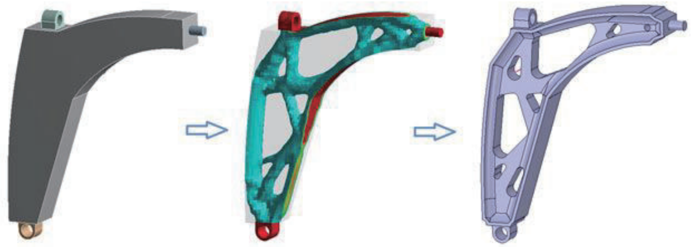
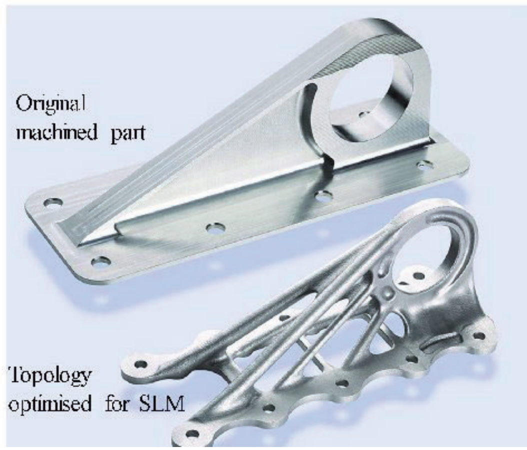
香港中文大學
The Chinese University of Hong Kong

MAEG5160: Design for Additive Manufacturing

Lecture 1: Introduction to AM and AM economy





Prof SONG Xu
Department of Mechanical and Automation Engineering,
The Chinese University of Hong Kong.

Course Outline

Wk	Date	Lecture (1st 45 minutes, 2nd 1 hour 30 minutes)
01	Jan 9, 11	Introduction to AM, AM economy, and different AM technologies
02	Jan 16, 18	Design for polymer AM and metal AM
03	Jan 23, 25	Lunar New Year Break
04	Jan 30, Feb 1	Digital Design for AM and Generative Design
05	Feb 6,8	Topological Optimization for isotropic material
06	Feb 13,15	Topological Optimization for isotropic material (continue) (release of 1st assignment)
07	Feb 20,22	Topological Optimization in different applications
08	Feb 27, Mar 1	Topological Optimization in different applications (continue) (release of 2nd assignment)
09	Mar 6, 8	Topological Optimization for anisotropic material (collect the 1st assignment)
10	Mar 13, 15	Topological Optimization for anisotropic material (continue) (release of the final project)
11	Mar 20, 22	Topological Optimization for truss structure (collect the 2nd assignment)
12	Mar 27, 29	Lattice and TPMS structures
13	Apr 3, 5	Consolidation, tooling and postprocessing (collect the final project)
14	Apr 10, 12	Future outlook and Case study of AM in Aerospace
15	Apr 17, 19	Revision (1st session, 45 mins) and Examination in class (2nd session, 1.5 hours)

Monday 11:30am-12:15pm — Lee Shau Kee Building 304 (LSK)

Wednesday 16:30pm -18:15pm — Mong Man Wai Building 703 (MMW)

Learning Outcomes and Assessment

Upon completion of the course, students should have achieved the following outcomes:
(1) Explain the topological optimization algorithms used in existing CAD/CAE systems;
(2) Apply mathematical formulations in their programming implementation for topological optimization;
(3) Understand and apply different design rules for polymer and metal Additive Manufacturing;
(4) Understand advantages and disadvantages of different Additive Manufacturing Technologies and corresponding design constraints.

Task nature	**Percentage**
Homework or assignment (two in total)	40%
Project + final report (one in total)	20% + 10%
Short answer test or exam (non-centralized)	30%

Contact information and course materials

Instructor	
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Email	jhding@mae.cuhk.edu.hk	Email	ycfeng@mae.cuhk.edu.hk

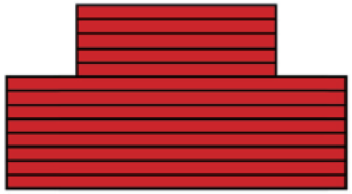
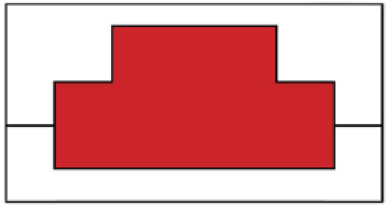
Reference books

1. Martin Bendsoe, Topological Optimization. Theory, Methods and Applications, Springer, 2004
2. Olaf Diegel, A Practical Guide to Design for Additive Manufacturing, Springer, 2019
3. Martin Leary, Design for Additive Manufacturing, Elsevier, 2019

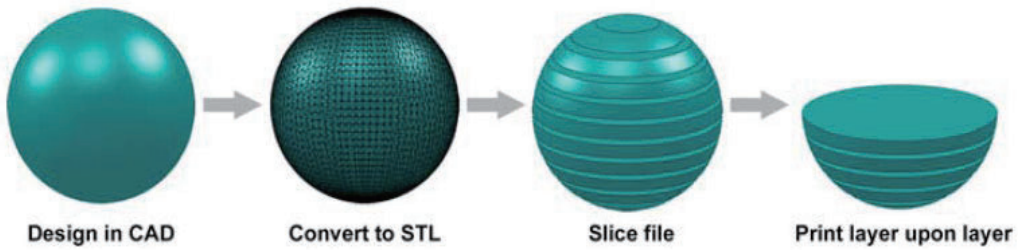
Prerequisite knowledge

1. Finite Element Method
2. Optimization Methods
3. Manufacturing Processes (especially AM)

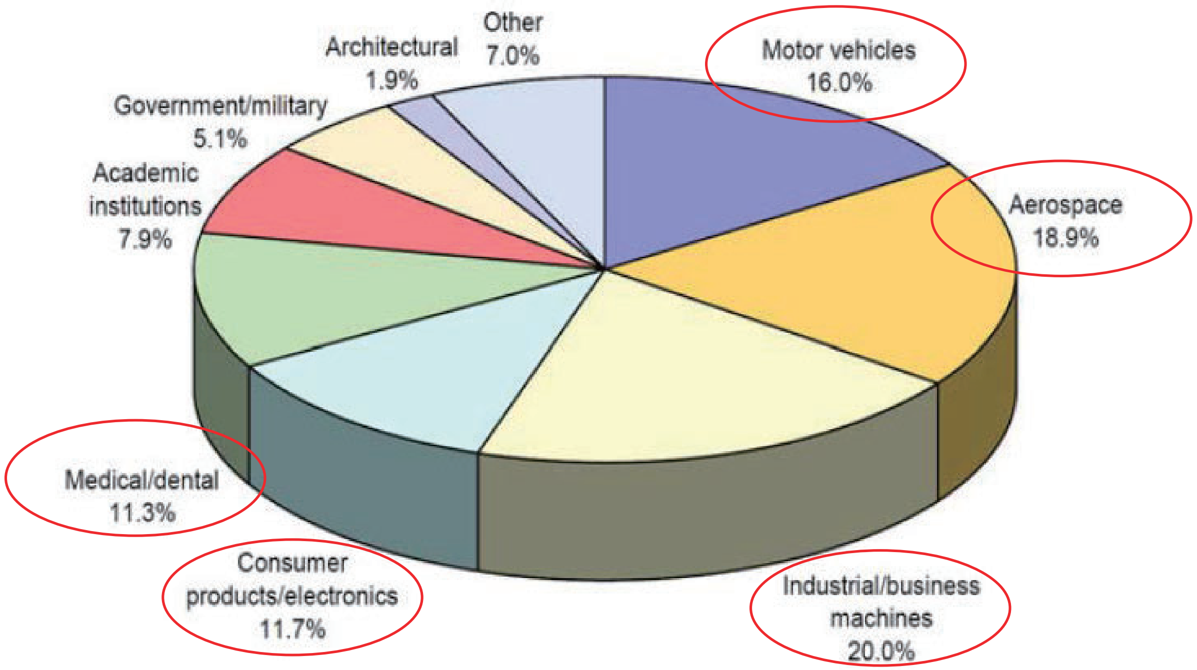
Introduction to AM process

	Additive	*Formative*	*Subtractive*
Schematic			
Example			
Advantages	• No master reference • Common unit material • Low-cost at low-volume • High-complexity achievable • Unique microstructure • Mass-customisation	• High material quality • Relatively low unit-cost at high-volumes • High quality surface finish • Robust material properties • Precedence of commercial application	• Low-unit cost at moderate volumes • Relatively high quality surface finish • No master reference required • Application precedence
Challenges	• Surface finish • High-cost at high-volume • Certification challenges for novel method	• Requires the fabrication of master reference • Low achievable complexity	• Low buy-to-fly ratio • Moderately low achievable complexity
	Additive	*Formative*	*Subtractive*

AM general process chain and industry applications



AM process chain

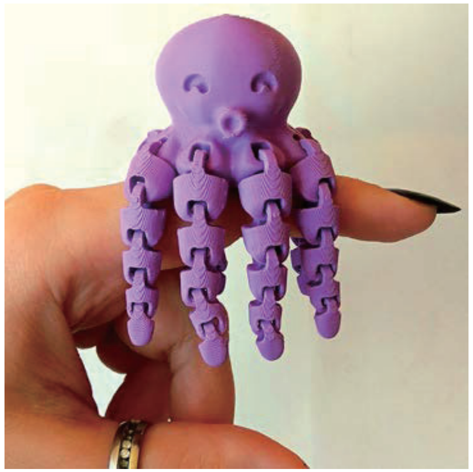


AM industry applications

AM advantages

1. Complex part fabrication / design freedom

2. Instant Assemblies



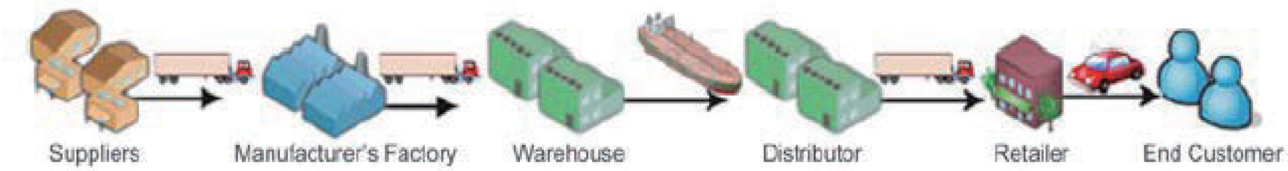
AM advantages

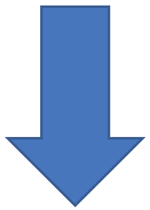
3. Part consolidation

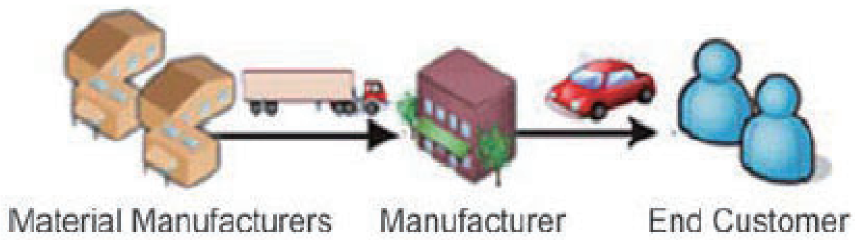
4. Mass customization/personalization

AM advantages

5. On-demand manufacturing

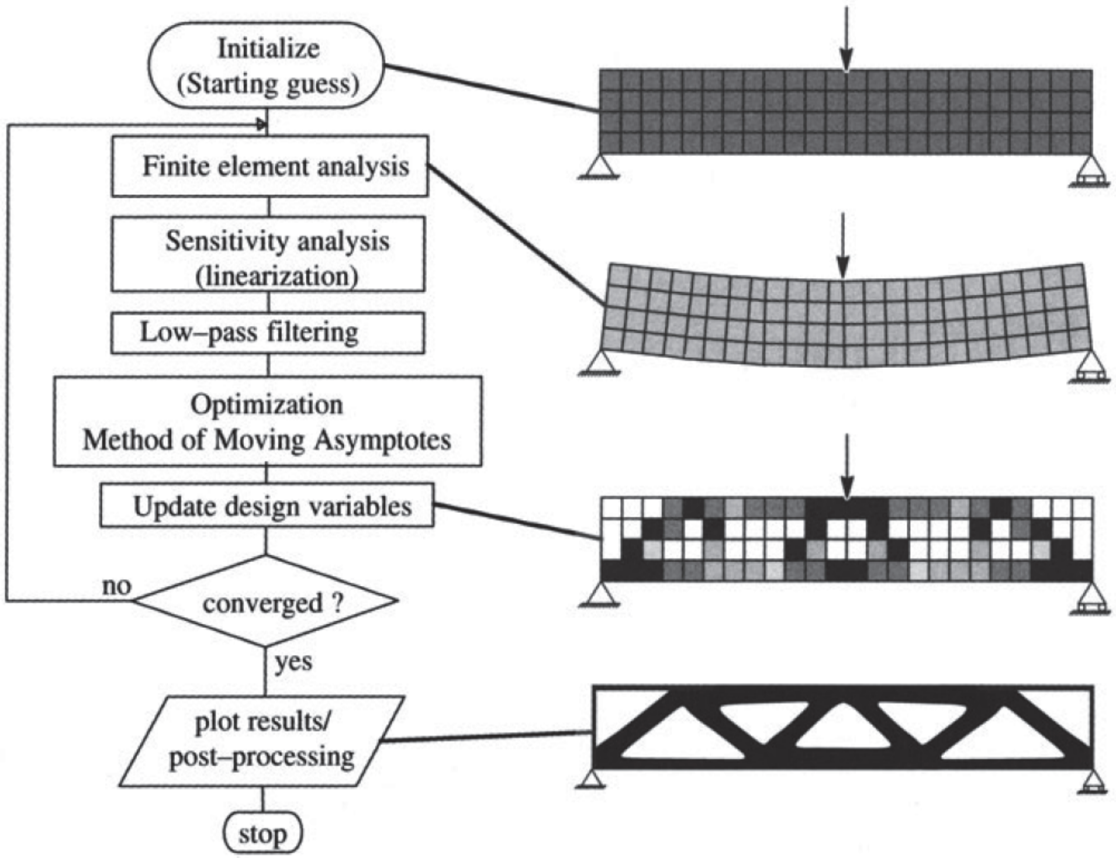


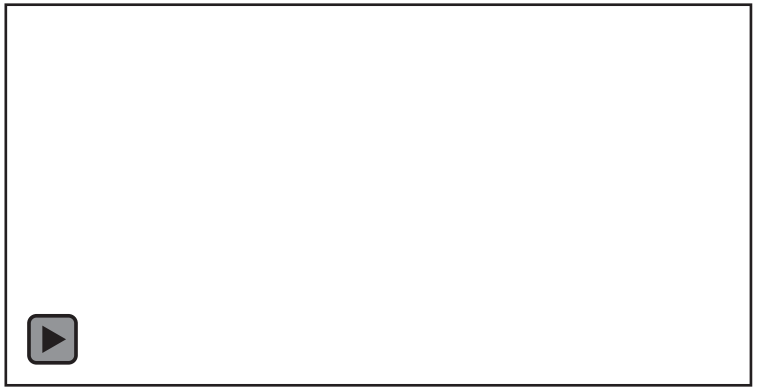


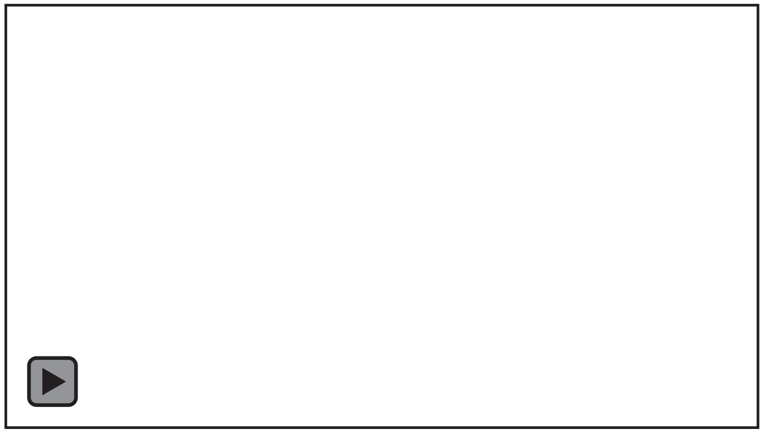


AM advantages

6. Lightweighting (targeted to reduce weight) / topological optimization

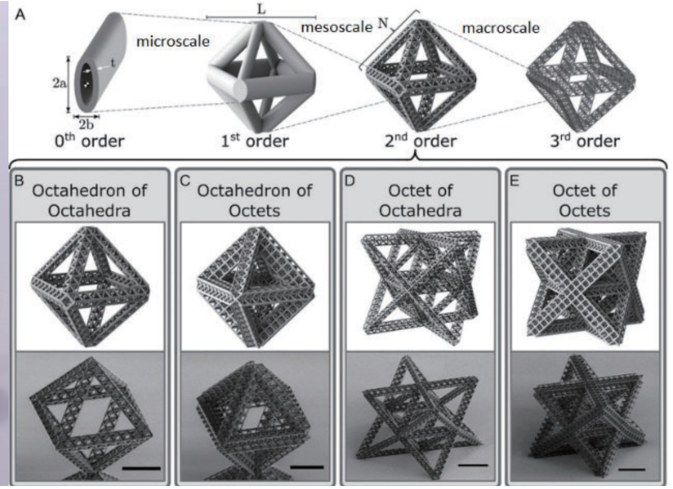


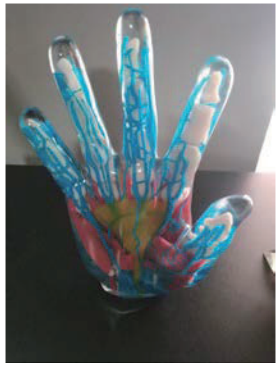




Design for AM – methods

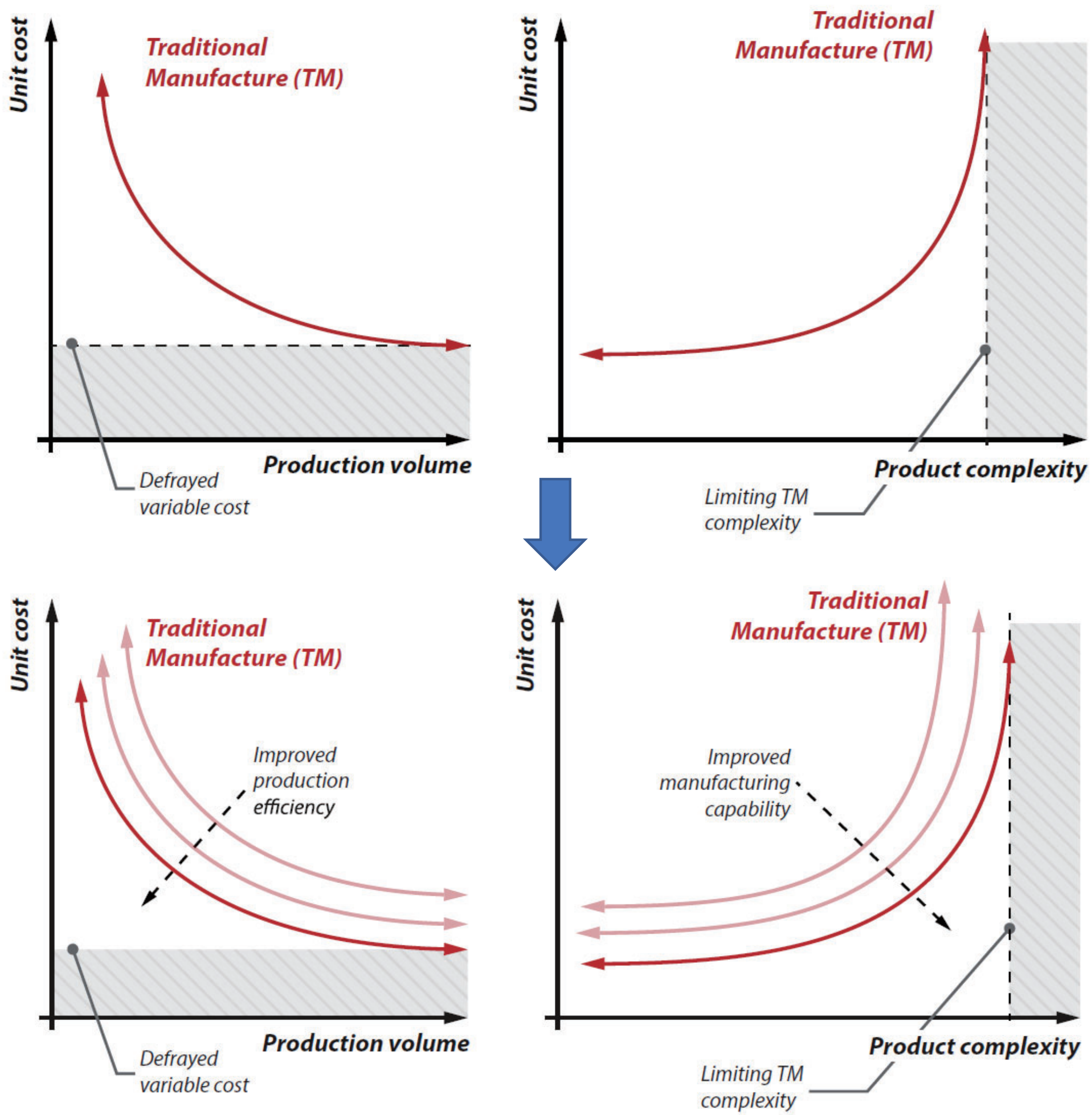
1. **Topology optimization** √
2. **Multiscale structure design**
3. **Multi-material design**
4. **Design for mass customization**
5. **Parts consolidation** √
6. **Lattice structures** √





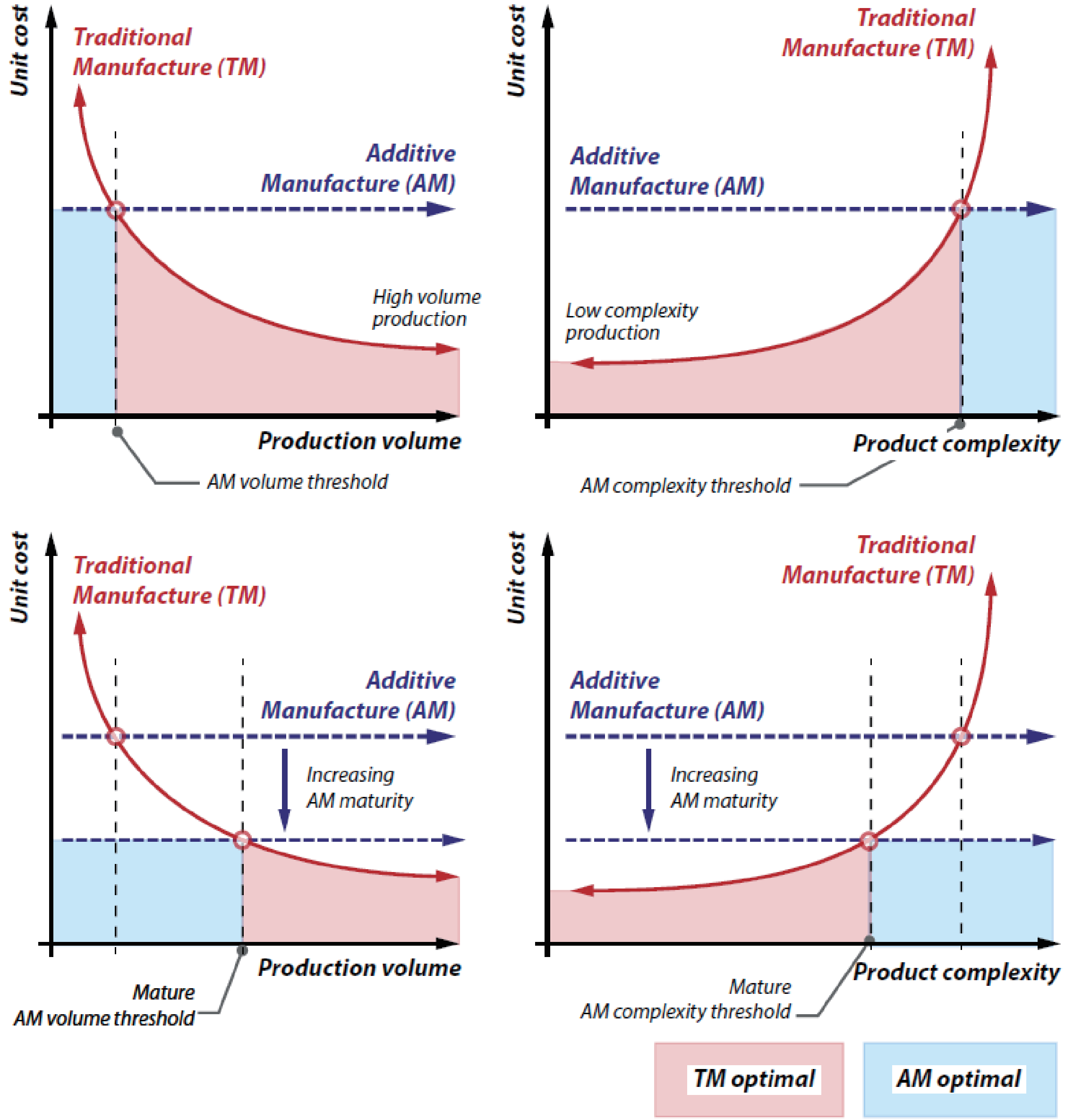
AM economics – a quick estimation

Classical Engineering Economics



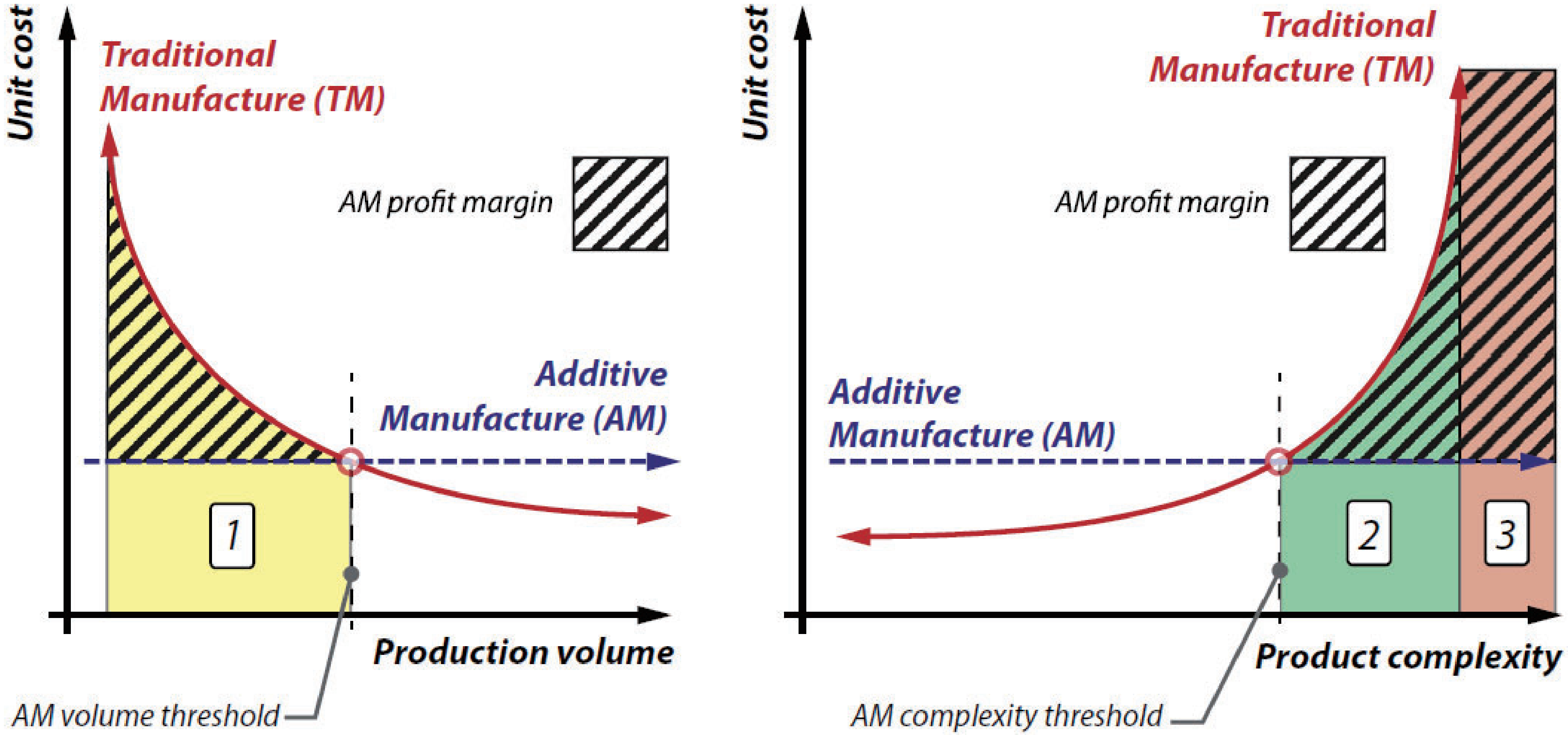
AM economics – a quick estimation

AM Economics – ideal scenario



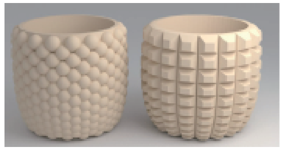
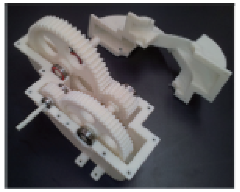
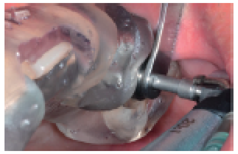
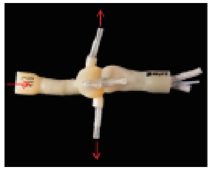
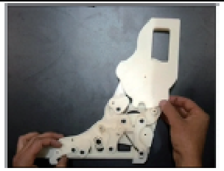
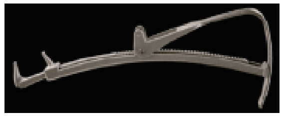
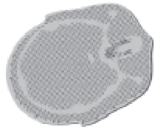
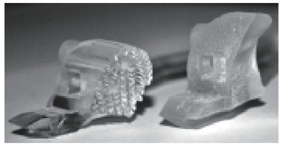
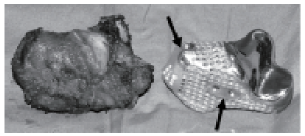
AM economics – a quick estimation

AM economically advantageous scenario



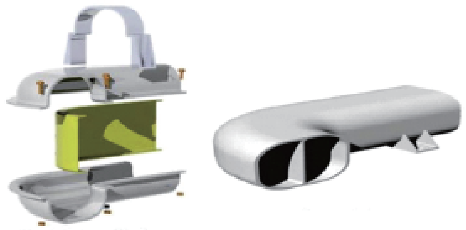
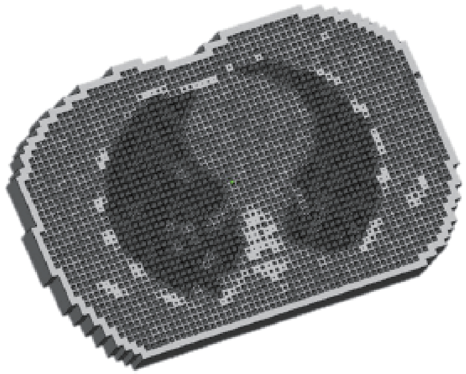
Zone 1: Batch-enabled scenarios.
Zone 2: Complexity-enabled scenarios.
Zone 3: Ultra-high complexity scenarios.

AM economics – a quick estimation

Pre-production conceptual design models	 *Product design [1]*	 *Prototype system design*
Surgical planning model	 *Lung model [2]*	 *Surgical guidance [3]*
Pre-production technical validation models	 *Functional aortic valve [4]*	 *Automotive latch assembly*
Bespoke design of functional devices and surgical tools	 *Bespoke surgical tools [5]*	 *Patient-specific phantom*
Jigs and fixtures	 *Form and fit fixtures [6]*	 *Patient-specific surgical guides [7]*
Short volume production runs	 *Aerospace structures*	 *Patient-specific implants [8]*

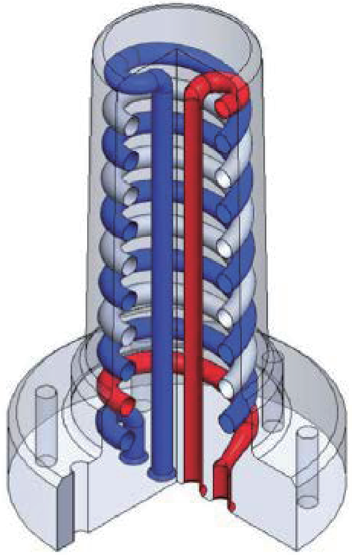
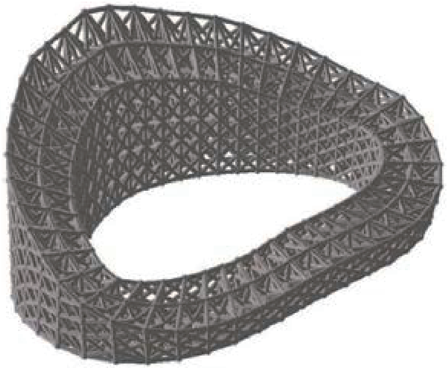
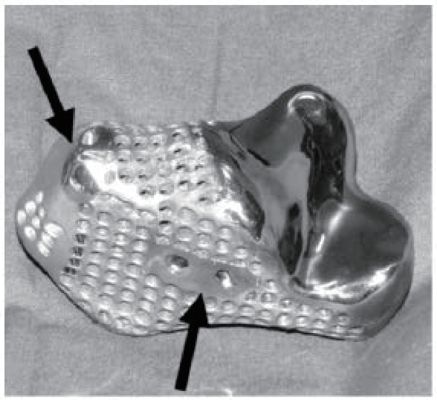
Batch-enabled scenarios

AM economics – a quick estimation

High efficiency topologies	 *Topology optimised aerospace structures*
Functionally integrated designs	 *Parts consolidation [9]*
Series production of complex geometries	 *Patient-specific radiation dosimetry phantoms*

Complexity-enabled scenarios

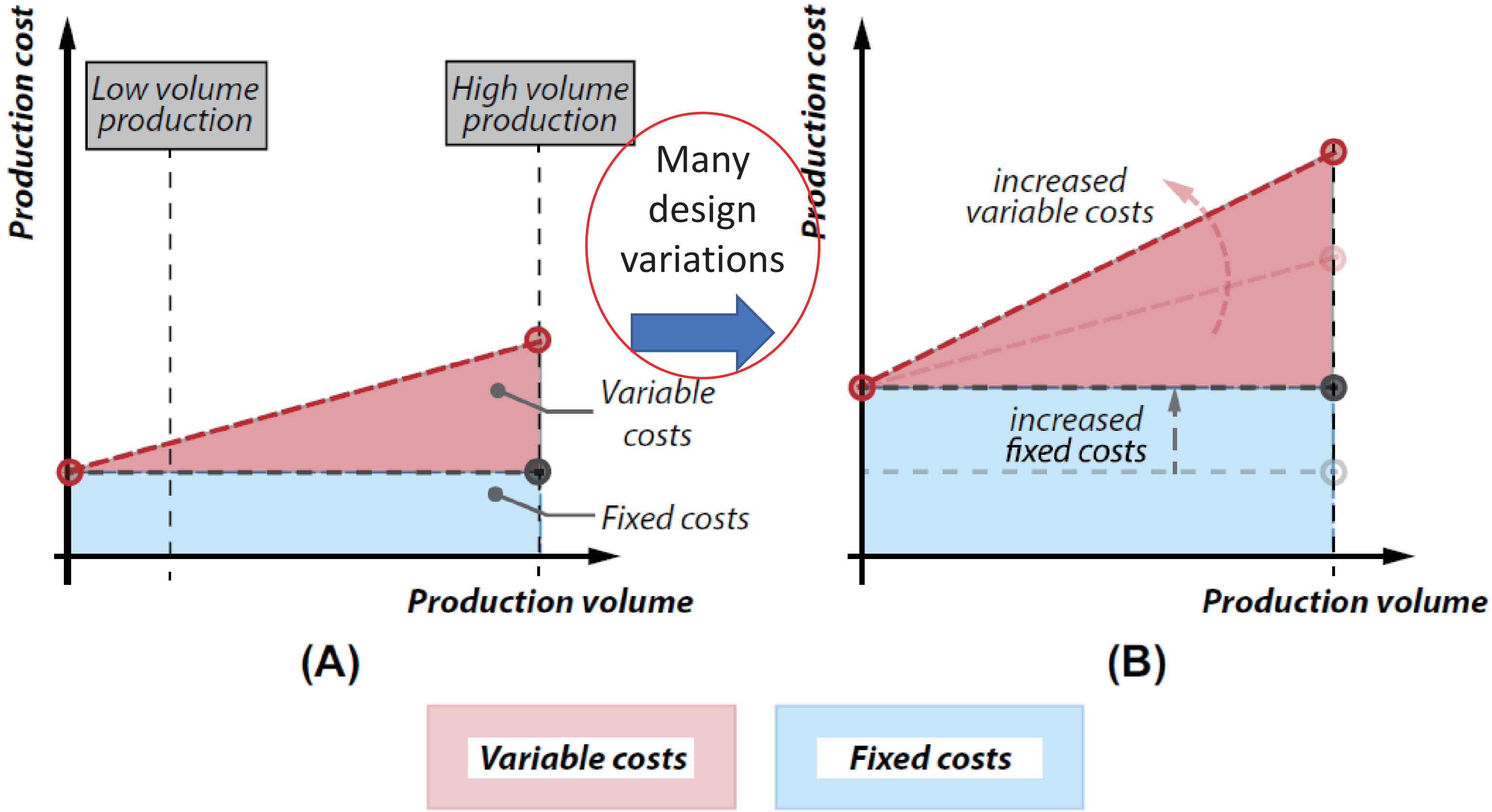
AM economics – a quick estimation

Ultra-High efficiency topologies	 *Conformal cooling*	 *Gyroid structure*
Generative design	 *3D lattice structure*	 *Patient-specific medical implants [8]*

Ultra-high complexity scenarios

AM economics – a quick estimation

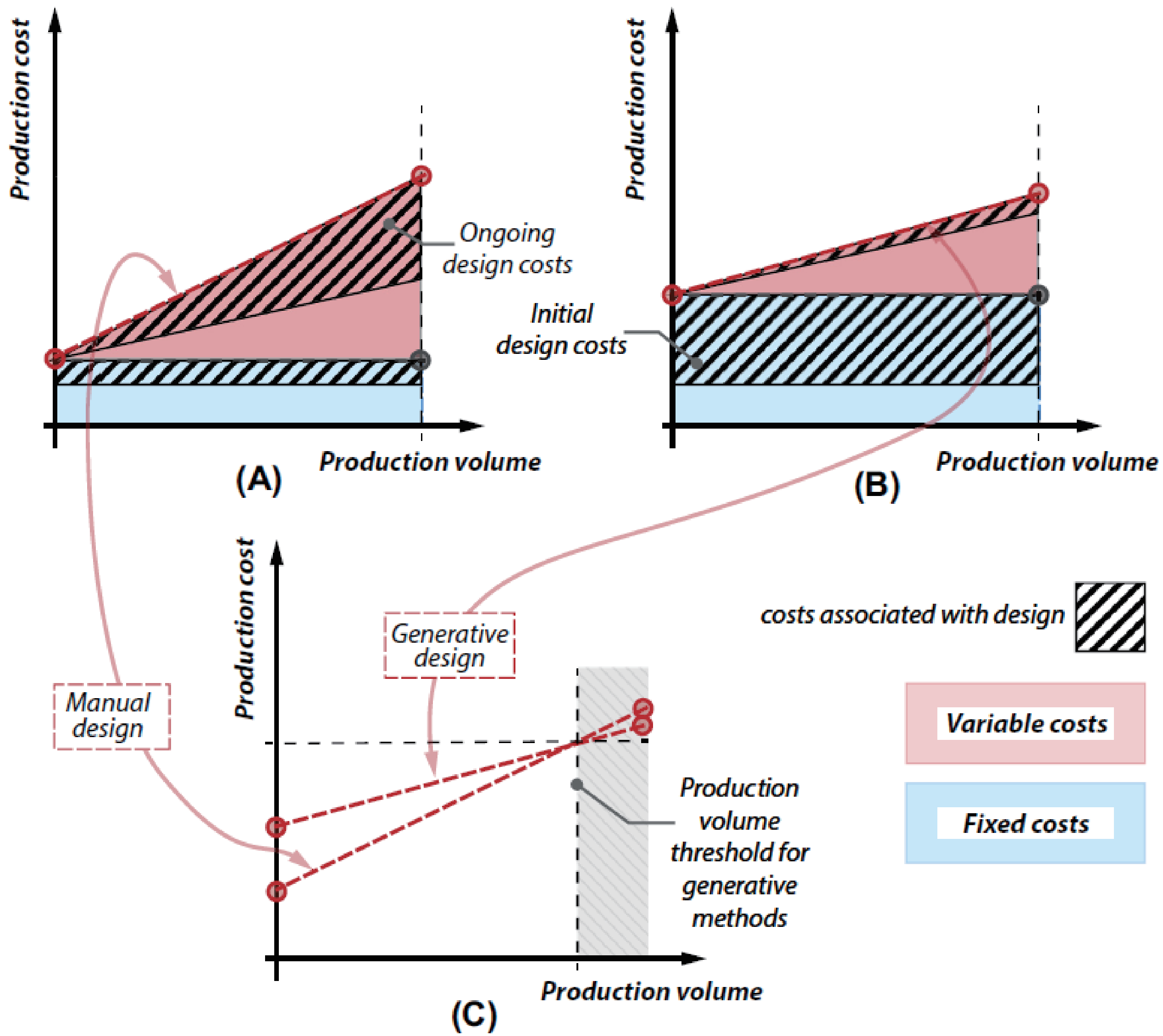
Mass-customization scenarios



Initial design as fixed cost, and on-going design as variable cost

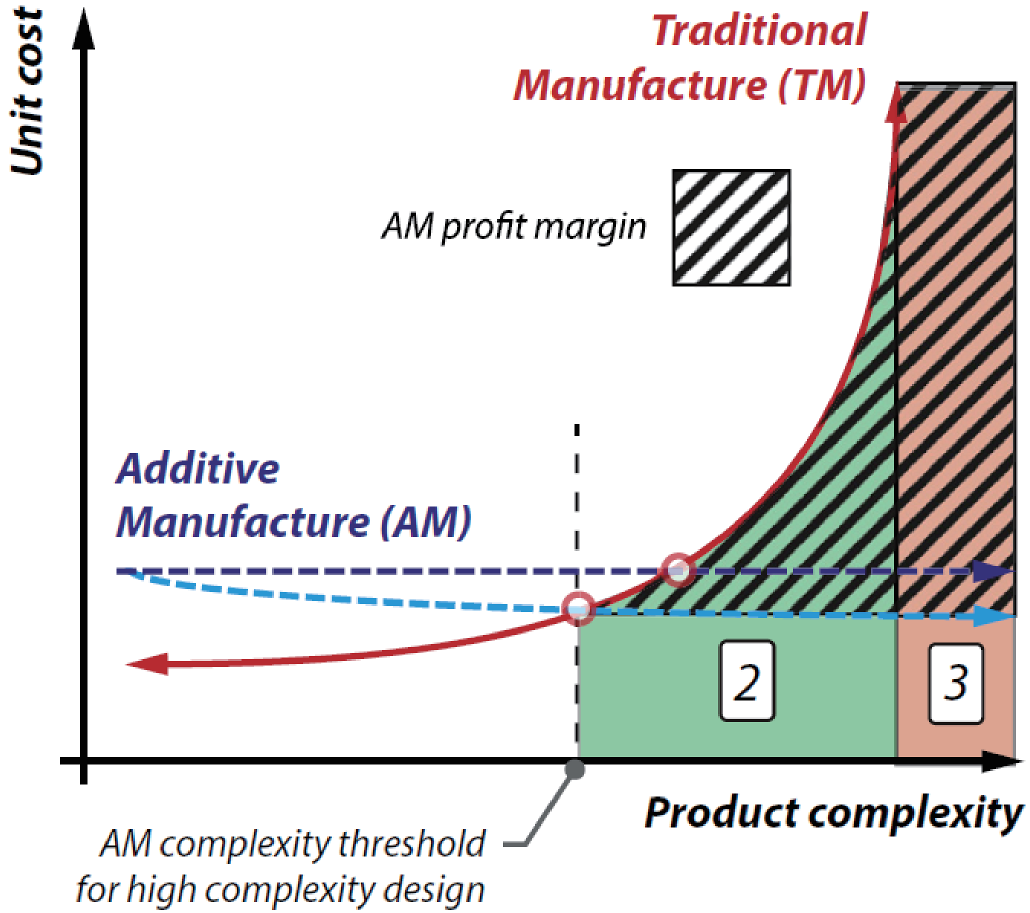
AM economics – a quick estimation

Use of generative design: Mass-customization scenarios



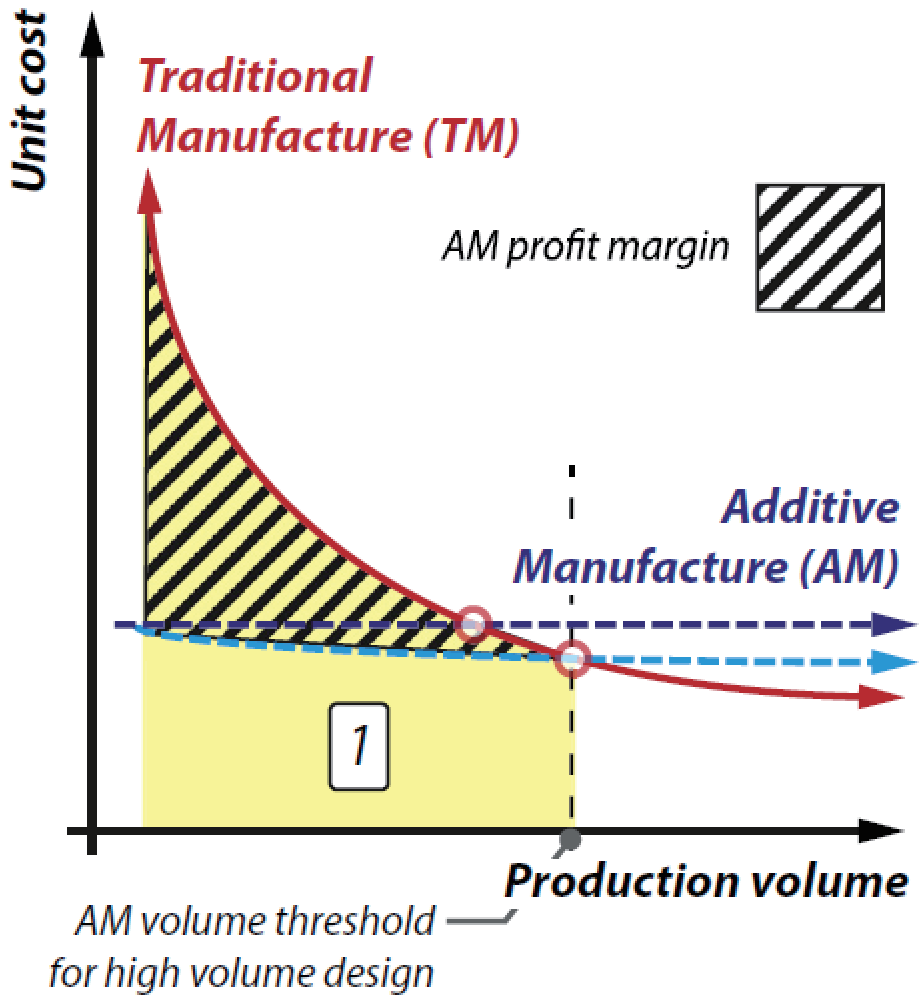
AM economics – a quick estimation

Use of generative design: high complexity scenario



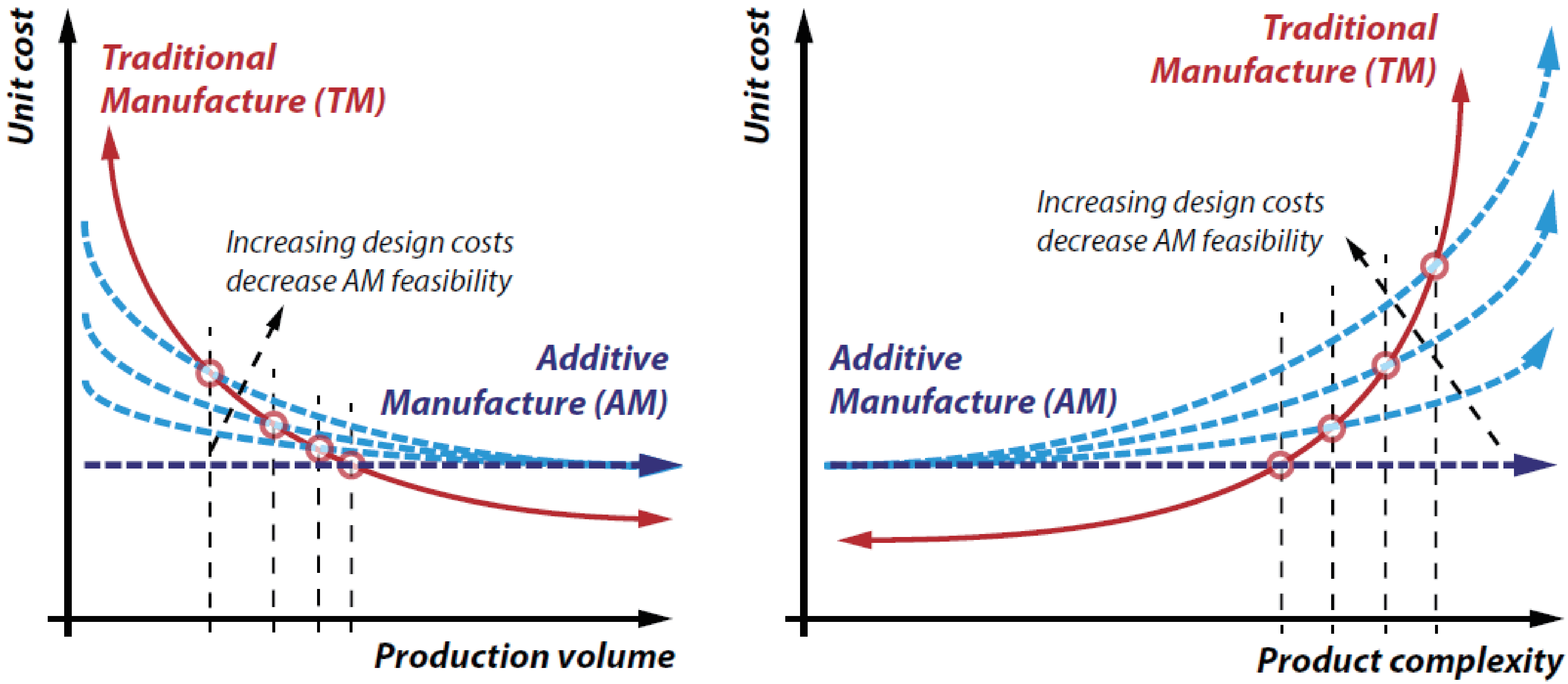
AM economics – a quick estimation

High volume AM production – real scenario



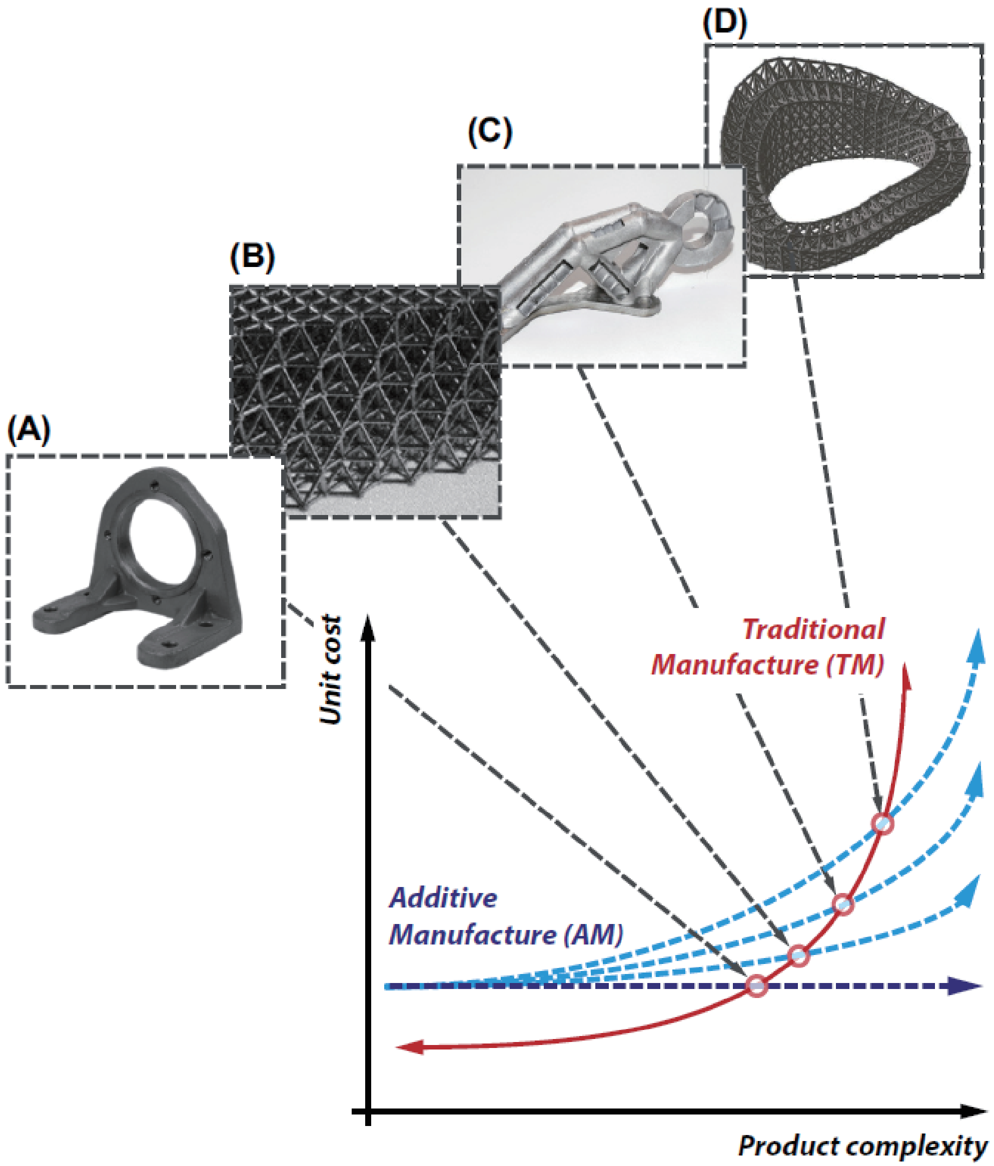
AM economics – a quick estimation

The flawed cost-independence assumption of AM



AM economics – a quick estimation

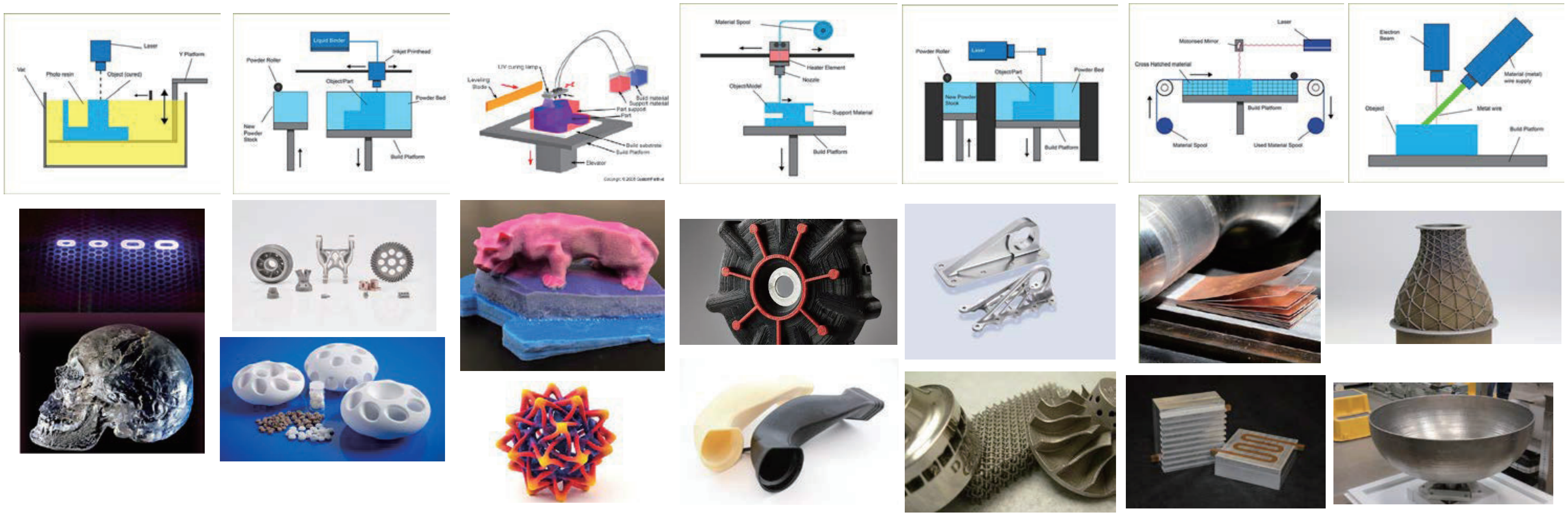
The economic necessity of design for AM



Additive Manufacturing (AM) processes

Additive Manufacturing (AM)

- Vat Photopolymerization
- Binder Jetting
- Material Jetting
- Material Extrusion
- Powder Bed Fusion
- Sheet Lamination
- Directed Energy Deposition



ISO/ASTM52900-15 Standard Terminology for Additive Manufacturing – General Principles – Terminology

https://www.lboro.ac.uk/research/amrg/about/whatisam/

Vat Photopolymerization

Photopolymerization – Step by Step

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.

VAT Photopolymerization

The SLA process has a high level of accuracy and good finish but often requires support structures and post curing for the part to be strong enough for structural use. The process of photo polymerisation can be achieved using a single laser and optics. Blades or recoating blades pass over previous layers to ensure that there are no defects in the resin for the construction of the next layer. The photo-polymerisation process and support material may have likely caused defects such as air gaps, which need to be filled with resin in order to achieve a high quality model. Typical layer thickness for the process is 0.025 – 0.5mm.

Post Processing: Parts must be removed from the resin and any excess resin fully drained from the vat. Supports can be removed using a knife or sharp implement. Care must be taken not to contaminate the resin and the appropriate safety precautions must be taken. Methods for removing resin and supports include the use of an alcohol rinse followed by a water rinse. The processing may be lengthy as parts may require additional scrubbing to remove material fully. Finally, parts can be dried naturally or by using an air hose. UV light is often used as well, for a final post cure process to ensure a high quality object.

Materials:

The Vat polymerisation process uses Plastics and Polymers.

Polymers: UV-curable Photopolymer resin (thermoset)

Resins: Visijet range (3D systems)

Advantages:

•High level of accuracy and good finish
•Relatively quick process
•Typically large build areas: object 1000: 1000 x 800 x 500 and max model weight of 200 kg

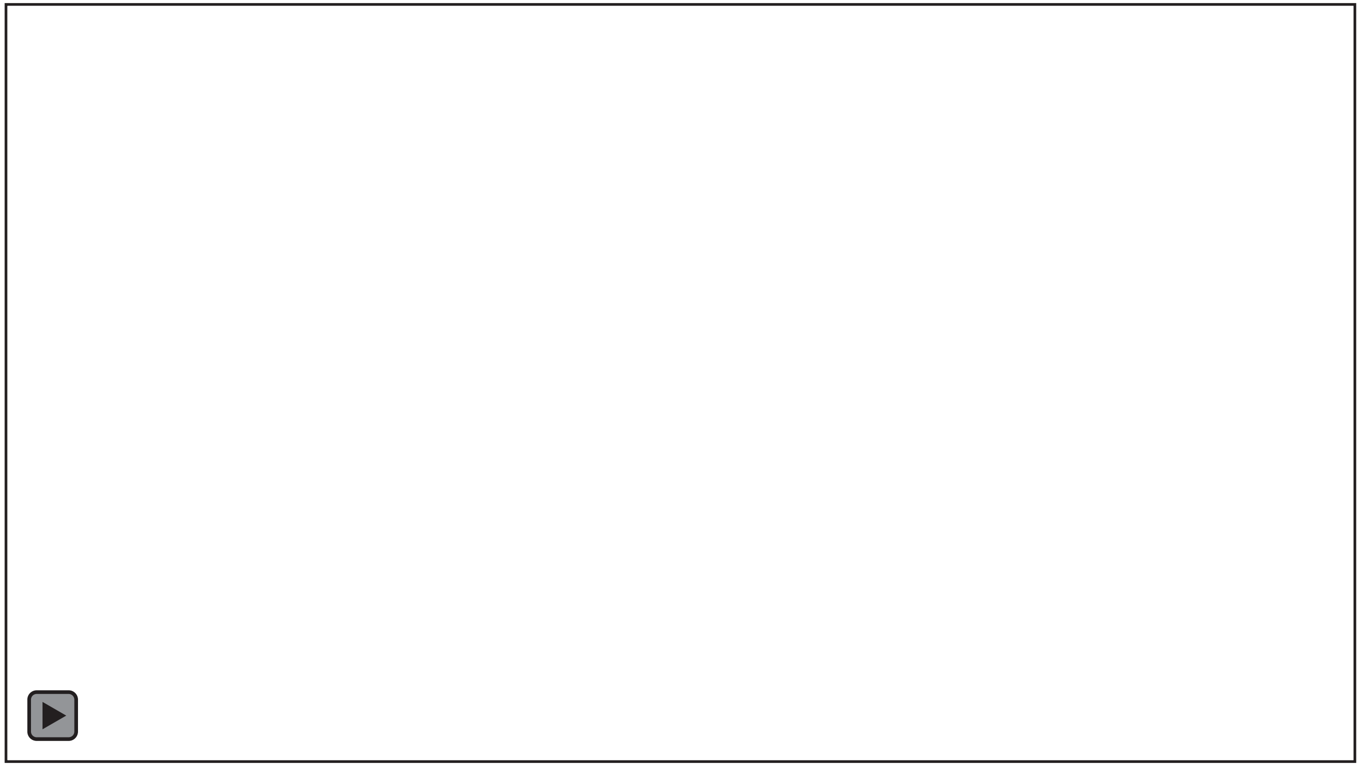
Disadvantages:

•Relatively expensive
•Lengthy post processing time and removal from resin
•Limited material use of photo-resins
•Often requires support structures and post curing for parts to be strong enough for structural use

Binder Jetting

Binder Jetting – Step by Step

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.



Binder jetting

The binder jetting process allows for colour printing and uses metal, polymers and ceramic materials. The process is generally faster than others and can be further quickened by increasing the number of print head holes that deposit material. The two material approach allows for a large number of different binder-powder combinations and various mechanical properties of the final model to be achieved by changing the ratio and individual properties of the two materials. The process is therefore well suited for when the internal material structure needs to be of a specific quality.

Layers of build material, often in granular and powder form, are held together using the adhesive binder. The print head deposits the binding material in micro amounts and the powder material is used in creating the majority of the overall object mass. A heated build chamber can help to speed up the printing process by increasing the viscosity of the materials.

Post Processing: The overall process time is extended as it requires the binder to set and the part is often allowed to cool in the machine to fully solidify to achieve a high quality finish. Post processing is often required to make the part stronger and give the binder-material better mechanical and structural properties.

Materials:

Metals: Stainless steel

Polymers: ABS, PA, PC

Ceramics: Glass

All three types of materials can be used with the binder jetting process.

Advantages:

- Parts can be made with a range of different colours
- Uses a range of materials: metal, polymers and ceramics
- The process is generally faster than others
- The two material method allows for a large number of different binder-powder combinations and various mechanical properties

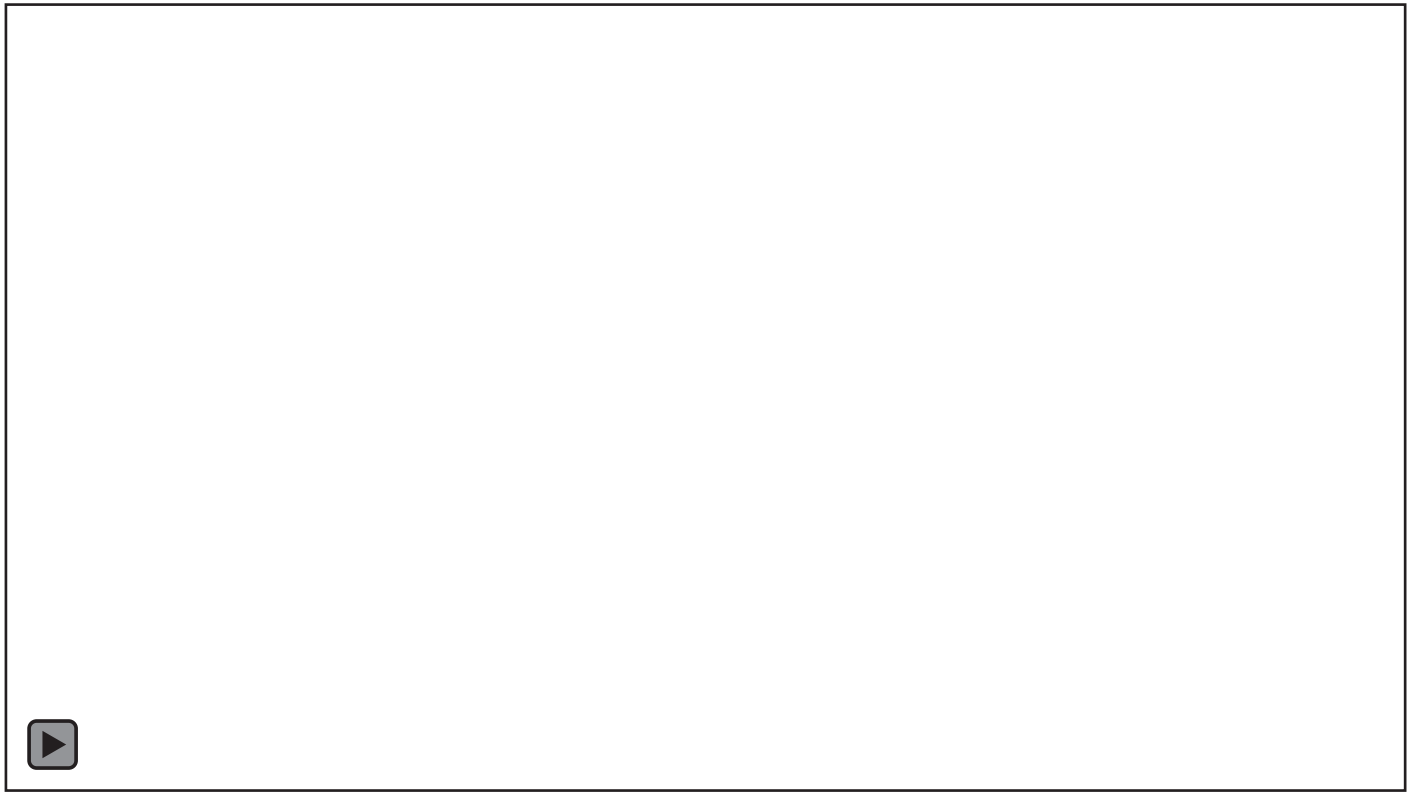
Disadvantages:

- Not always suitable for structural parts, due to the use of binder material
- Additional post processing can add significant time to the overall process

Material Jetting

Material Jetting – Step by Step

1.The print head is positioned above build platform.
2.Droplets of material are deposited from the print head onto surface where required, using either thermal or piezoelectric method.
3.Droplets of material solidify and make up the first layer.
4.Further layers are built up as before on top of the previous.
5.Layers are allowed to cool and harden or are cured by UV light. Post processing includes removal of support material.



Material jetting

Material Jetting builds objects in a similar method to a two dimensional ink jet printer. Multiple materials can be used in one process and the material can be changed during the build stage. Material is jetted onto the build platform surface in droplets, which are formed using an oscillating nozzle. Droplets are then charged and positioned onto the surface using charged deflection plates. This is a continuous system which allows for a high level of droplet control and positioning. Droplets which are not used are recycled back into the printing system.

Drop on Demand (DOD) is used to dispense material onto the required surface. Droplets are formed and positioned into the build surface, in order to build the object being printed, with further droplets added in new layers until the entire object has been made. The nature of using droplets, limits the number of materials available to use. Polymers and waxes are often used and are suitable due to their viscous nature and ability to form drops. Viscosity is the main determinant in the process; there is a need to re-fill the reservoir quickly and this in turn affects print speed. Unlike a continuous stream of material, droplets are dispensed only when needed, released by a pressure change in the nozzle from thermal or piezoelectric actuators. Thermal actuators deposit droplets at a very fast rate and use a thin film resistor to form the droplet. The piezoelectric method is often considered better as it allows a wider range of materials to be used. The designs of a typical DOD print head changes from one machine to another but according to Ottnad, typically include a reservoir, sealing ring, Piezo elements and silicon plate with nozzle, held together with high temperature glue.

Post processing: Support material can be removed using a sodium hydroxide solution or water jet. Due to the high accuracy of the process technology, the level of post processing required to enhance the properties is limited and the functional and aesthetic qualities of a part are largely determined during the printing stage. Stratasys polyjet technology cures the material using UV light and therefore no post curing process is needed.

Materials:

The material jetting process uses polymers and plastics.

Polymers: Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP

Advantages:

•The process benefits from a high accuracy of deposition of droplets and therefore low waste

•The process allows for multiple material parts and colours under one process

Disadvantages:

•Support material is often required

•A high accuracy can be achieved but materials are limited and only polymers and waxes can be used

Material Extrusion

Material Extrusion – Step by Step

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.

Material Extrusion

Advantages of the material extrusion process include use of readily available ABS plastic, which can produce models with good structural properties, close to a final production model. In low volume cases, this can be a more economical method than using injection moulding. However, the process requires many factors to control in order to achieve a high quality finish. The nozzle which deposits material will always have a radius, as it is not possible to make a perfectly square nozzle and this will affect the final quality of the printed object. Accuracy and speed are low when compared to other processes and the quality of the final model is limited to material nozzle thickness.

When using the process for components where a high tolerance must be achieved, gravity and surface tension must be accounted for. Typical layer thickness varies from 0.178 mm – 0.356 mm.

One method of post processing to improve the visual appearance of models is through improving material transmissivity. Methods have been explored, include increasing temperature and the use of resin. Experiments using cyamo acrylate resin, often used to improve the strength of parts, resulted in a 5% increase in transmissivity after 30 seconds and sanding. As with most heat related post processing processes, shrinkage is likely to occur and must be taken into account if a high tolerance is required.

Materials:

The Material Extrusion process uses polymers and plastics.

Polymers: ABS, Nylon, PC

Advantages:

- Widespread and inexpensive process
- ABS plastic can be used, which has good structural properties and is easily accessible

Disadvantages:

- The nozzle radius limits and reduces the final quality
- Accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness
- Constant pressure of material is required in order to increase quality of finish

Powder Bed Fusion

Powder Bed Fusion – Step by Step

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

Selective laser sintering (SLS) machines are made up of three components (Gibson et al., 2010): a heat source to fuse the material, a method to control this heat source and a mechanism to add new layers of material over the previous. The SLS process benefits from requiring no additional support structure, as the powder material provides adequate model support throughout the build process. The build platform is within a temperature controlled chamber, where the temperature is usually a few degrees below that of the material melting point, reducing the dependency of the laser to fuse layers together. The chamber is often filled with nitrogen to maximise oxidation and end quality of the model. Models require a cool down period to ensure a high tolerance and quality of fusion. Some machines monitor the temperature layer by layer and adapt the power and wattage of the laser respectively to improve quality.

Selective Laser Melting (SLM) Compared to SLS, SLM is often faster (Gibson et al., 2010), but requires the use of an inert gas, has higher energy costs and typically has a poor energy efficiency of 10 to 20 % (Gibson et al., 2010). The process uses either a roller or a blade to spread new layers of powder over previous layers. When a blade is sed, it is often vibrated to encourage a more even distribution of powder (Gibson et al., 2010). A hopper or a reservoir below or aside the bed provides a fresh material supply.

Selective Heat Sintering (SHS) uses a heated thermal printhead to fuse powder material together. As before, layers are added with a roller in between fusion of layers. The process is used in creating concept prototypes and less so structural components. The use of a thermal print head and not a laser benefits the process by reducing significantly the heat and power levels required. Thermoplastics powders are used and as before act as support material. The 'Blue printer' is a desktop 3D printer that uses the SHS technology, with a build chamber of 200mm x 160mm x 140mm, print speed of 2-3mm/hour and a layer thickness of 0.1mm (Blue Printer SHS , 2014).

Direct Metal Laser Sintering (DMLS) uses the same process as SLS, but with the use of metals and not plastic powders. The process sinters the powder, layer by layer and a range of engineering metals are available.

Electron Beam Melting (EBM) Layers are fused using an electron beam to melt metal powders. Machine manufacturer Arcam used electromagnetic coils to control the beam and a vacuum pressure of 1×10-5 mba (EBM Arcam , 2014). EBM provides models with very good strength properties due to an even temperature distribution of during fusion (Chua et al., 2010). The high quality and finish that the process allows for makes it suited to the manufacture of high standard parts used in aeroplanes and medical applications. The process offers a number of benefits over traditional methods of implant creation, including hip stem prosthesis (Agaruala, 1995). Compared to CNC machining, using EBM with titanium and a layer thickness of 0.1mm, can achieve better results, in an faster time and can reduce the cost by up to 35%.

Post processing requirements include removing excess powder and further cleaning and CNC work. One advantage and common aim of post processing is to increase the density and therefore the structural strength of a part. Liquid phase sintering is a method of melting the metal powder or powder combination in order to achieve homogenisation and a more continuous microstructure throughout the material, however, shrinking during the process must be accounted for. Hot isotactic pressing is another method to increase density; a vacuum sealed chamber is used to exert high pressures and temperatures of the material. Although this is an effective technique to improve strength, the trade-off is a longer and more expensive build time.

Powder Bed Fusion

Materials:

The Powder bed fusion process uses any powder based materials, but common metals and polymers used are:

SHS: Nylon DMLS, SLS, SLM: Stainless Steel, Titainium, Aluminium, Cobalt Chrome, Steel

EBM: titanum, Cobalt Chrome, SS, Al and copper (Materials Arcam, 2014).

Advantages:

•Relatively inexpensive

•Suitable for visual models and prototypes

•Ability to integrate technology into small scale, office sized machine

•Powder acts as an integrated support structure

•Large range of material options

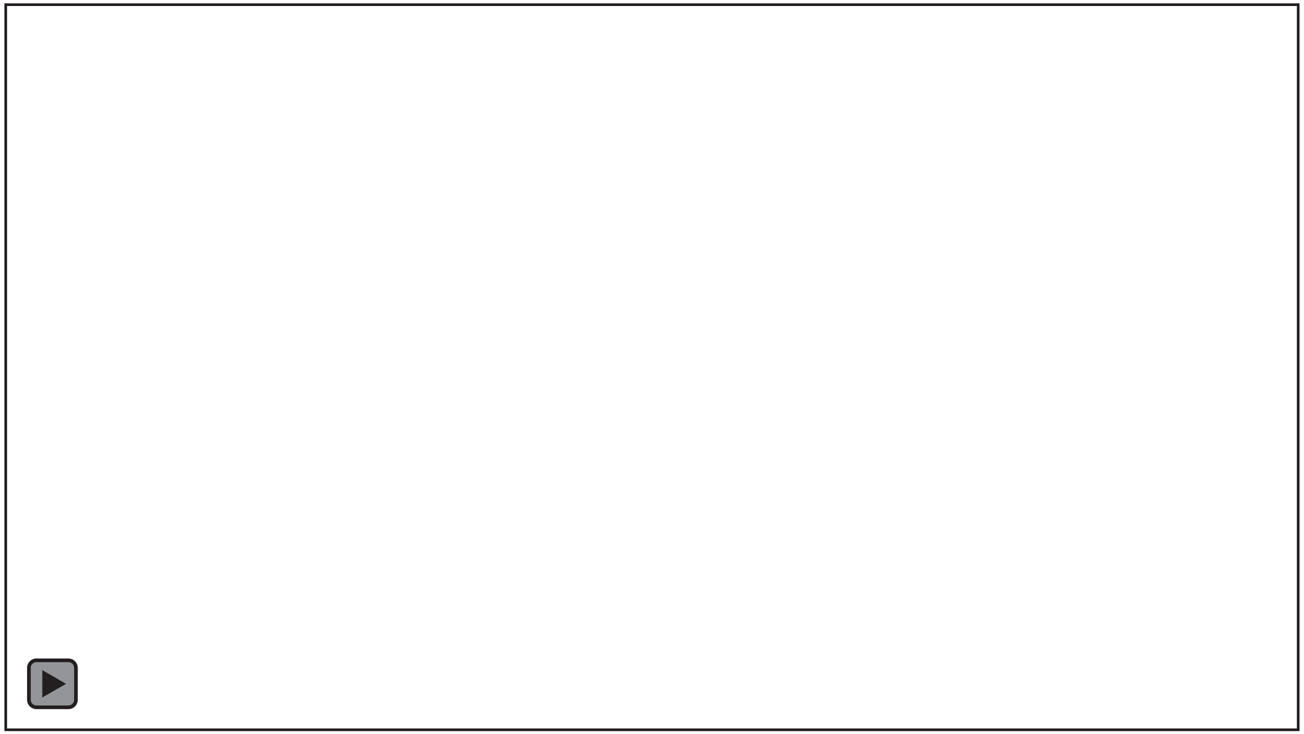
Disadvantages:

•Relatively slow speed

•Size limitations

•High power usage

•Finish is dependent on powder grain size



Sheet Lamination

Sheet Lamination – Step by Step

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.

Sheet Lamination

Laminating (LOM) is one of the first additive manufacturing techniques created and uses a variety of sheet material, namely paper. Benefits include the use of A4 paper, which is readily available and inexpensive, as well as a relatively simple and inexpensive setup, when compared to others.

The Ultrasonic Additive Manufacturing (UAM) process uses sheets of metal, which are bound together using ultrasonic welding. The process does require additional CNC machining of the unbound metal. Unlike LOM, the metal cannot be easily removed by hand and unwanted material must be removed by machining. Material saving metallic tape of 0.150mm thick and 25mm wide does however, result in less material to cut off afterwards. Milling can happen after each layer is added or after the entire process. Metals used include aluminum, copper, stainless steel and titanium. The process is low temperature and allows for internal geometries to be created. One key advantage is that the process can bond different materials and requires relatively little energy as the metal is not melted, instead using a combination of ultrasonic frequency and pressure. Overhangs can be built and main advantage of embedding electronics and wiring. Materials are bonded and helped by plastic deformation of the metals. Plastic deformation allows more contact between surface and backs up existing bonds.

Post processing requires the extraction of the part from the surrounding sheet material. With LOM, cross hatching is used to make this process easier, but as paper is used, the process does not require any specialist tools and is time efficient. Whilst the structural quality of parts is limited, adding adhesive, paint and sanding can improve the appearance, as well as further machining.

Materials:

Effectively any sheet material capable of being rolled. Paper, plastic and some sheet metals.

The most commonly used material is A4 paper.

Advantages:

- Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used
- Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross sectional area

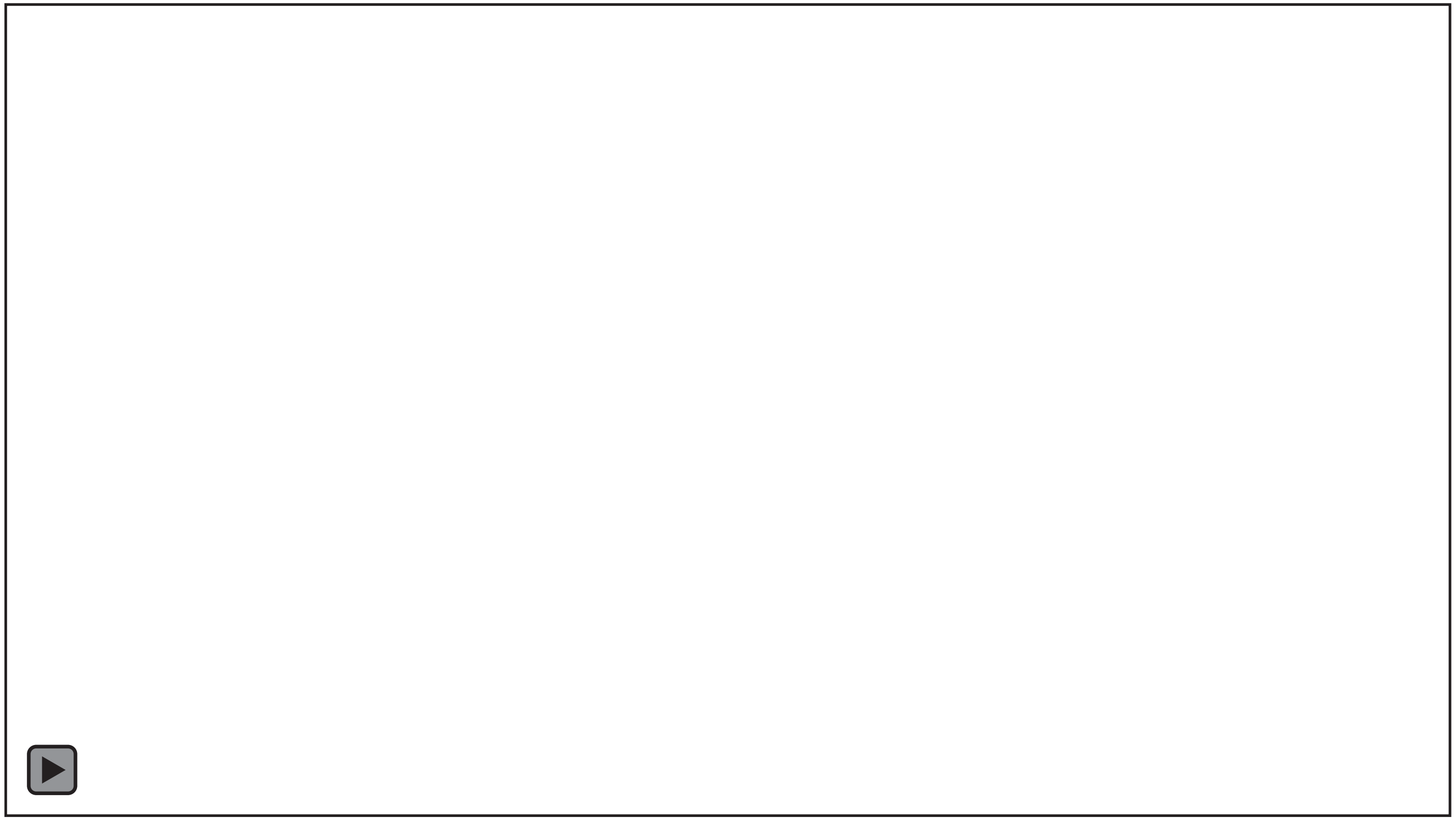
Disadvantages:

- Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
- Limited material use
- Fusion processes require more research to further advance the process into a more mainstream positioning

Directed Energy Deposition

Direct Energy Deposition – Step by Step

1. A 4 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.



Directed Energy Deposition

The DED process uses material in wire or powder form. Wire is less accurate due to the nature of a pre- formed shape but is more material efficient when compared to powder, as only required material is used. The method of material melting varies between a laser, an electron beam or plasma arc, all within a controlled chamber where the atmosphere has reduced oxygen levels. With 4 or 5 axis machines, the movement of the feed head will not change the flow rate of material, compared to fixed, vertical deposition.
Whilst in most cases, it is the arm that moves and the object remains in a fixed position, this can be reversed and a platform could be moved instead and the arm remain in a fixed position. The choice will depend on the exact application and object being printed. Material cooling times are very fast, typically between 1000 – 5000 degrees celsius / second. The cooling time will in turn affect the final grain structure of the deposited material, although the overlapping of material must also be considered, where the grain structure is changed as the overlapping can cause re-melting to occur, resulting in a uniform but alternating micro-structure. Typical layer thicknesses of 0.25 mm to 0.5 mm.

Materials:
Mostly metals
•Titanium Alloys.
•Steels.
•Nickel Alloys.
•Cobalt Alloys.
•Others.

Advantages:
•Ability to control the grain structure to a high degree, which lends the process to repair work of high quality, functional parts
•A balance is needed between surface quality and speed, although with repair applications, speed can often be sacrificed for a high accuracy and a pre- determined microstructure

Disadvantages:
•Finishes can vary depending on material but may require post processing to achieve desired effect
•Limited material use
•Limited complexity on geometry
•Fusion processes require more research to further advance the process into a more mainstream positioning

Thank you for your attention

Mini quiz: for the sole of ADDIDAS 4DFWD, which printing technology do they use?