste: The volume powder waste due to AM build process (mm^3)

P density: The powder density (Kg/mm^3)

P melted density: The Melted powder density (Kg/mm^3)

Our cost Model

For the sake of example, lets assume that the product will have one activity (build job), and the final cost will be as follow:

Build job

Final product cost= Material cost + Build platform cost + Build job cost

This value can vary, based on material type of the platform (which is mainly similar to the powder material type), and size of the build platform.

$$C_{build-machine} = T_{build} * C_{AmMach}$$

T **build**: The time for building the entire job (h)

C **AmMach**: AM machine's hourly rate (€/h))

The Build time is out of our scope, however, several software are able to estimate this value, in which we based our model.

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