Algorithmic Design for Additive Manufacturing

Joana Schulte, Omid Zarei | 27.09.2022

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Introduction
Subdivision of Manufacturing Processes

Subtractive Manufacturing

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Manufacturing of geometry by removing of defined areas from wrought material

- Milling
- Lathing
- …

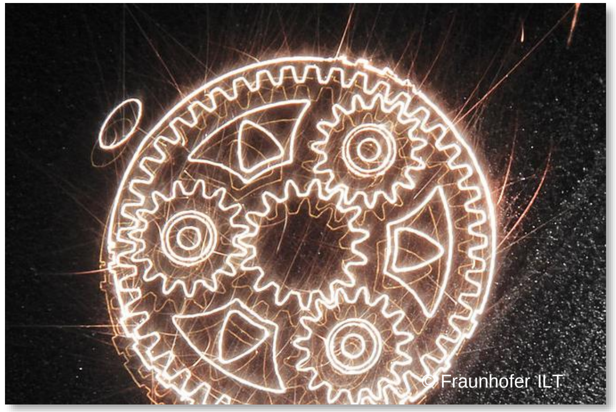
Formative Manufacturing

© Roth & Effinger

Forming a given volume into geometry under the condition of volume constancy

- Casting
- Forging
- …

Additive Manufacturing



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Automated stacking of volume elements (layers)

- L-PBF
- LMD
- …

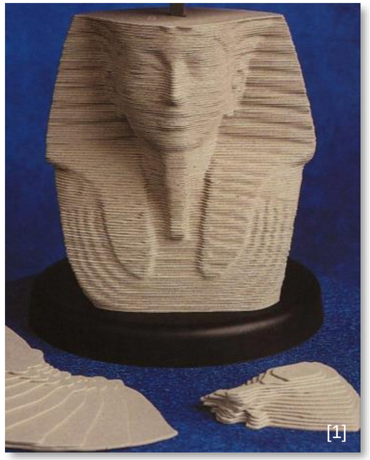
Introduction to Additive Manufacturing (AM)
Definitions

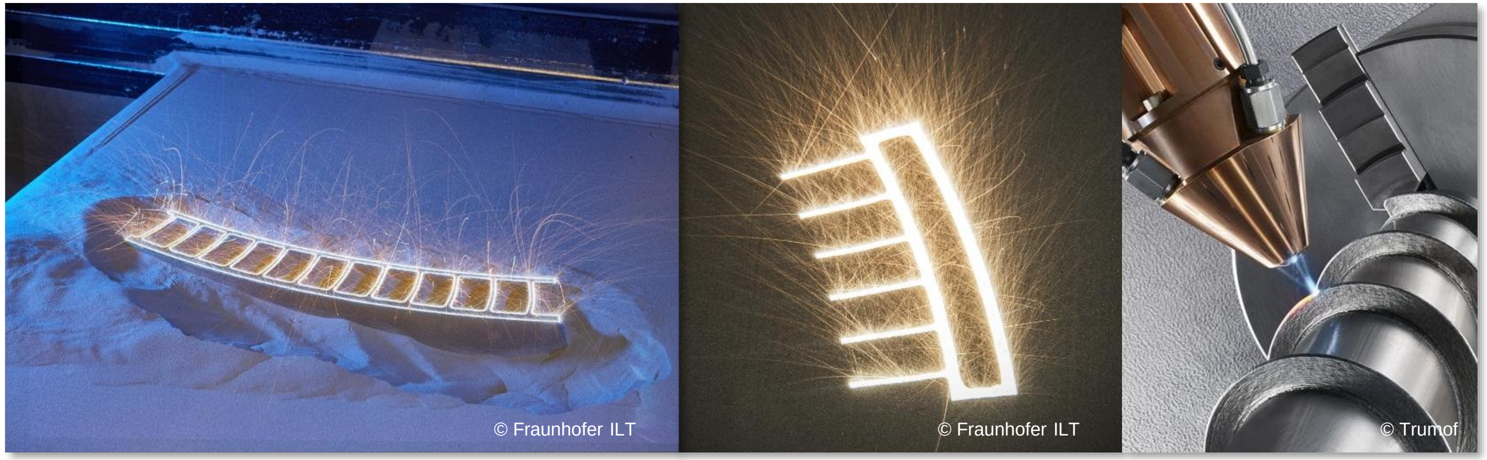
Definition (ASTM 52900)

“Additive Manufacturing (AM) is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.”

Definition (VDI 3405)

“Manufacturing process in which the workpiece is built up element by element or layer by layer.”





[1] Gebhardt, Andreas; Kessler, Julia; Thurn, Laura (2019): 3D Printing: Understanding Additive Manufacturing

Introduction to AM
Typical Areas of Application

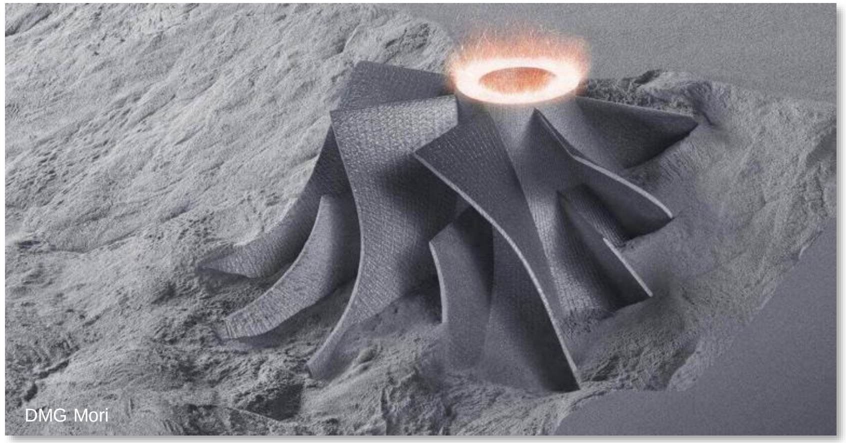
- Production on site
- Production on demand
- Prototyping
- Lightweight construction
- Reduction of iteration cycles in product development
- Small quantities and/or customer-specific products
- Production of spare parts for older serial products


APWorks


3d-grenzenlos.de


BEGO


Philipp Manger


DMG Mori

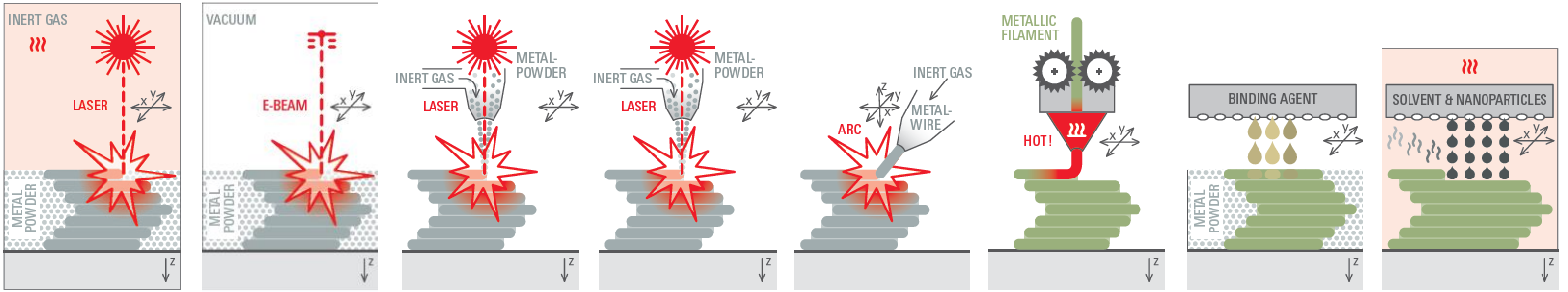
Source: Adapted from University Duisburg-Essen

Introduction to AM
Established Metal AM Technologies

Metal Additive Manufacturing

Powder Bed Fusion		*Direct Energy Deposition*			*Material Extrusion*	*Binder Jetting*	*Material Jetting*
Fused with laser	Fused with electron beam	Laser energy absorbed by substrate	Laser energy absorbed by powder feedstock	Fused with electric arc	With filament, green part to be sintered	Joined with bonding agent, to be sintered	Cured with heat, to be sintered
L-PBF Laser Powder Bed Fusion	**EBM** Electron Beam Melting	**LMD** Laser Metal Deposition	**EHLA** Extreme High Speed LMD	**WAAM** Wire Arc Additive Manufacturing	**Metal FDM** Metal Fused Deposition Modeling	**BJ** Binder Jetting	**NPF** Nano Particle Jetting

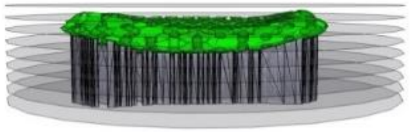
Market share: 72 %



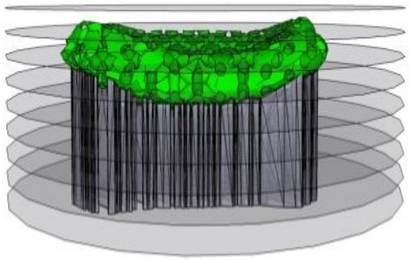
Source: Derived from Formnnext AM Field Guide Compact and DIN EN ISO/ASTM Terminology

Introduction to AM
Laser Powder Bed Fusion

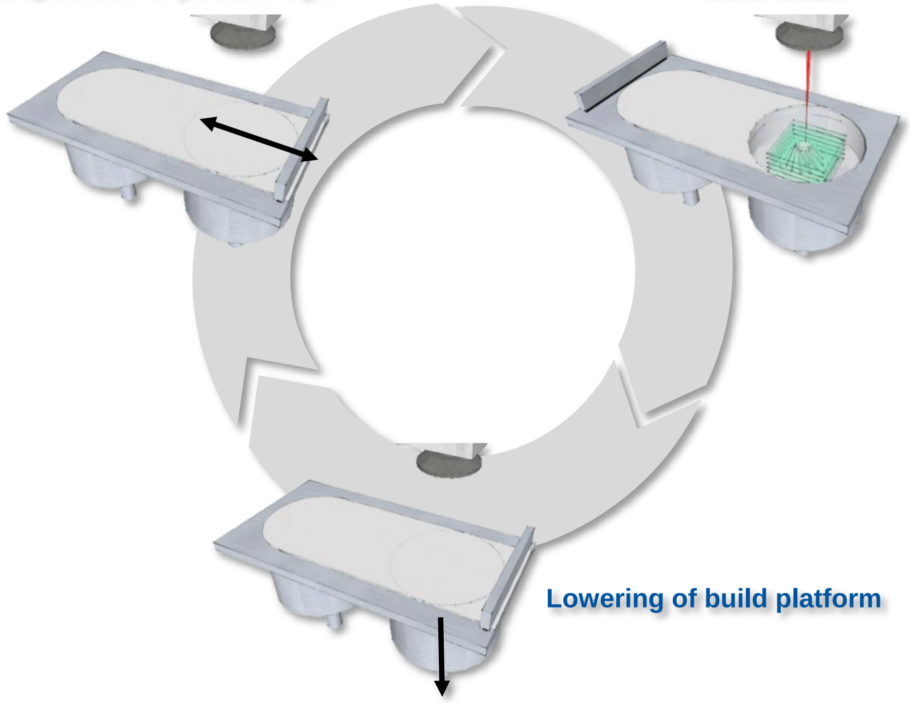
Pre-Process



Slicing

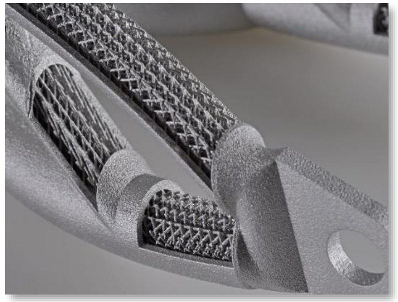


In-Process



Post-Process

Depowdering & removal from substrate



Final part with ultra-complex geometrical features

Introduction to AM
Key Characteristics

Additive


[1]

Geometry is generated by adding material instead of removing or forming

Toolless

Component geometry is independent from tools during building process


Fraunhofer ILT


Aniwaa

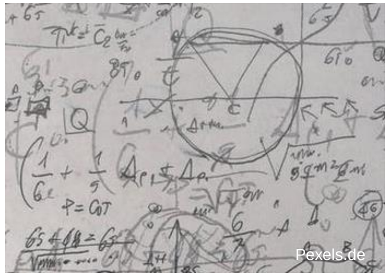
Digital


Pexels.de

Direct manufacturing based on 3D models

Complex

Different technologies require specific expert knowledge


Pexels.de

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Introduction to AM
Benefits and Barriers

AM Benefits

- **Design freedom**: Complex features, lightweight, monolithic
- **Flexible design** iterations and engineering changes
- **Integration of functions**
- **Tool-less** production
- Economic **small quantities** and **individualization**
- **Short time** and efficiency **idea to product**
- **Short supply chain**
- **Sustainability** by material reduction or efficiency in performance

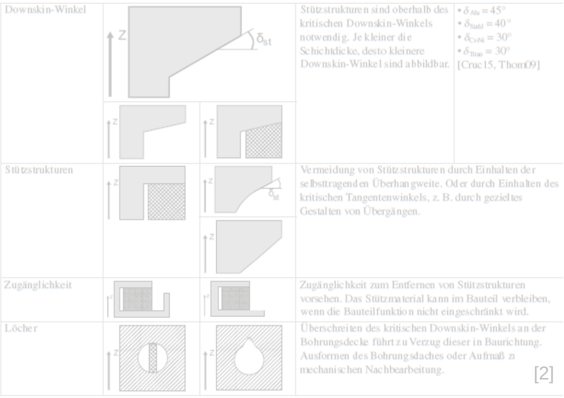
AM Barriers

- **Long printing times**
- Almost **no economies of scale**
- **Low surface quality** as-built
- **Large geometrical tolerances** as-built
- Limited **component size**

Design for AM
Potentials

Design for LPBF

- Design Restrictions
- Potential
  - Lattice Structures
  - Topology Optimization
  - Monolithic Design
  - Function Integration



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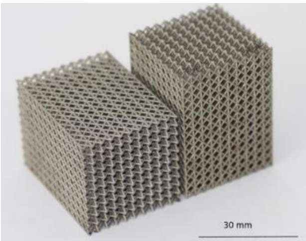
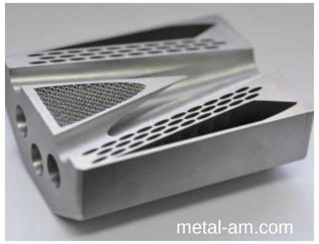
Zugänglichkeit		Zugänglichkeit zum Entfernen von Stützstrukturen vorsehen. Das Stützmaterial kann im Bauteil verbleiben, wenn die Bauteilfunktion nicht eingeschränkt wird.	
Löcher		Überschreiten des kritischen Downskin-Winkels an der Bohrungsdecke führt zu Verzug dieser in Baurichtung. Ausformen des Bohrungsdaches oder Aufmaß zu mechanischen Nachbearbeitung.	

[2]



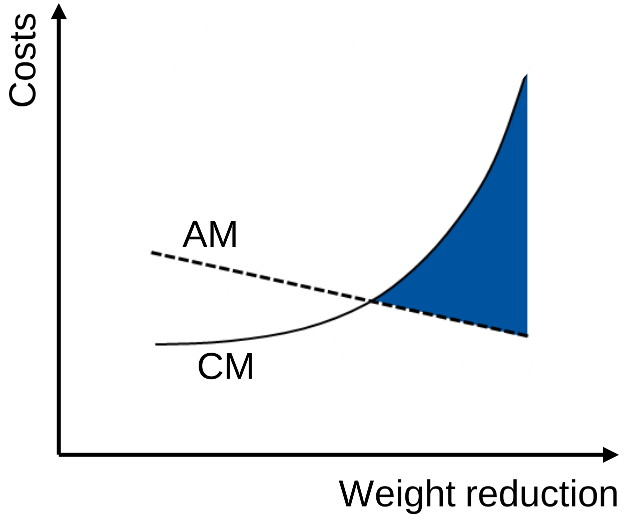


[2] Lachmayer, Roland; René B. Lippert (2020): Entwicklungsmethodik für die Additive Fertigung

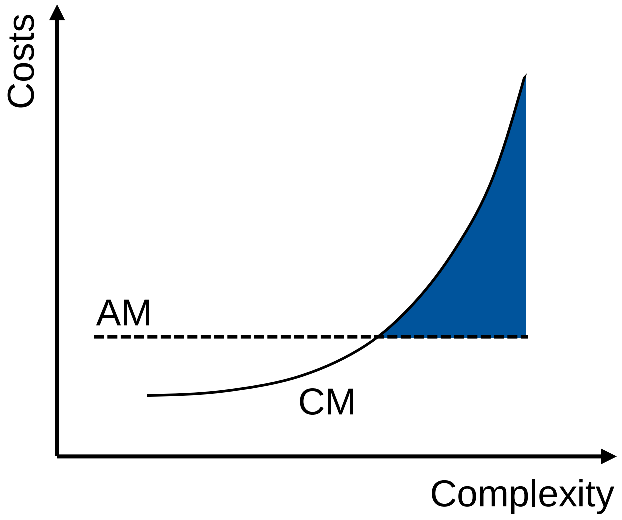
Design for AM

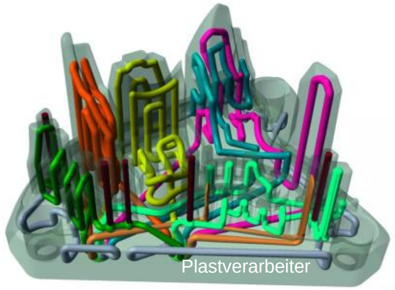
Different Cost Structure of Conventional Manufacturing (CM) and AM

Weight reduction means cost reduction

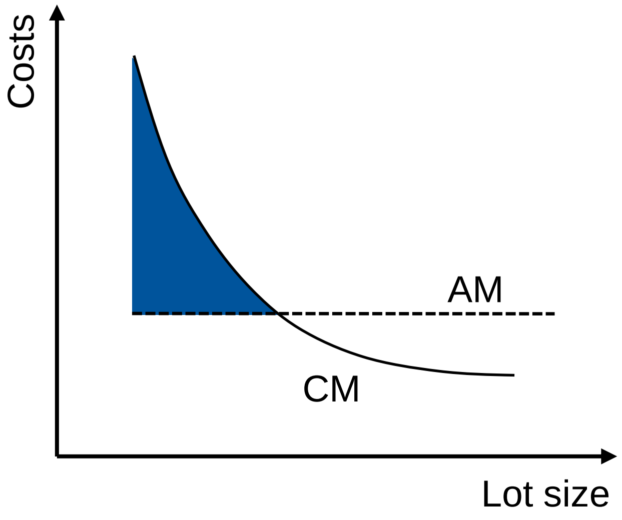


Complexity for free





Individualization for free



Design for AM

Potentials – Lattice Structures

Design for LPBF

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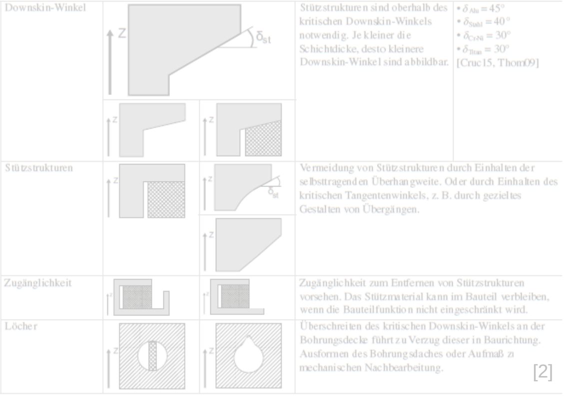

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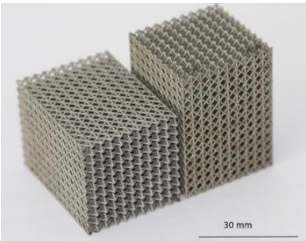

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Design for AM

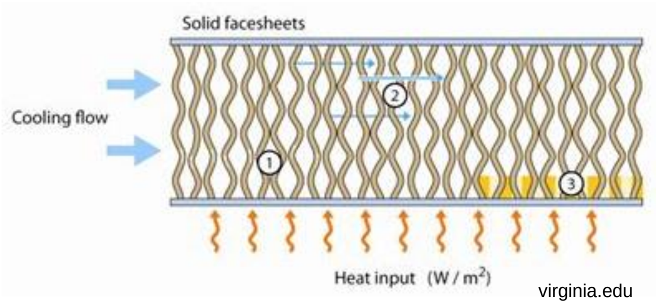
Potentials – Lattice Structures

Lightweight Structures

- Material reduction
- Increasing the strength to weight ratio

Heat conduction mechanisms in lattices

- Convection between struts and fluid
- Heat conduction through lattice structures



virginia.edu

Thermal Insulation

- Filigree lattice structures can restrict convection
- Gas can get trapped in lattice cells
- Low gas velocity

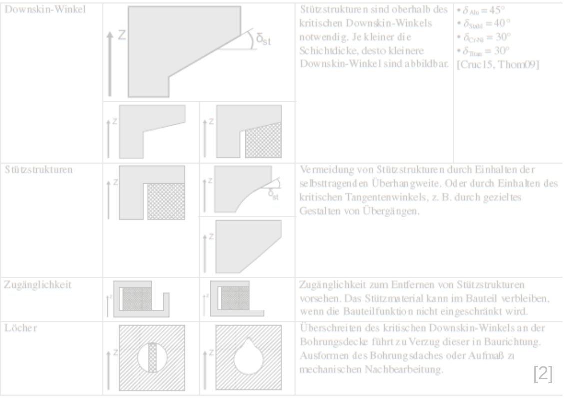
altairenlighten.com

Design for AM

Potentials – Topology Optimization

Design for LPBF

- Design Restrictions
- Potential
  - Lattice Structures
  - Topology Optimization
  - Monolithic Design
  - Function Integration



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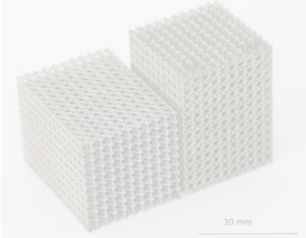

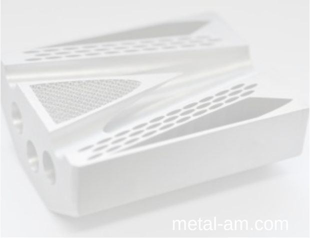

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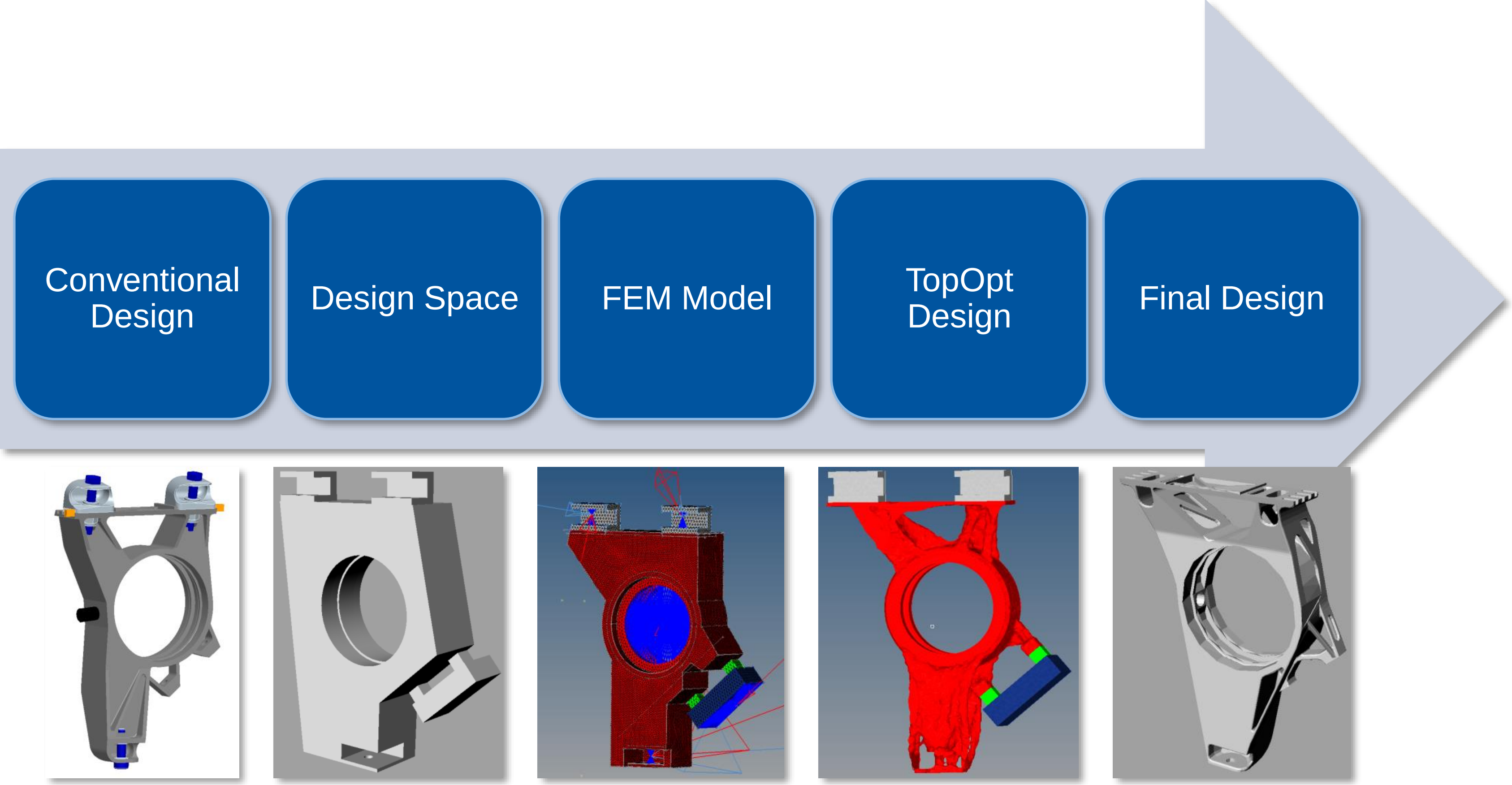
Design for AM
Potentials – Topology Optimization

- Material and weight efficiency by finding the optimal material distribution within a part
  - Optimization criteria, e.g.
    - Maximizing stiffness
  - Objective, e.g.
    - Defined volume / mass reduction



Source: Fraunhofer ILT

Design for AM

Potentials – Monolithic and Function Integration

Design for LPBF

- Design Restrictions
- Potential
  - Lattice Structures
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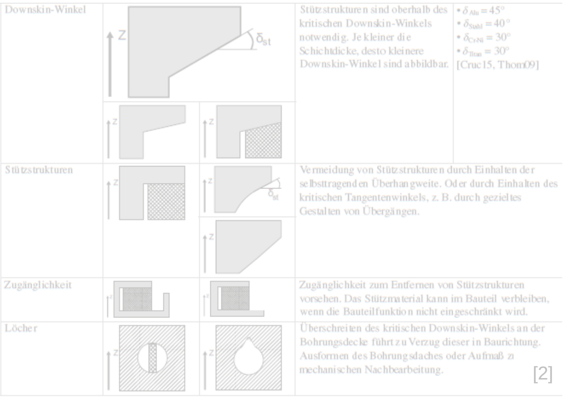
  - Monolithic Design
  - Function Integration



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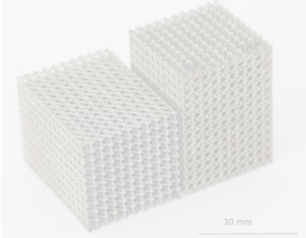
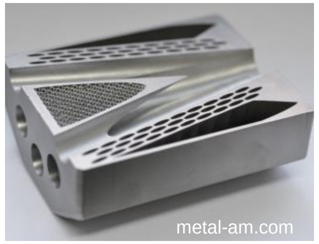



General Electric


metal-am.com

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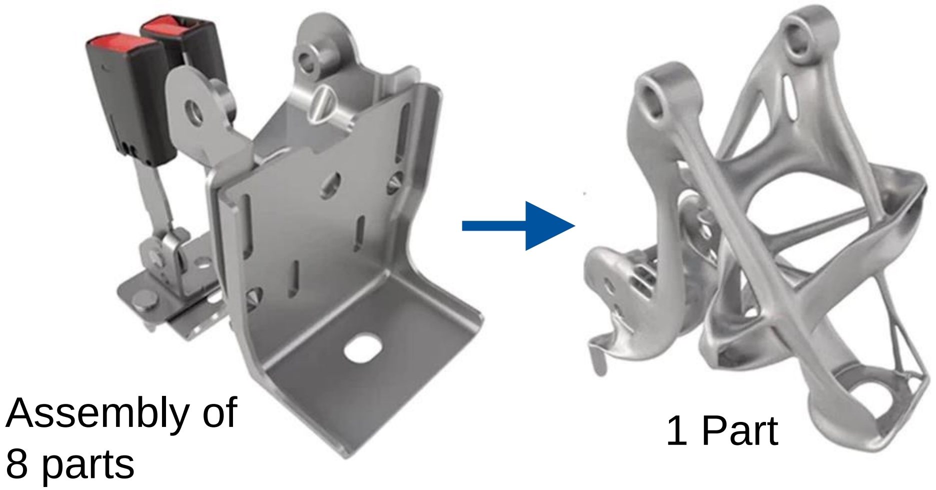
Design for AM

Potentials – Monolithic Design and Function Integration

GM Seat Bracket

- Lightweight engineering for the automotive industry
- Part number reduction: 8 parts → 1 part
- 40% weight reduction



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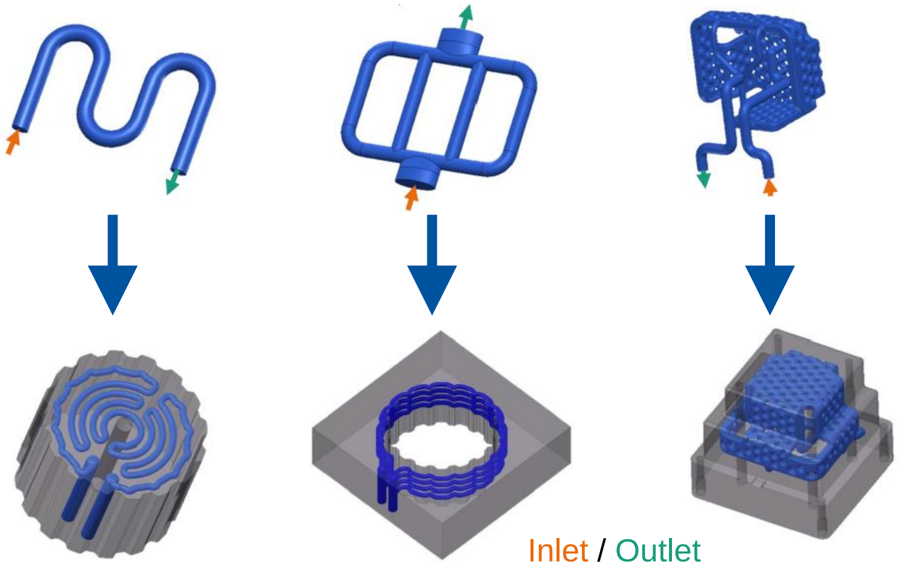
Integrated Cooling

- Internal cooling channels for improved cooling efficiency
- Conformal cooling channels can be arranged in series, in parallel and net shape configuration



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Design for AM
Restrictions

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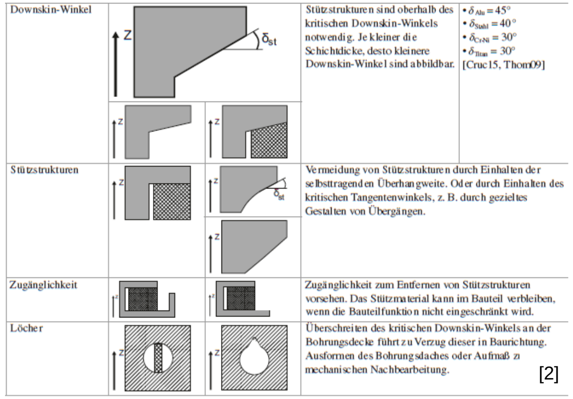

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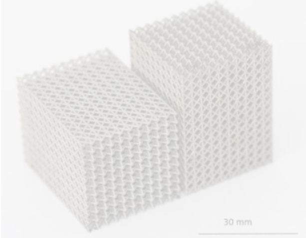

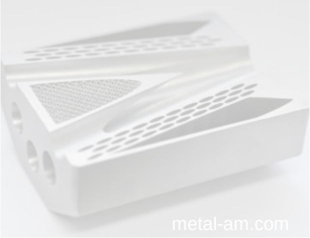

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Design for AM
Challenges

Myth

…realisieren, die man weder gießen noch schmied…
…n ansonsten bestenfalls aufwändig aus einem vollen Materialblock gefräst werden müssten. Vorteile des 3D-Verfahrens sind neben den uneingeschränkten Gestaltungsmöglichkeiten („Geometriefreiheit“) die extreme Leichtigkeit bei gleichzeitig enor…mer Stabilität.

Source: waz.de

…eat time to get into 3D printing because this time, I think, …

With 3D printing, you have unlimited design freedom and can make feat… impossible because you can change the physical part as quickly as you c…

…lly speaking, we can now design for f…

Source: mddionline.com

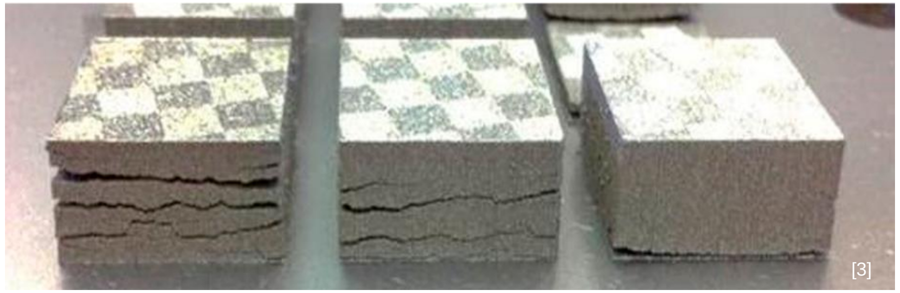
… 12, 2015 – 3D Systems (NYSE:DDD) announced today its lat… …plexity is Free," an in-depth look at how 3DS' advanced metal 3D …turers to leverage the unlimited complexity afforded by 3D printing to …ction of structural components. Through a series of real-world … defies the limi…

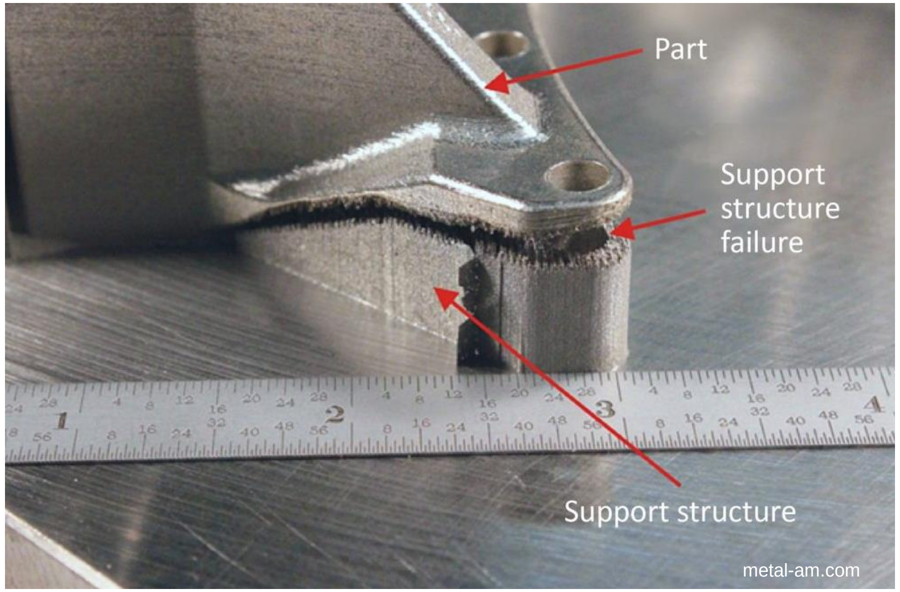
Source: 3dsystems.com

…n a CNC mill, or poured into a mold. But because 3D printing allows for virtually unlimited complexity it is actually quite cost effective to use additive

Source: 3dprint.com

Reality





[3] W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff & S. S. Babu (2016): The metallurgy and processing science of metal additive manufacturing

Design for AM
Design Rules and Restrictions for AM

- Design restrictions exist for all ~~**conventional**~~ processes to enable engineers to design parts that can be manufactured
- Design rules need to be implemented to enable manufacturing suitable designs
  - Accessibility for tools used for post-processing
  - Depowdering
  - Overhang angle
  - Gap sizes
  - Wall thickness
  - Geometry deviation
  - …

➢ **The part design is always a trade-off between the functionality of the part and the possibility for (economic) manufacturing**


[1]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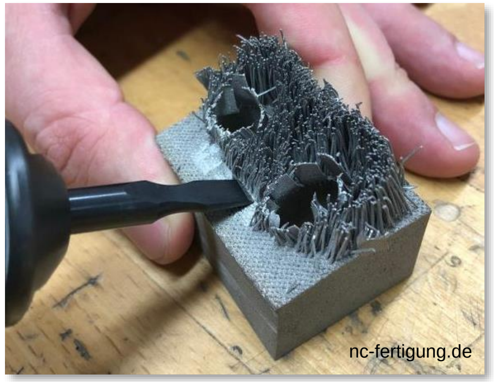

nc-fertigung.de

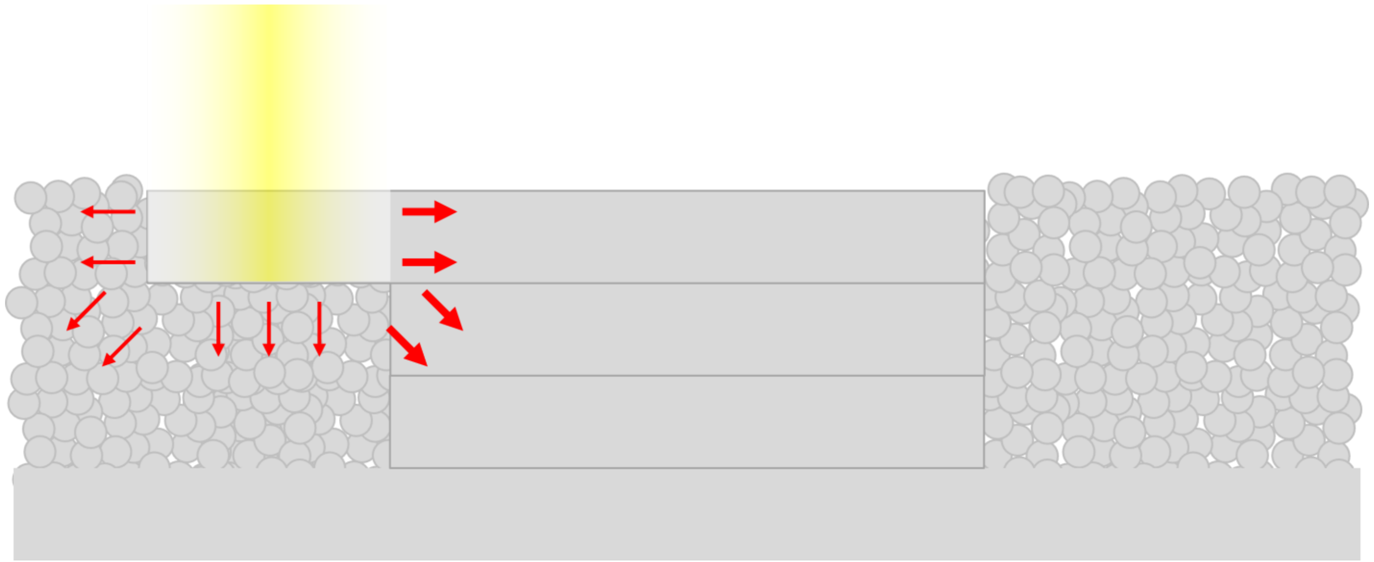

solukon.de

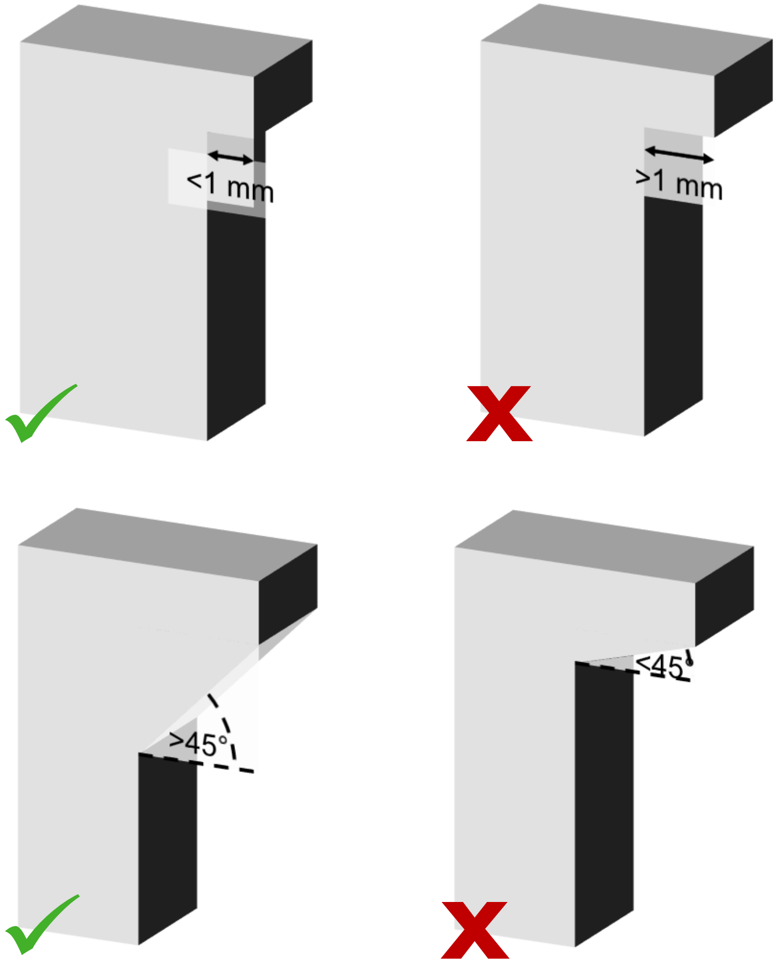
[1] Gebhardt, Andreas; Kessler, Julia; Thurn, Laura (2019): 3D Printing: Understanding Additive Manufacturing

Design for AM

Design Restrictions – Overhanging Surfaces

- Limited structural support of underlying powder
- Limited heat conductivity of surrounding powder to dissipate process heat



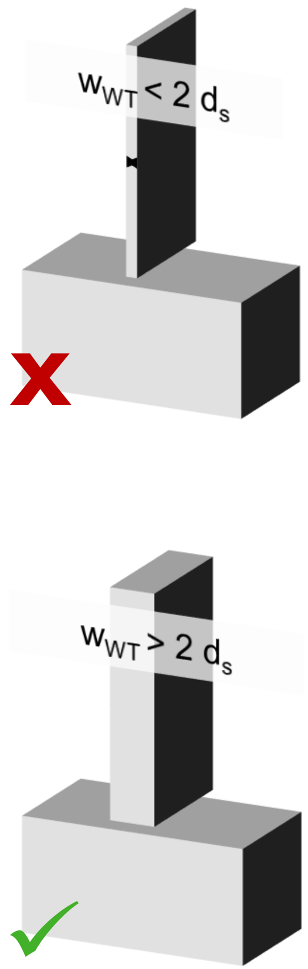


Overhanging surfaces can only be manufactured to a limited extent / limited surface inclination angle

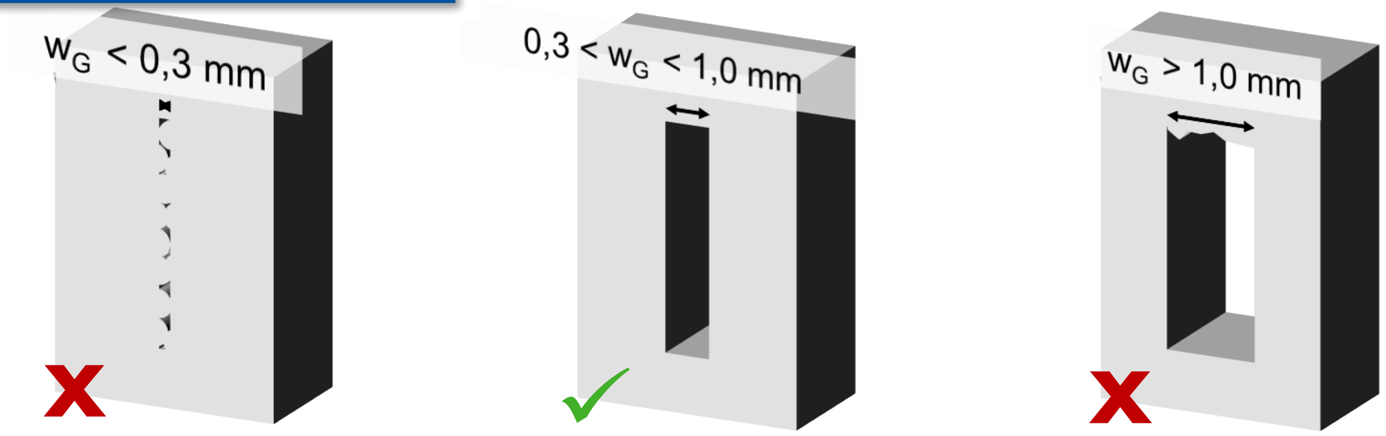
Design for AM

Design Restrictions – Feature Sizes

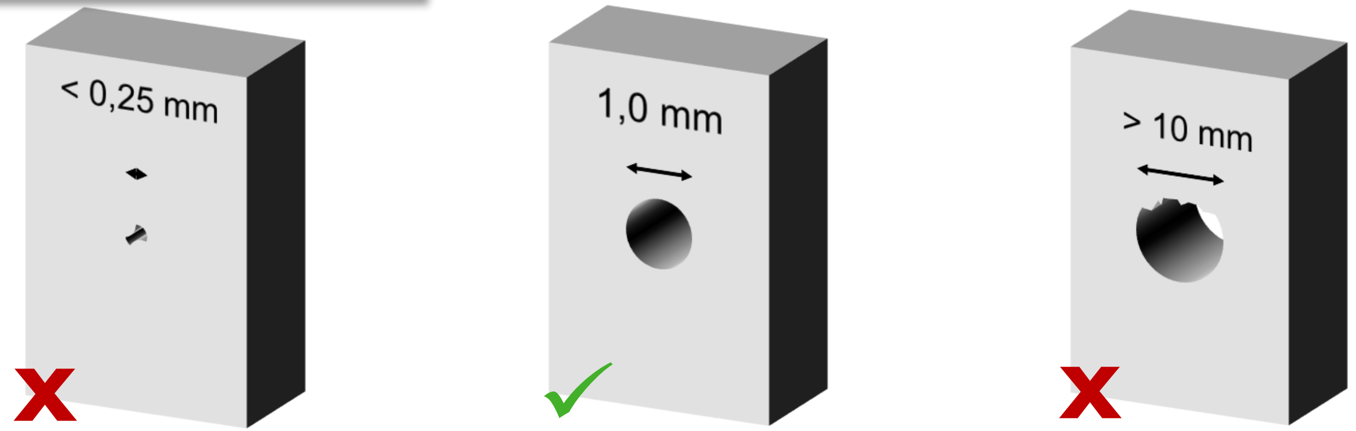
Minimum wall thickness



Gap size

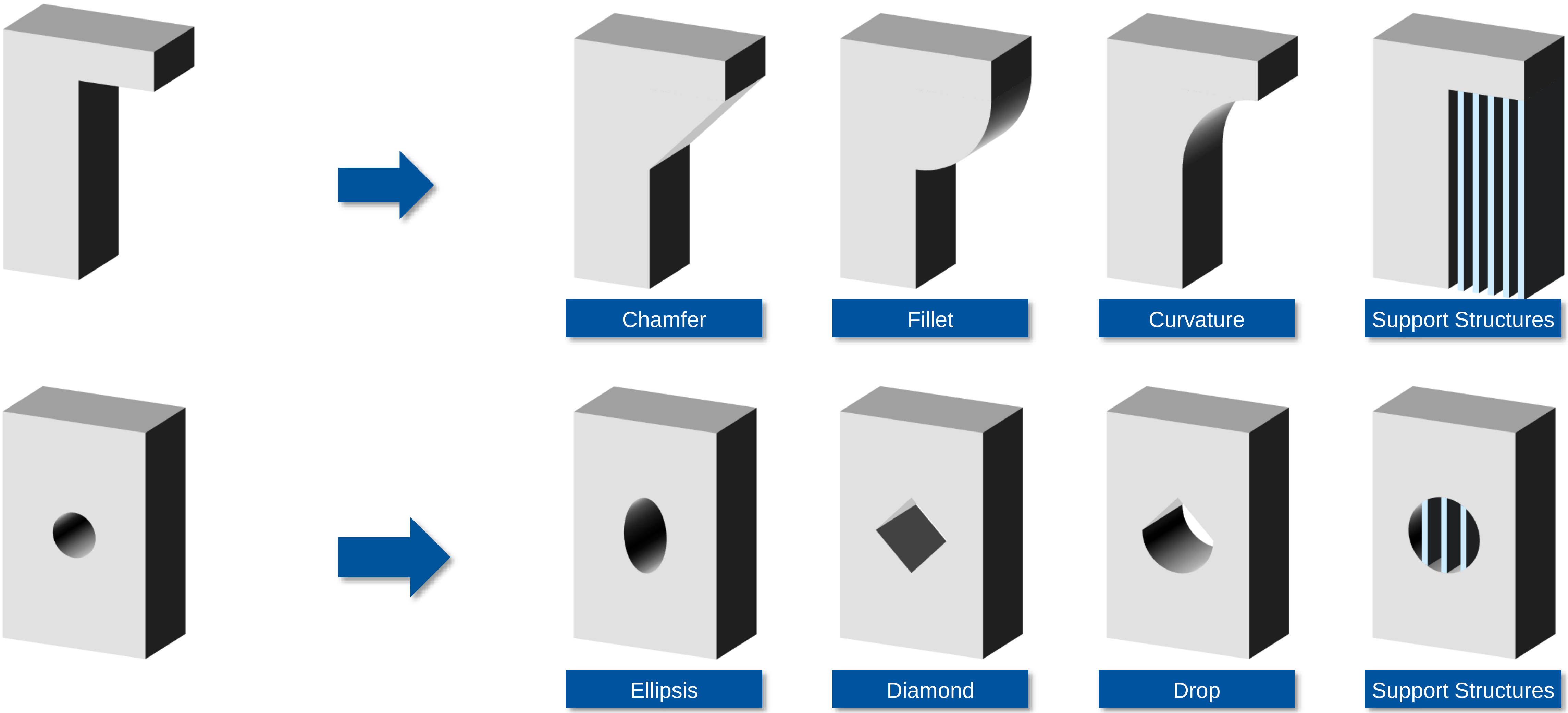


Drill hole diameter



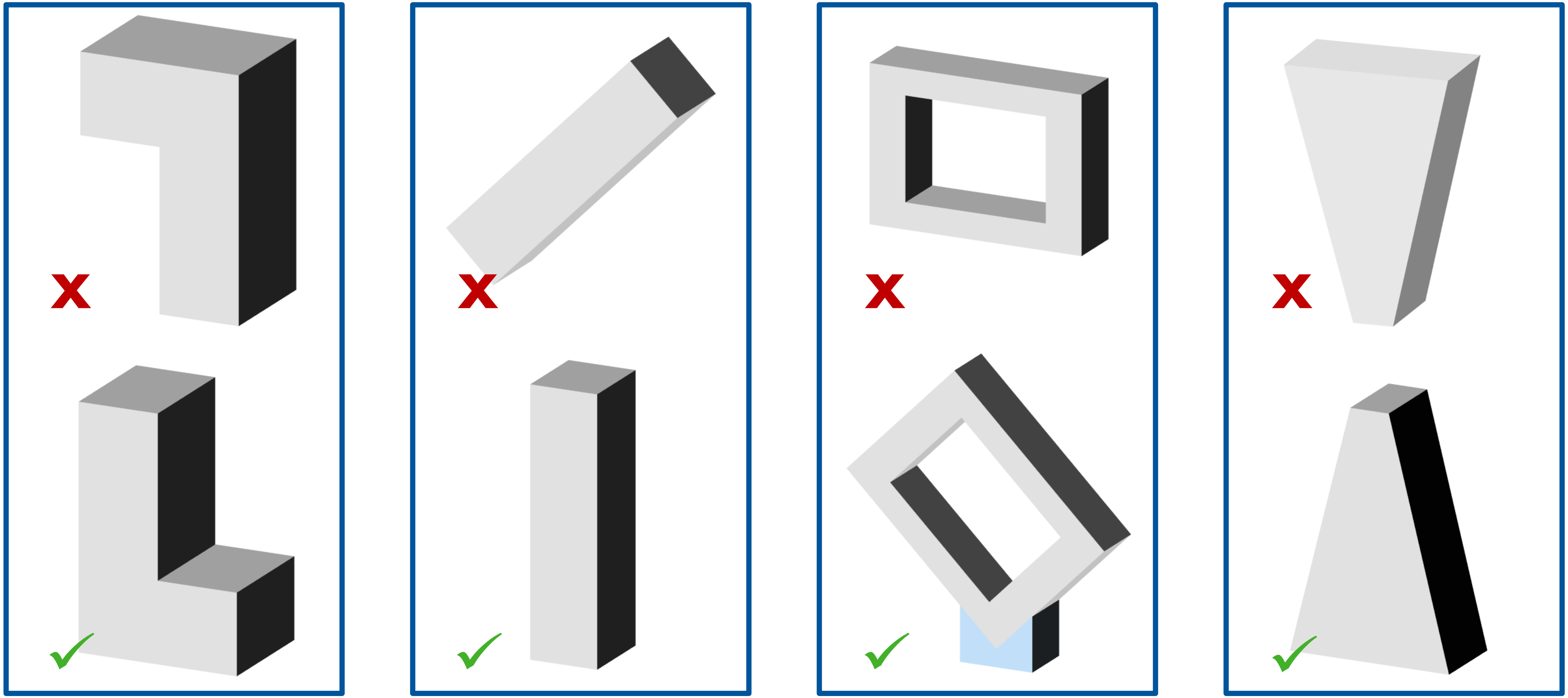
Design for AM

Overcoming Processability Restrictions – Overhanging Surfaces and Drill Holes



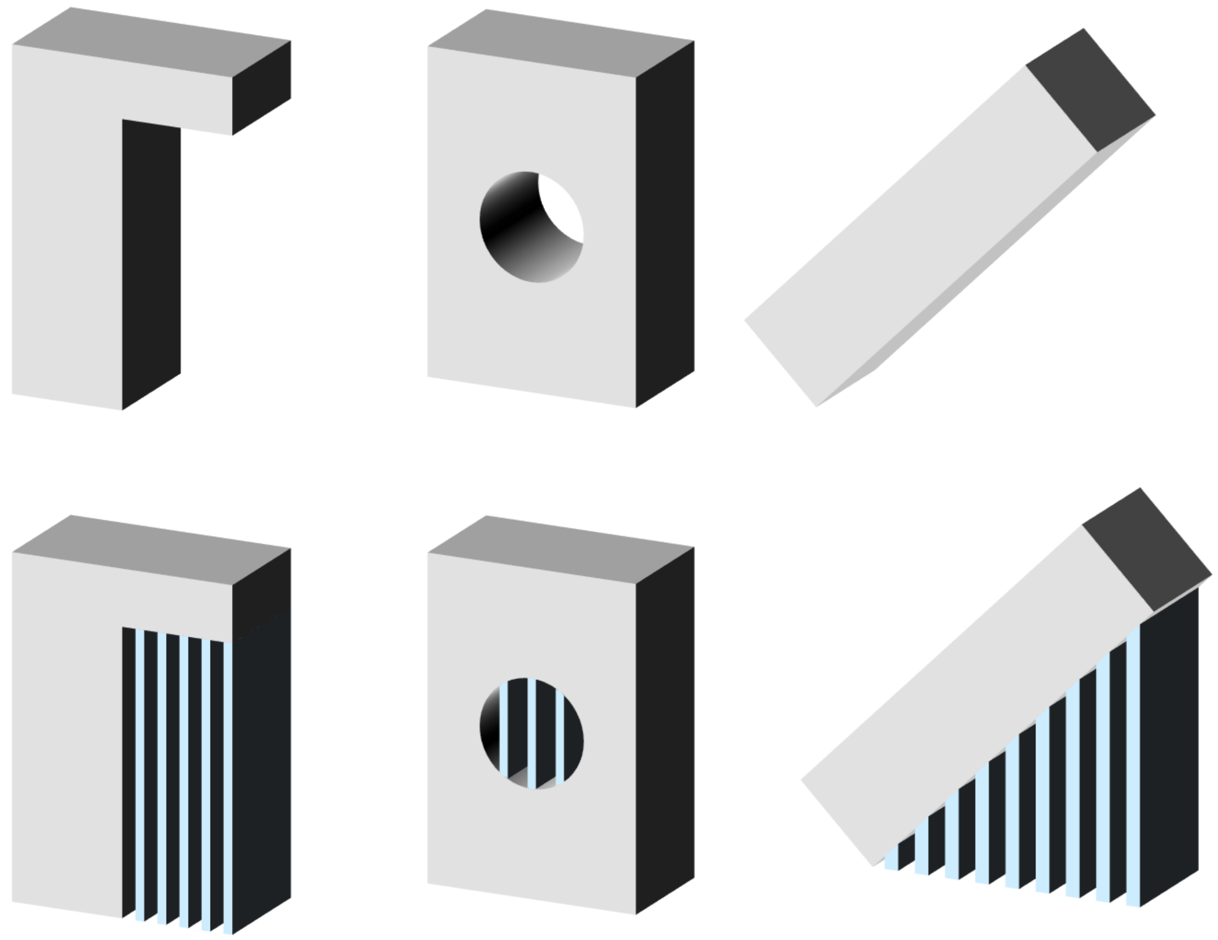
Design for AM

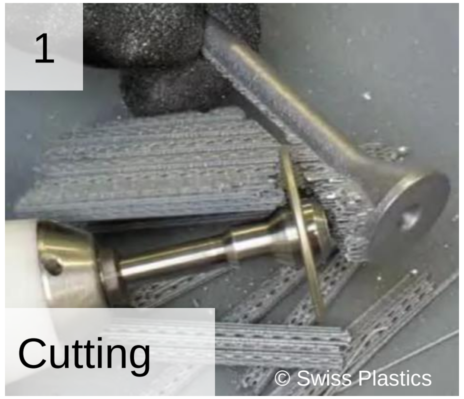
Overcoming Processability Restrictions – Part Orientation



Design for AM

Handling Overhanging Surfaces using Support Structures





Algorithmic Design for Additive Manufacturing
Generative Design

How?

Conventional design

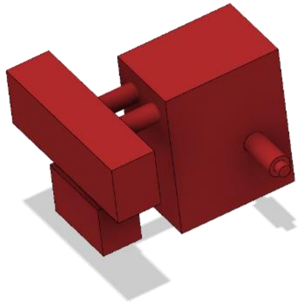
Additive design

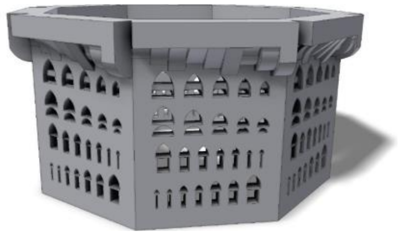
Source: RWTH DAP, e.GO

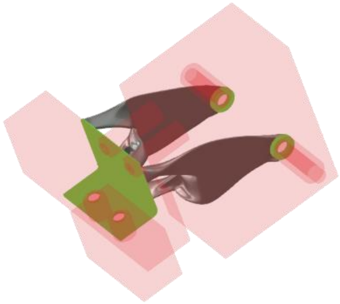
Algorithmic Design for Additive Manufacturing

Generative Design

Definition of design space → *Definition of manufacturing constraints* → *Definition of loading and boundary conditions* → ***Algorithmic shape optimization*** → *Evaluation and adaption of generated options by engineer*





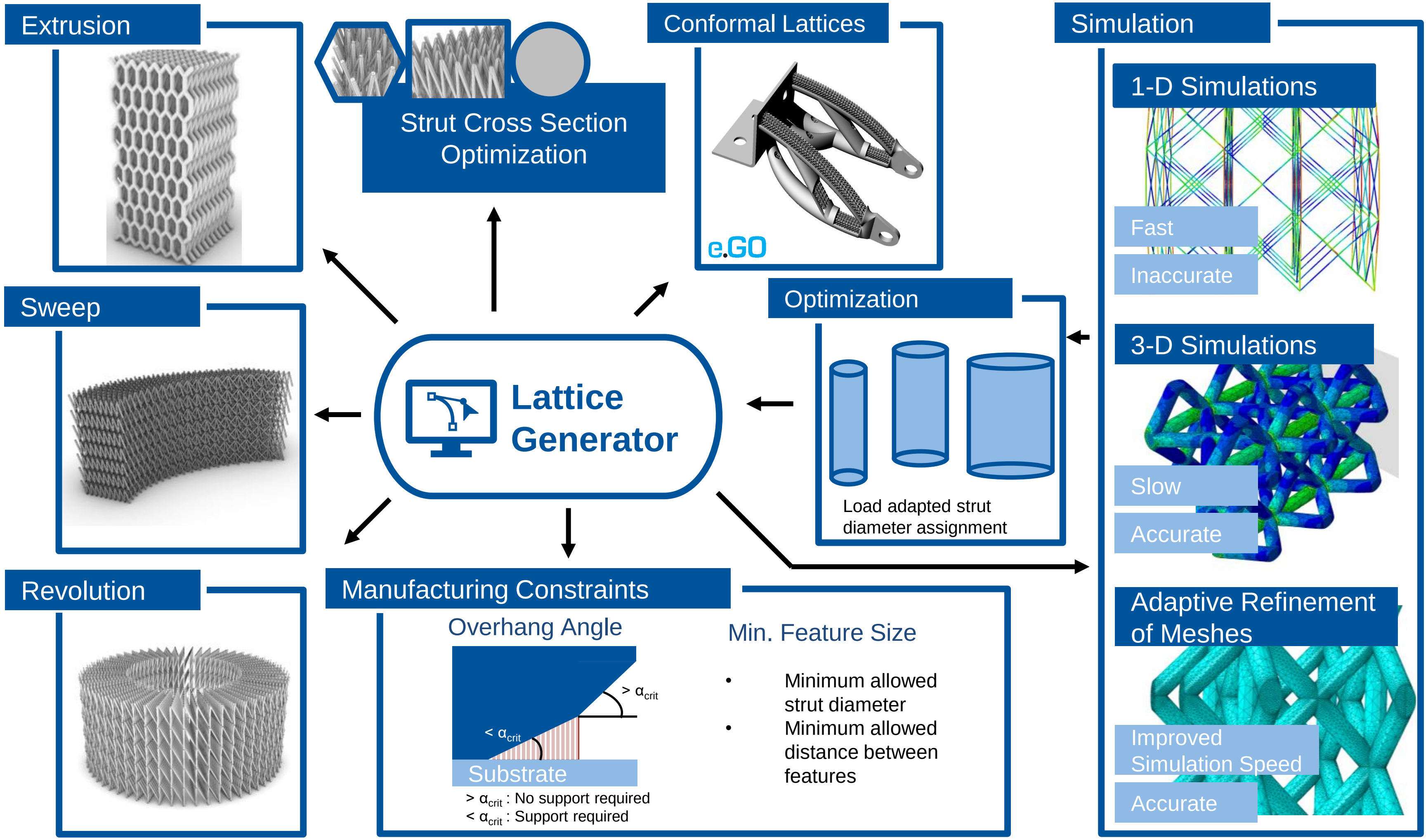


Design and process know how engineer | *Algorithmic optimization* | *Decision by engineer*

Source: RWTH DAP, e.GO

Algorithmic Design for Additive Manufacturing

Algorithmic Lattice Generation

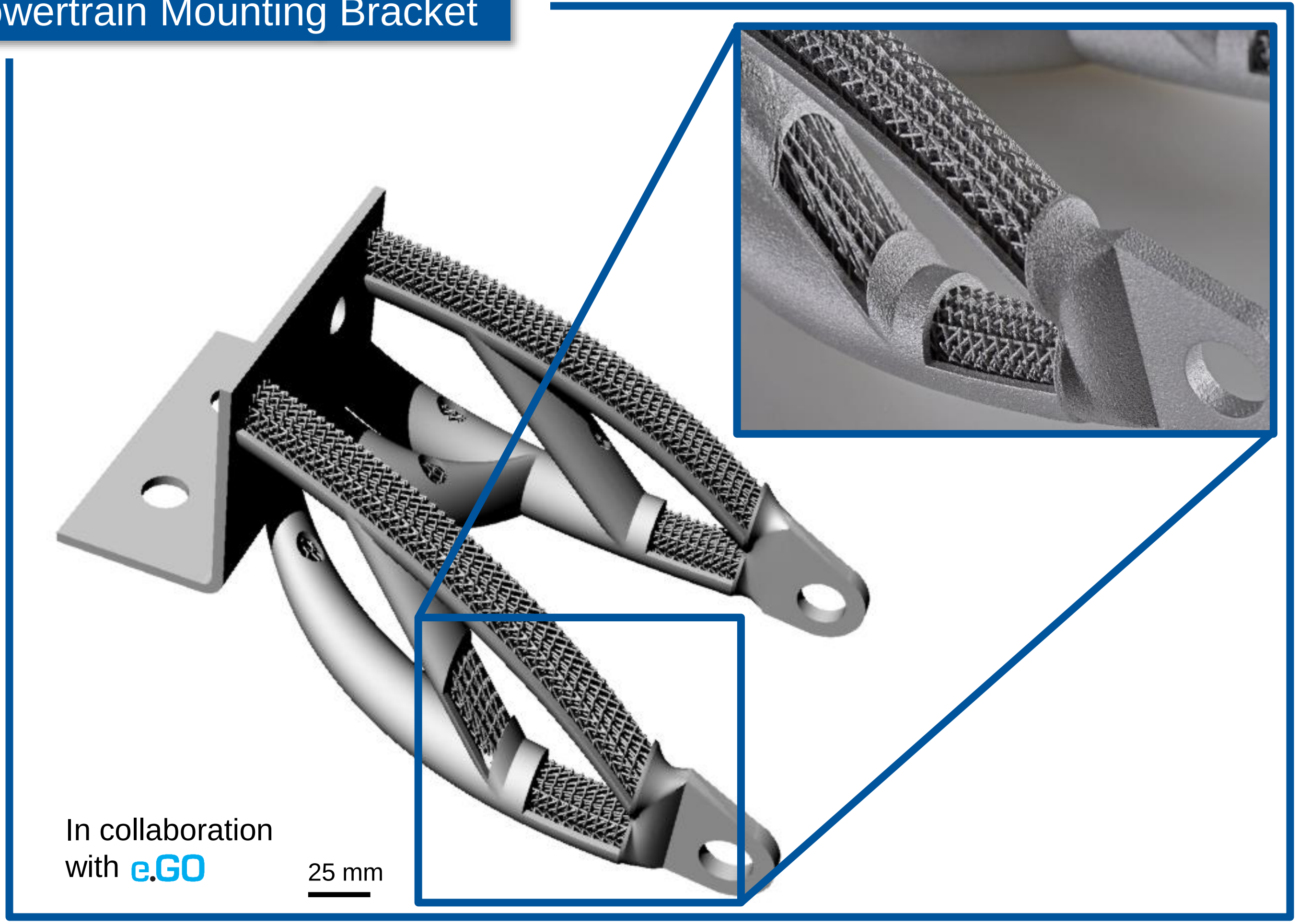


- Lattices are lightweight constructions with an excellent strength to weight ratio
- The generation of CAD-data for AM compliant lattices can be challenging
- The lattice generator enables quick adaptions in the design and respects manufacturing constraints by providing relevant algorithms

Algorithmic Design for Additive Manufacturing
Algorithmic Generation of Conformal Lattices

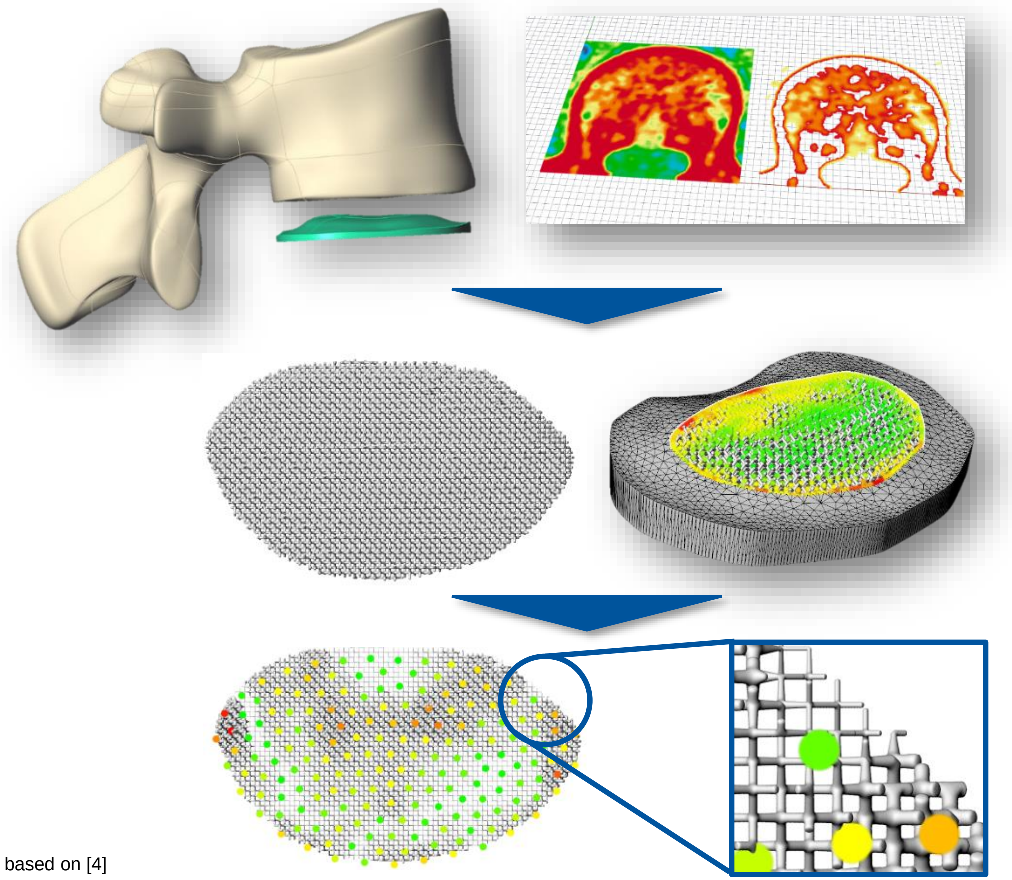
- Generation of conformal lattices for specific geometries
- Internal lattice structures enable efficient weight reduction by replacing solid material while maintaining sufficient strength
- Input for conformal lattice generation:
  - Definition of design space
  - Lattice type
  - Load and boundary conditions
  - Manufacturing constraints

Powertrain Mounting Bracket



Algorithmic Design for Additive Manufacturing
Algorithmic Generation of Load Adapted Lattices

Vertebral Body Implant



based on [4]

- Bones have locally load adapted stiffnesses to enable homogeneous stress distributions
- Using load adaptive lattice structures, implants can be adjusted to the patient's bone density
- Method:
  - Extraction of the patient's bone density using CT scans
  - Determination of strut diameters from the local stress values around each strut
  - Mapping of strut diameters to implant lattice structure

[4] Willkomm, J.; Jauer, L.; Ziegler, S. & Schleifenbaum, J.H. (2020): Development of individual medical implants with specific mechanical properties manufactured by Laser Powder Bed Fusion

Acknowledgments

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