C-Frame design optimization for selective laser melting

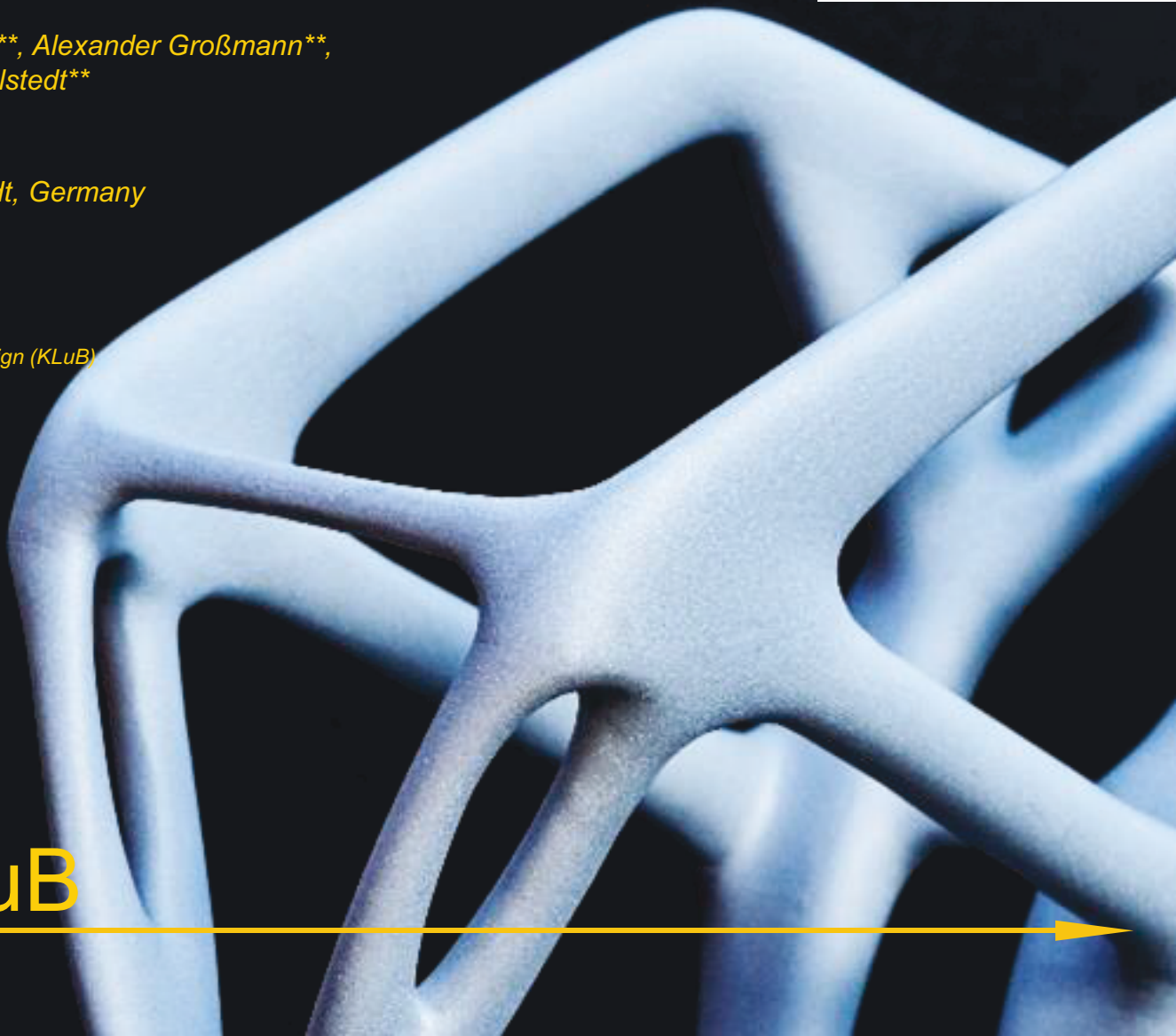
Guillaume Meyer **, Patrick Weis**, Alexander Großmann**,*
*Christof Clemen***, Christian Mittelstedt***

DLRK

30 Sept. – 02 Okt. 2019, Darmstadt, Germany

**) Corresponding author:*
guillaume.meyer@klub.tu-darmstadt.de
***) Technische Universität Darmstadt*
Institute for Lightweight Construction and Design (KLuB)
Otto-Berndt-Str. 2, 64287 Darmstadt
****) Stanley Engineered Fastening*
Max-Eyth-Str. 1, D-35394 Giessen, Germany

TECHNISCHE UNIVERSITÄT DARMSTADT



MASCHINENBAU
We engineer future KLuB

Agenda

TECHNISCHE UNIVERSITÄT DARMSTADT

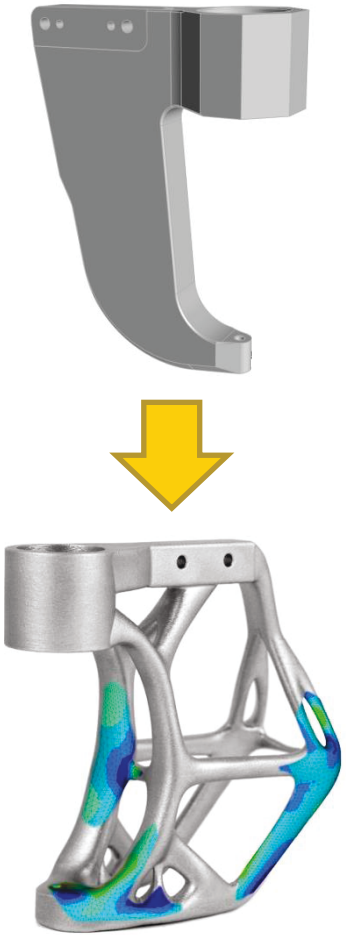
1 Introduction

2 Methodology

3 Topology Optimization

4 Design for AM

5 Evaluation



Agenda

TECHNISCHE UNIVERSITÄT DARMSTADT

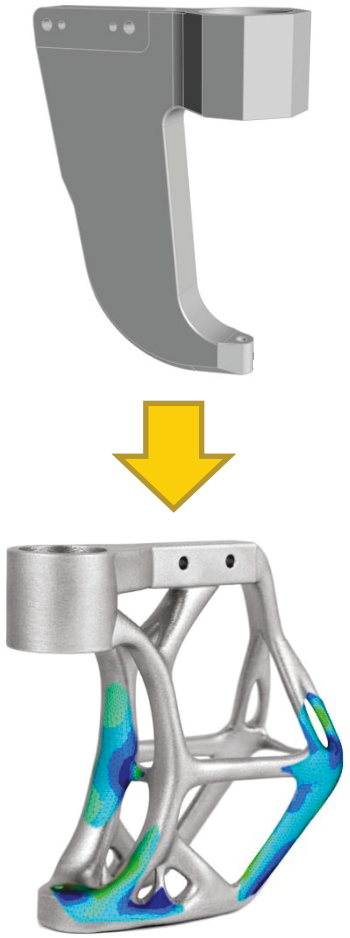
1 Introduction

2 Methodology

3 Topology Optimization

4 Design for AM

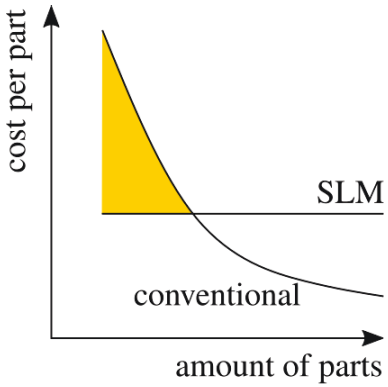
5 Evaluation

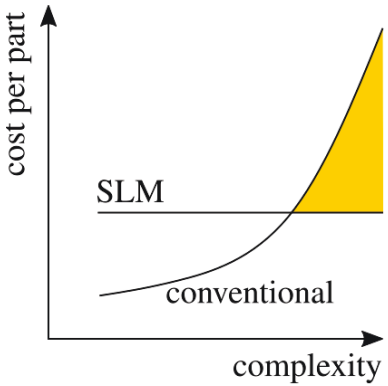


Motivation
Vision

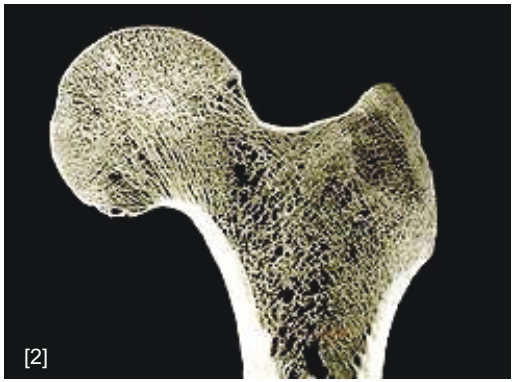
TECHNISCHE UNIVERSITÄT DARMSTADT

Why SLM* | **KLuB concept**

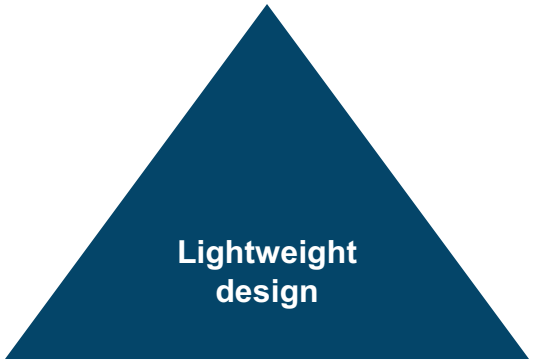




[1]



Manufacturing process
Laser driven design



Macroscale
Topology optimization

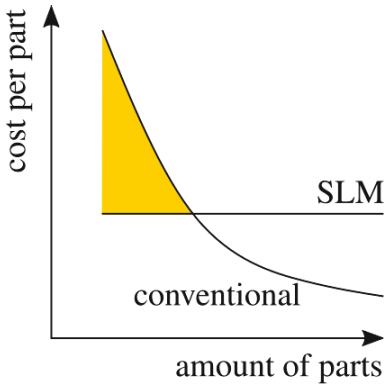
Mesoscale
Lattice structures

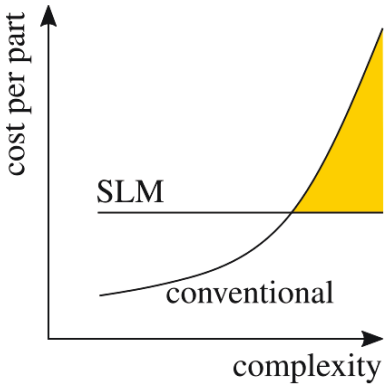
* Selective Laser Melting

Motivation
Vision

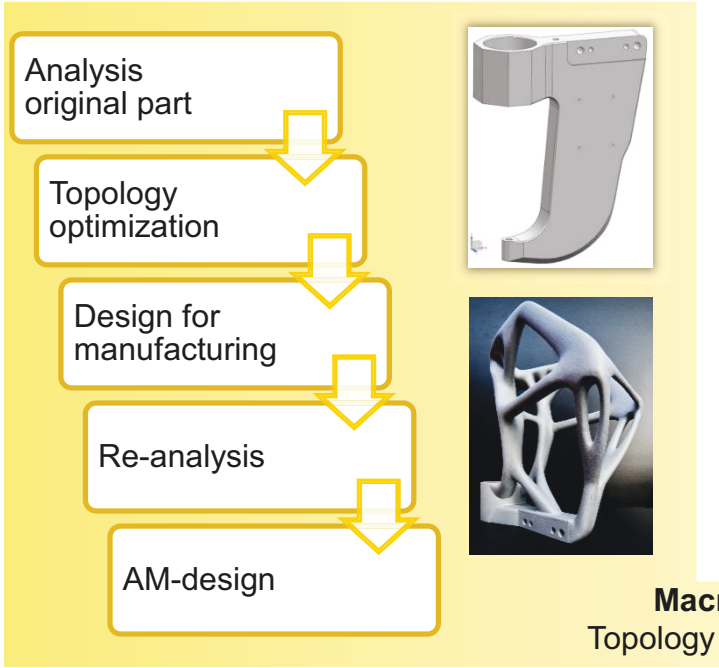
TECHNISCHE UNIVERSITÄT DARMSTADT

Why SLM → **KLuB concept**

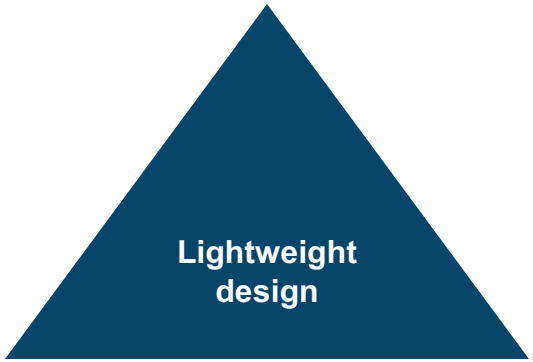




[1]



Manufacturing process
Laser driven design



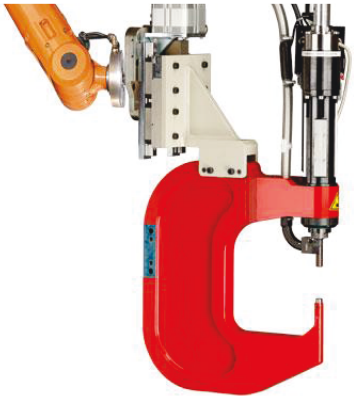
Macroscale
Topology optimization

Mesoscale
Lattice structures

- **Großmann, A., Weis, P., Clemen, C., Mittelstedt, C., *Optimization and Re-Design of a Metallic Riveting Tool for Selective Laser Melting - A Case Study*, Additive Manufacturing, accepted / in press**

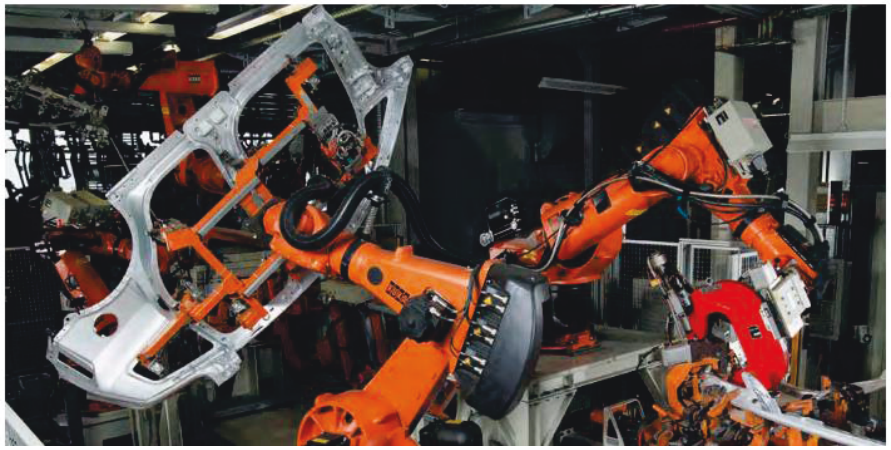
Motivation
Frame of work

TECHNISCHE UNIVERSITÄT DARMSTADT

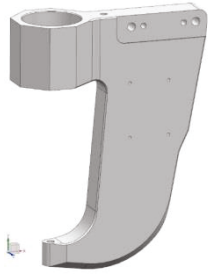


[3]

STANLEY Engineered Fastening



[3]



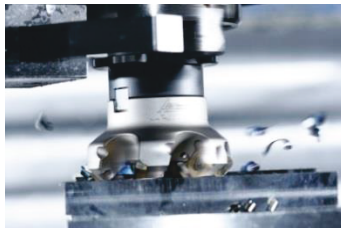
Topology optimization

Altair HyperWorks

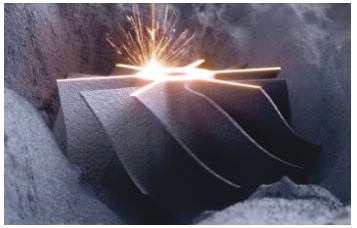
[4]

Manufacturing, performance & costs

Conventional vs. AM



[5]



[6]

Agenda

TECHNISCHE UNIVERSITÄT DARMSTADT

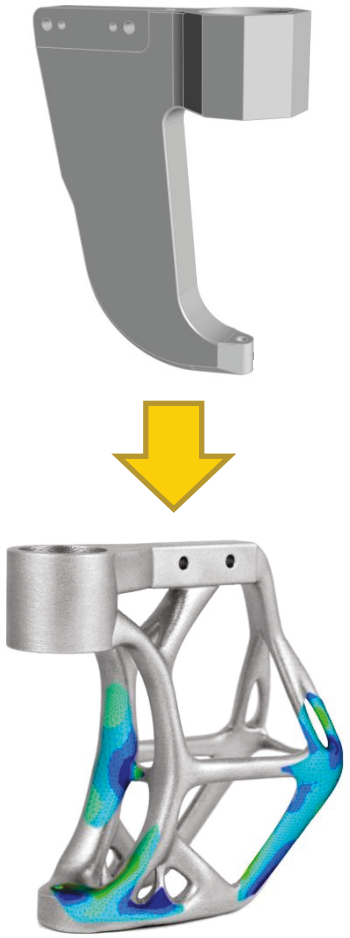
1 Introduction

2 Methodology

3 Topology Optimization

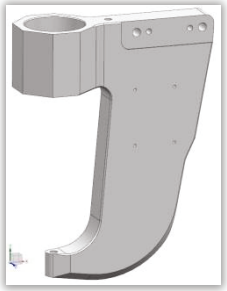
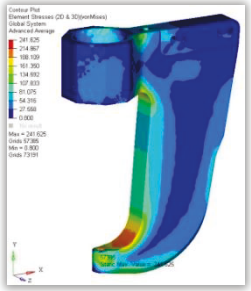
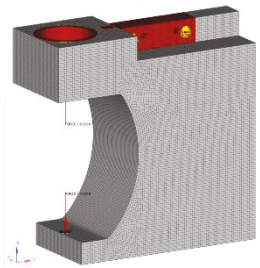
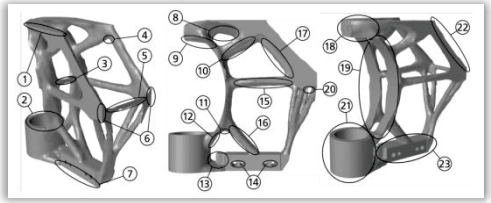
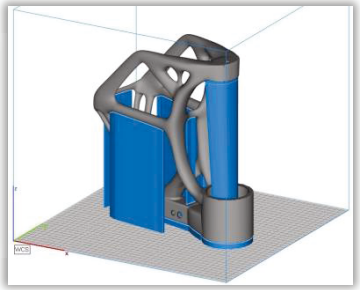
4 Design for AM

5 Evaluation

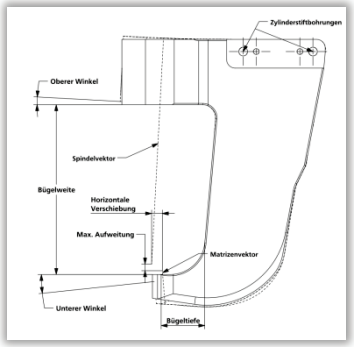


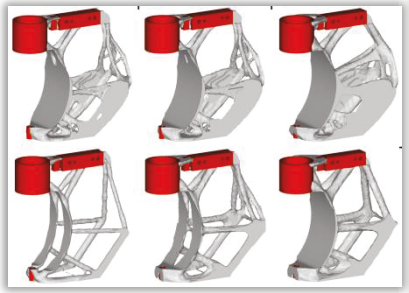
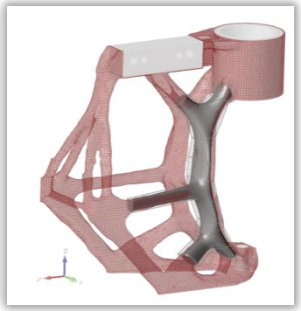
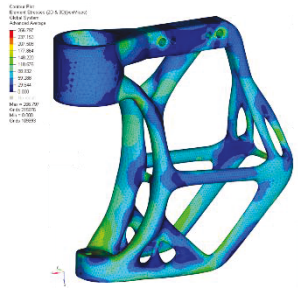
Methodology
Workflow

TECHNISCHE UNIVERSITÄT DARMSTADT

Analysis original part → **Topology optimization** → **Design for manufacturing** → **Re-analysis** → **AM-design**

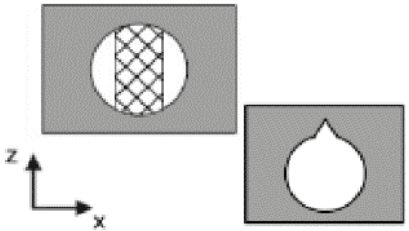


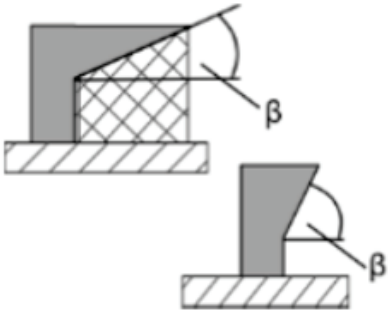

Methodology
Design rules

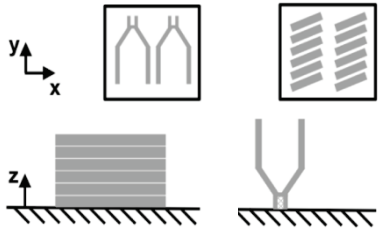
TECHNISCHE UNIVERSITÄT DARMSTADT

- **Product design**
  - EMMELMANN, KRANZ, SCHMIDT

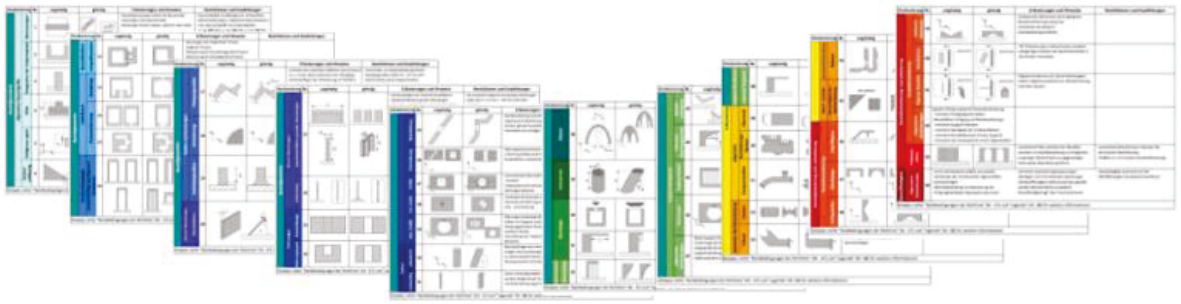


- **Manufacturing restrictions**
  - BUCHBINDER, KRANZ, KRUTH, VDI





- **Costs estimation**
  - ATZENI, GIBSON, KRANZ



[7]

Agenda

TECHNISCHE UNIVERSITÄT DARMSTADT

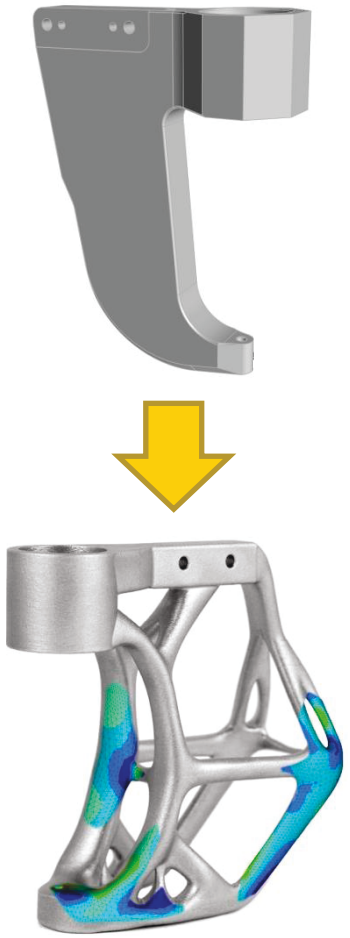
1 Introduction

2 Methodology

3 Topology Optimization

4 Design for AM

5 Evaluation



Topology optimization

Model

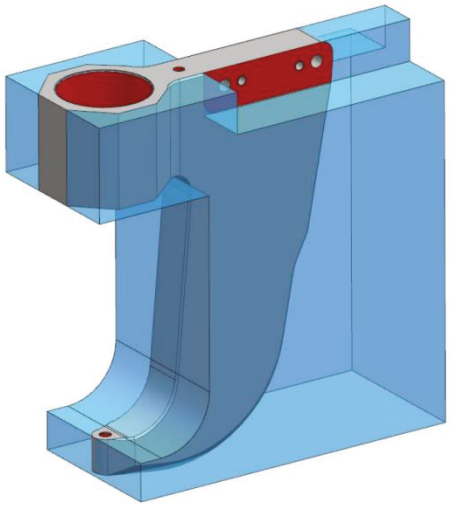
TECHNISCHE UNIVERSITÄT DARMSTADT

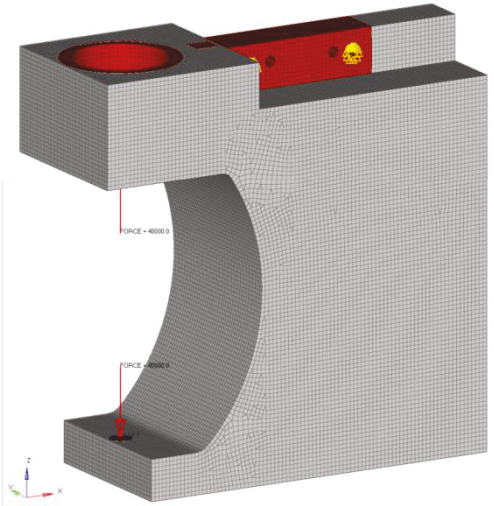
Optimization goal
- Minimize stresses

Parameter variation
- Design space
- Volume fraction
- Element dimension
- Manufacturing restrictions

2 pools
- Conventional
- AM design

➔ 24 Solutions



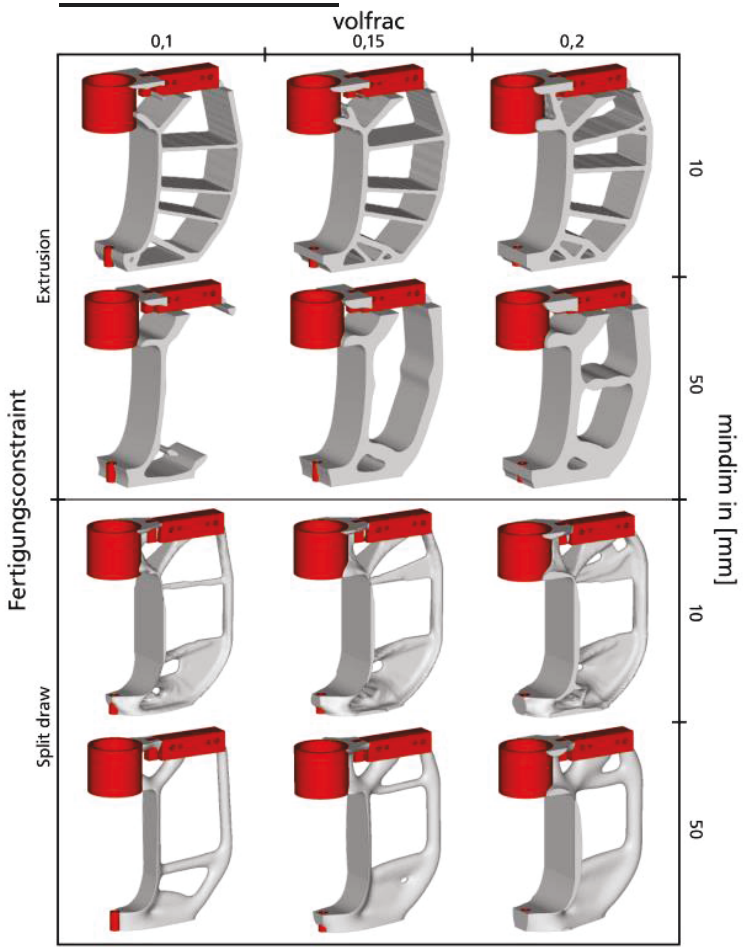


Topology optimization

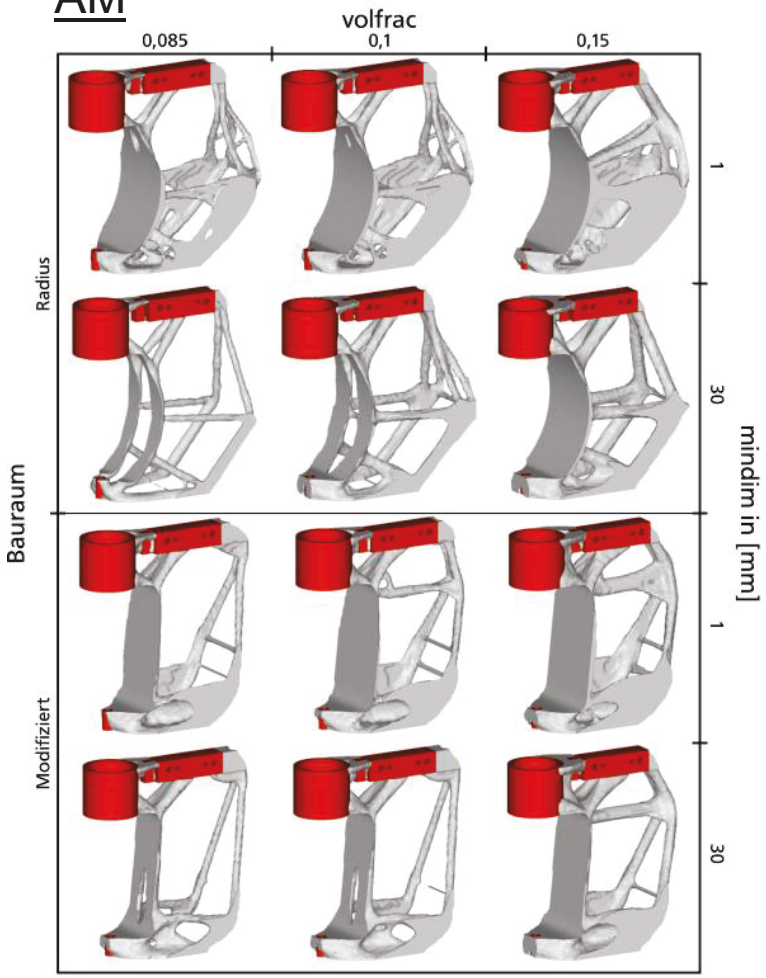
Result pool

TECHNISCHE UNIVERSITÄT DARMSTADT

Conventional



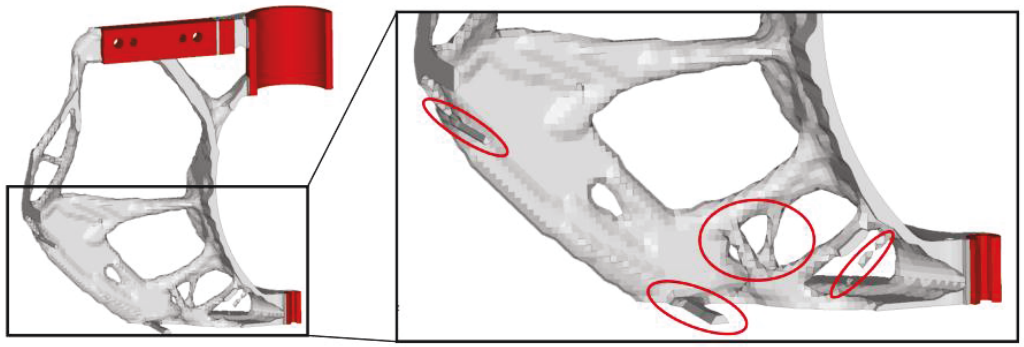
AM



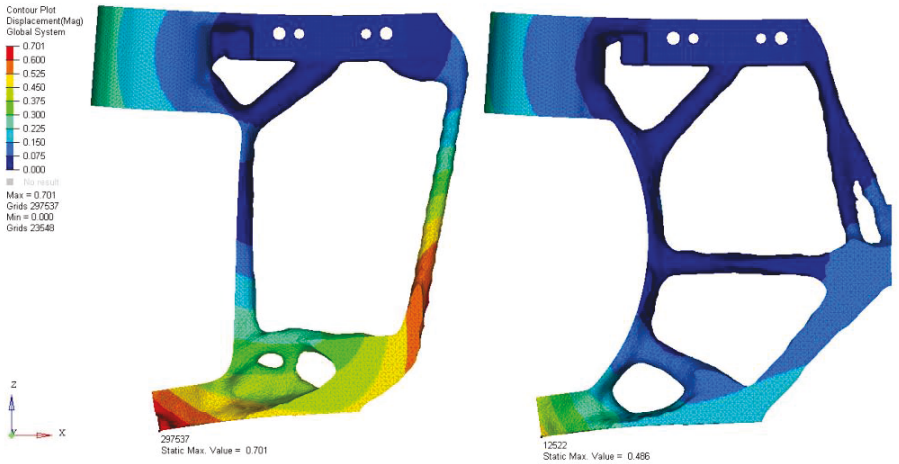
Topology optimization
Selection criteria

TECHNISCHE UNIVERSITÄT DARMSTADT

- Design
  - Thin walled structures
  - Material aggregation



- Performance
  - Load distribution
  - Displacement

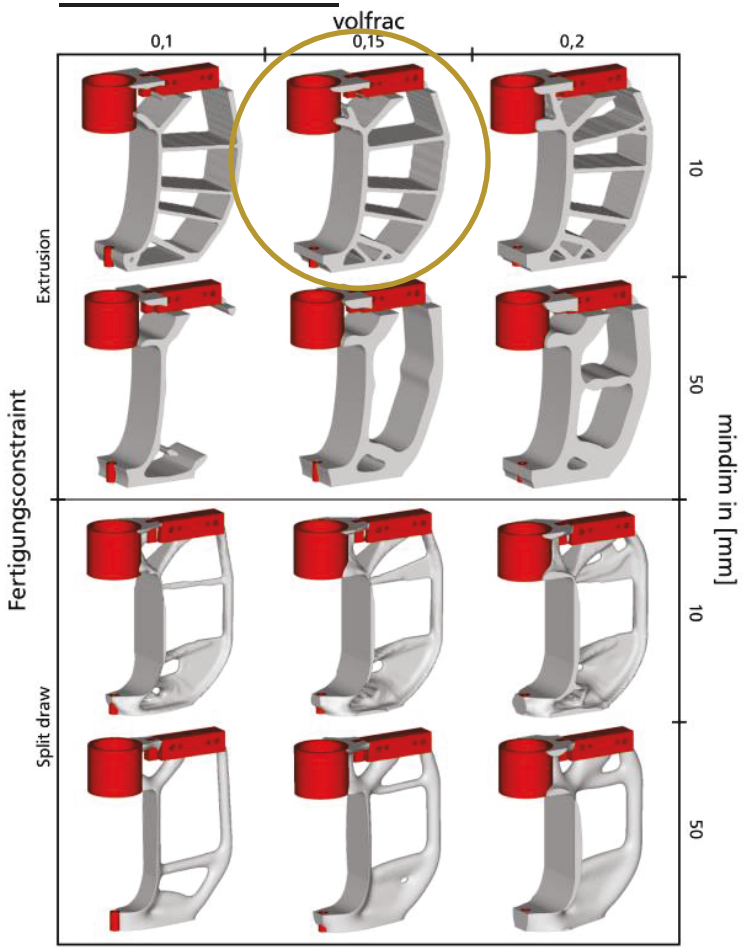


Topology optimization

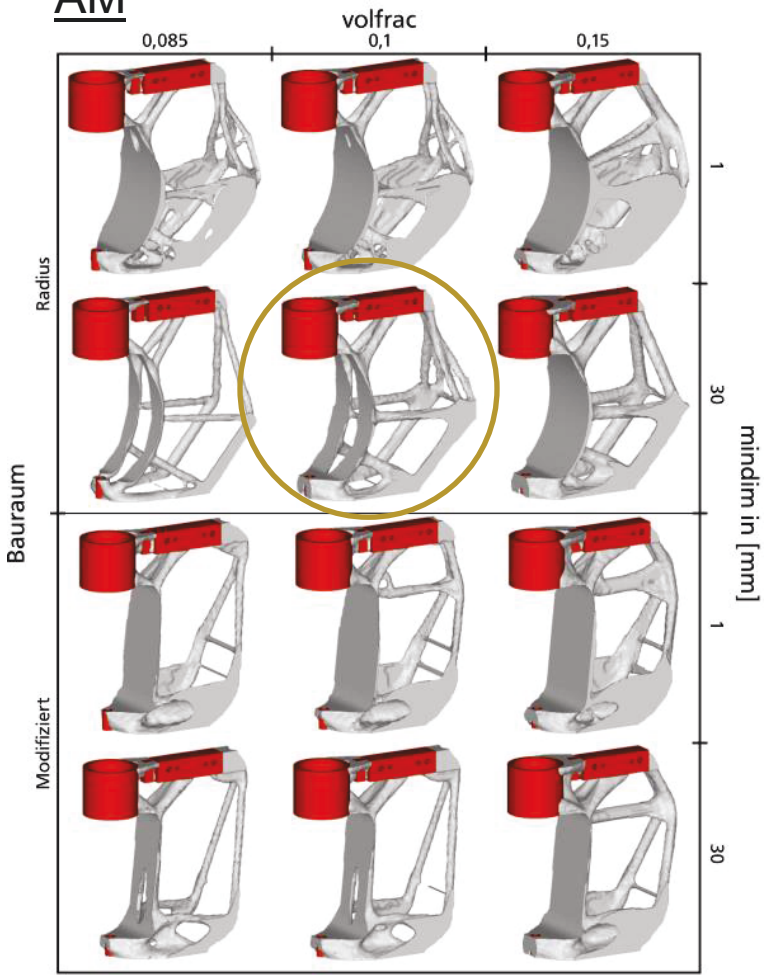
Chosen design

TECHNISCHE UNIVERSITÄT DARMSTADT

Conventional



AM



Agenda

TECHNISCHE UNIVERSITÄT DARMSTADT

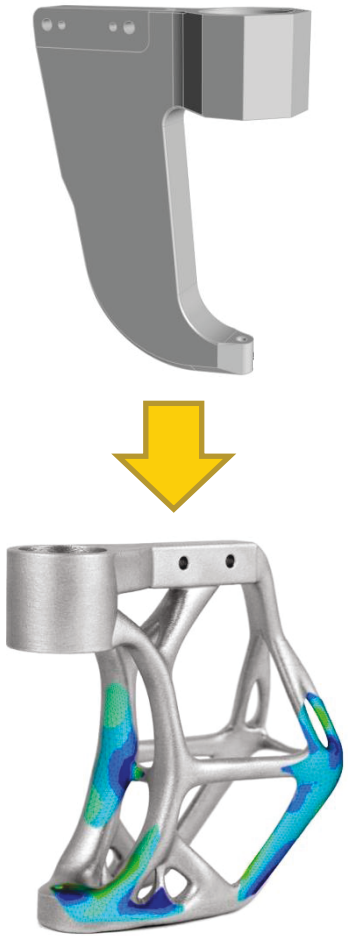
1 Introduction

2 Methodology

3 Topology Optimization

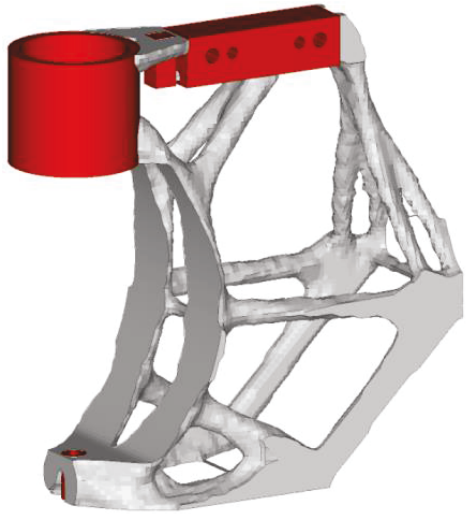
4 Design for AM

5 Evaluation



Design for AM
Principle

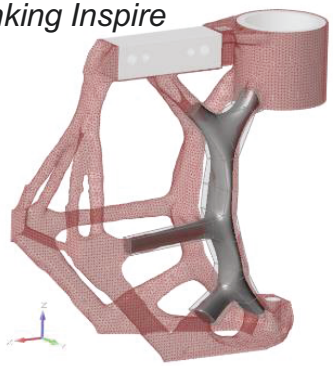
TECHNISCHE UNIVERSITÄT DARMSTADT



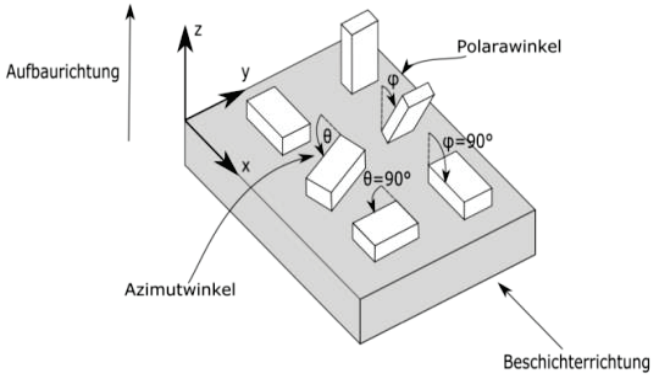
Template:
Optimization solution

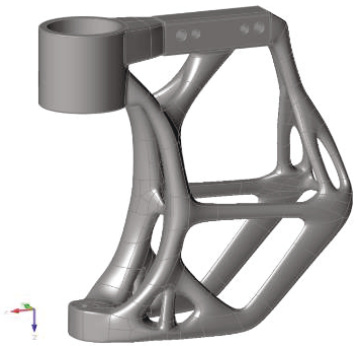
Re-design:
Technical, economic

SolidThinking Inspire



Design for manufacturing

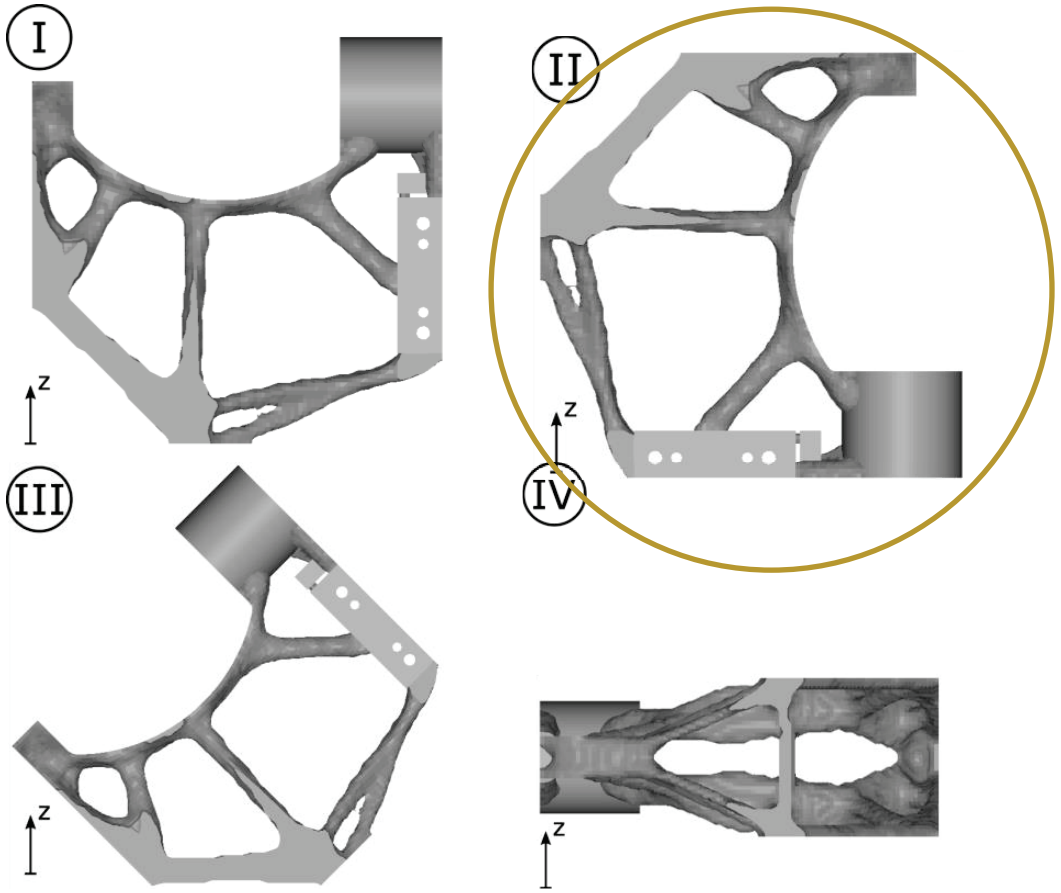




Design for AM
Build strategy

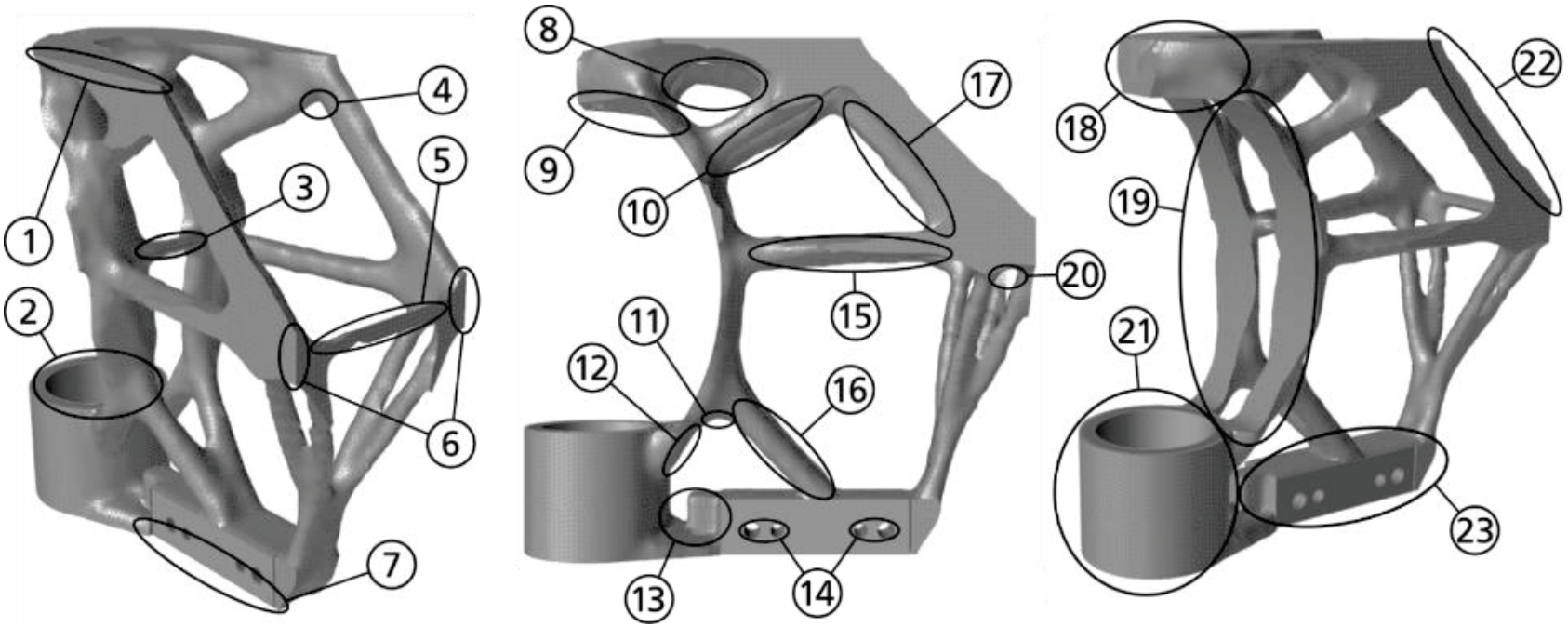
TECHNISCHE UNIVERSITÄT DARMSTADT

- Build height
- Downskin areas
- Anisotropy
- Thermal deformations
- Support volume
- Post processing effort



Design for AM

Critical areas for re-design

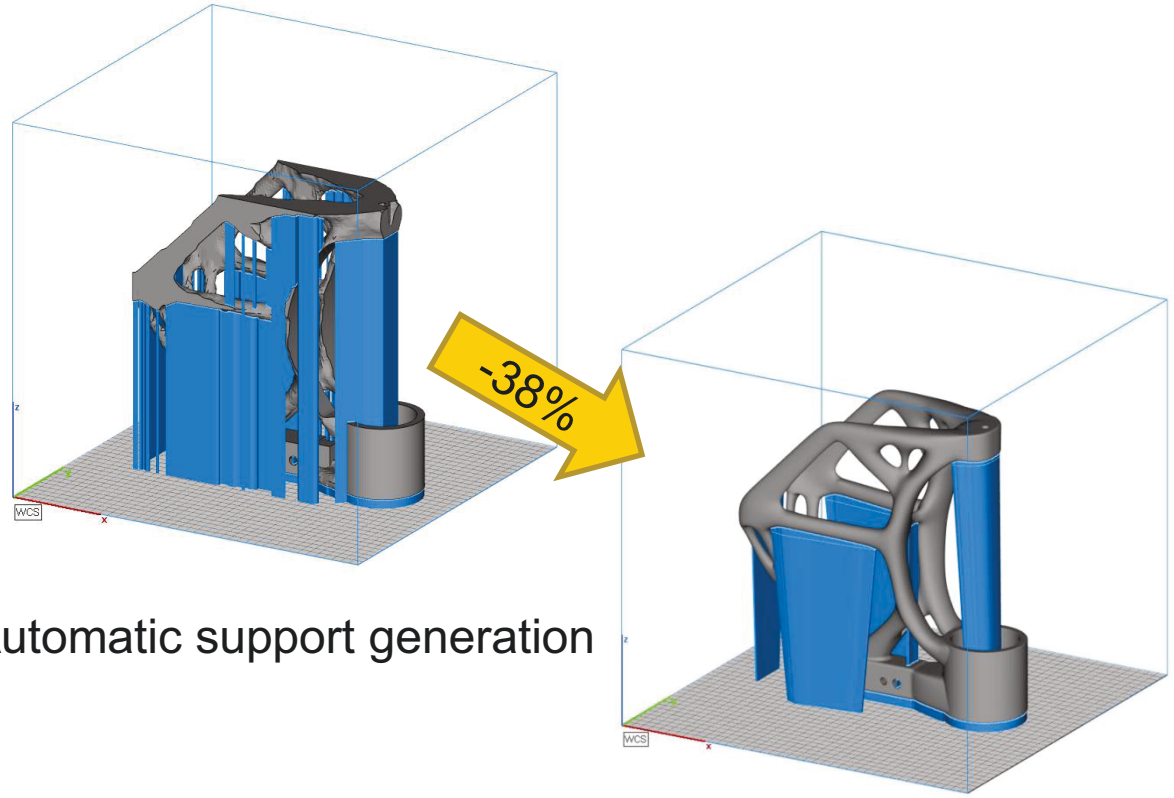


- Sharp edged transitions
- Horizontal struts
- Effective diameter

- Critical downskin angle
- Functional surfaces
- Horizontal bores
- Material accumulations

Design for AM
Manufacturing

TECHNISCHE UNIVERSITÄT DARMSTADT



Automatic support generation

Reworked support

Manufactured part

Agenda

TECHNISCHE UNIVERSITÄT DARMSTADT

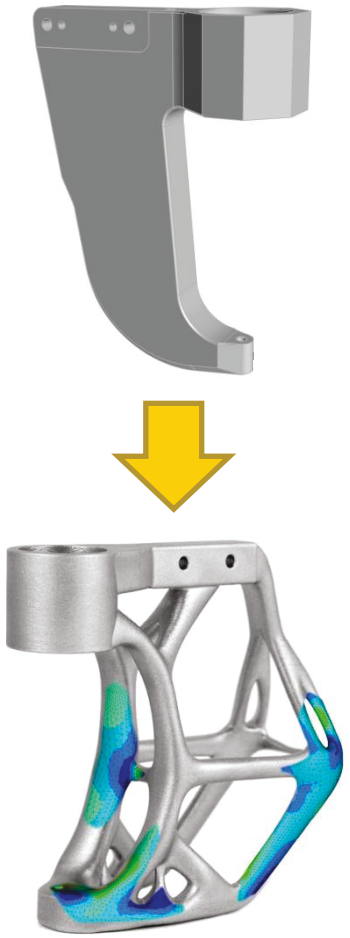
1 Introduction

2 Methodology

3 Topology Optimization

4 Design for AM

5 Evaluation

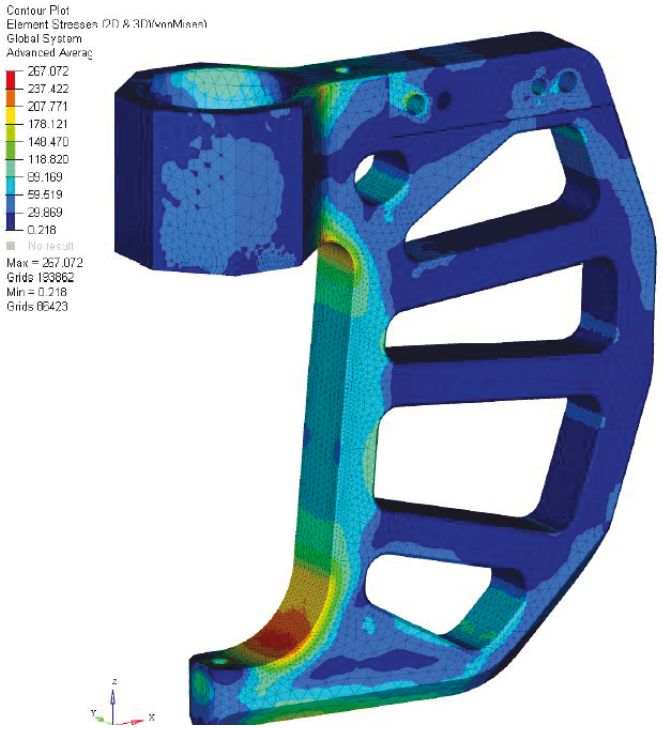


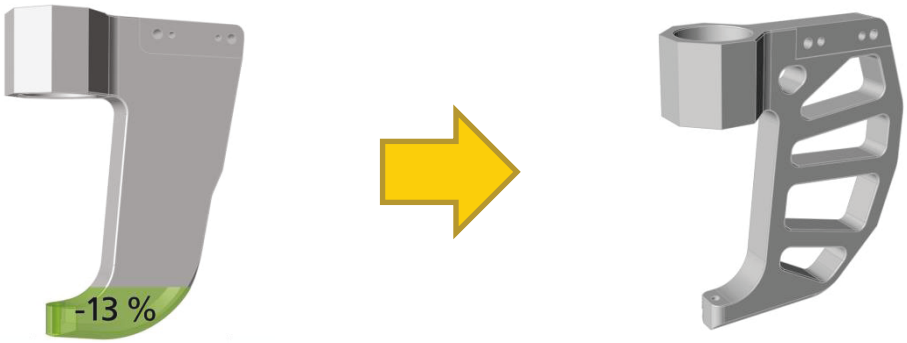
Evaluation

Milling design solution

TECHNISCHE UNIVERSITÄT DARMSTADT

- Final design for 316L
- All requirements fulfilled
  - max. stress VON MISES 267 N/mm²
  - max. displacement 0,35 mm
  - bend angle 0,13°
- Weight about 13% reduced
  - Down to 9,3 kg
- Estimated cost: 850 €

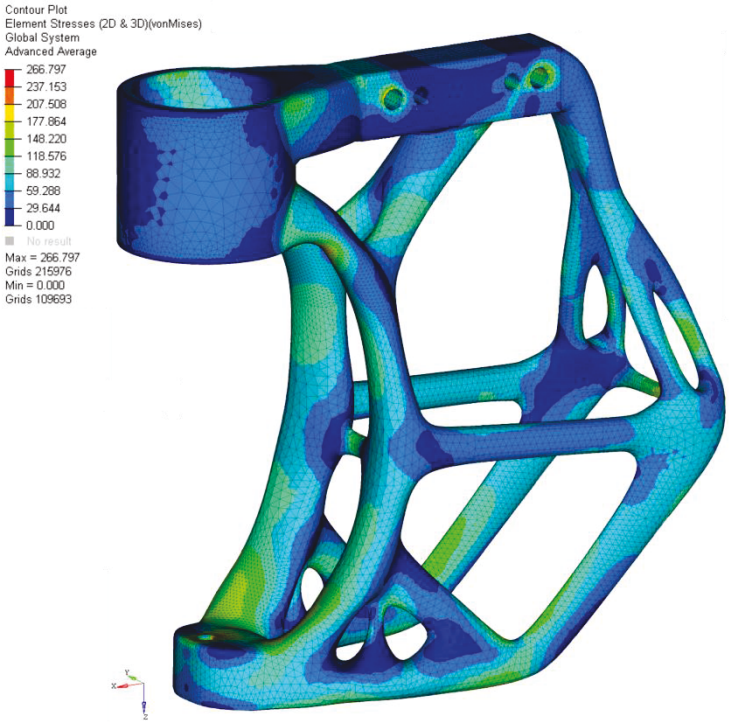


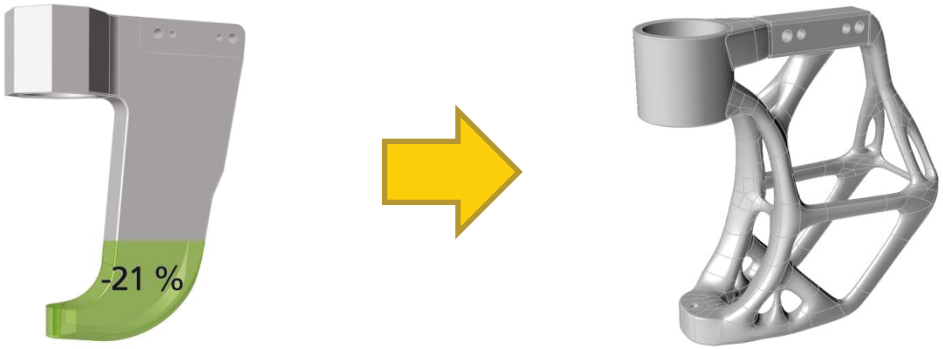


Evaluation
AM design solution

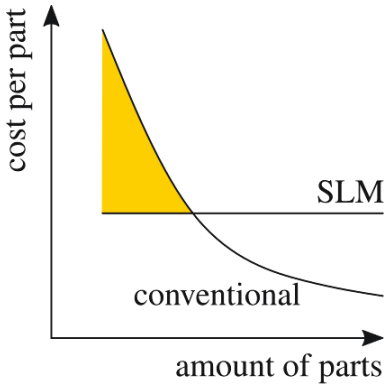
TECHNISCHE UNIVERSITÄT DARMSTADT

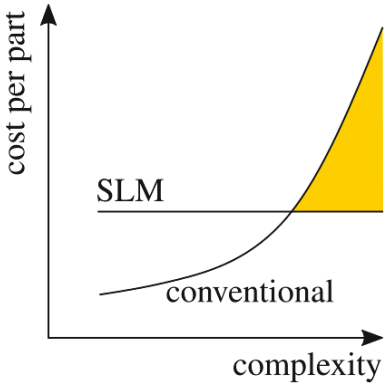
- Final design for 316L
- All requirements fulfilled
  - max. stress VON MISES 267 N/mm²
  - max. displacement 0,48 mm
  - bend angle 0,15°
- Weight about 21% reduced
  - Down to 8,5 kg
- Estimated cost: 1999 €





Evaluation
Comparison



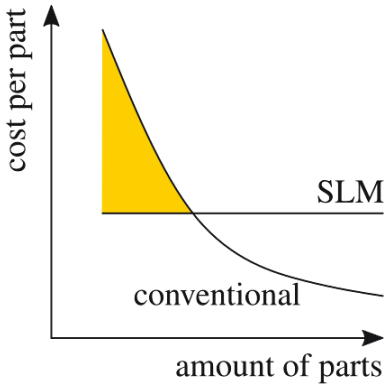


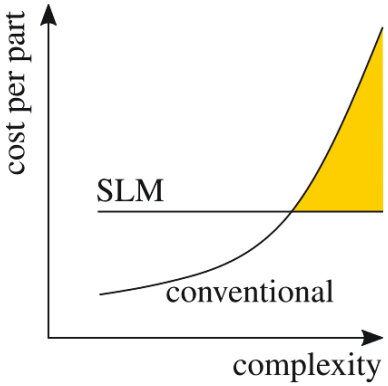
[1]

	Original part	Milling solution	AM solution
			
Weight	10.7kg	9.3kg	8.5kg
Material	DIN 1.2738	DIN 1.2738	316L
Costs	756.99€	846.09€	1998.75€
Manufact. time	3.5h	4h	49h
Max. disp.	0.39mm	0.35mm	0.48mm
Max. equiv. stress	300.1MPa	267.1MPa	266.8MPa
Scrap material	41.7kg	49kg	<1kg
Frame depth	50mm	50mm	55mm

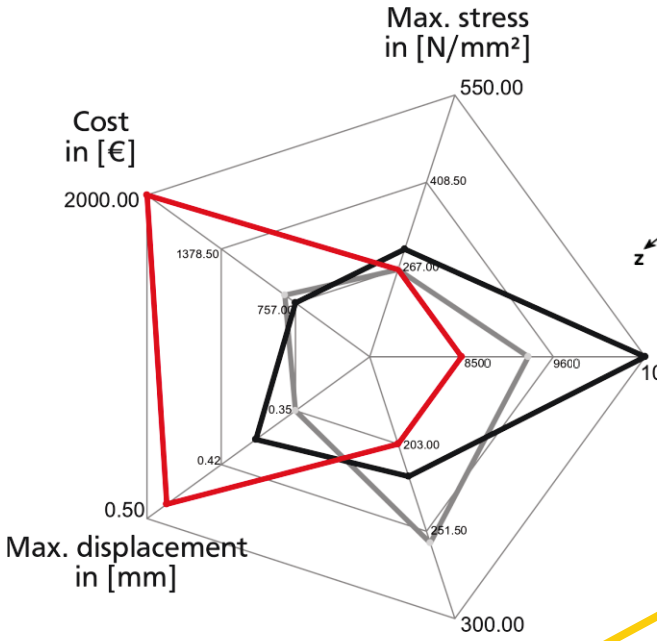
Evaluation

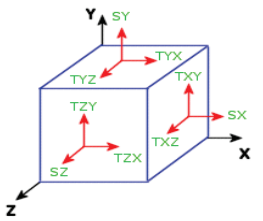
Comparison

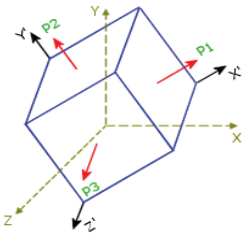


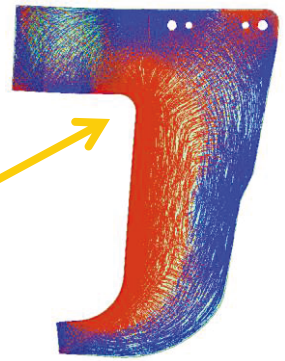


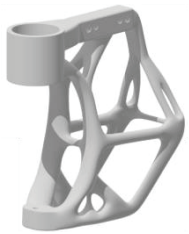
[1]







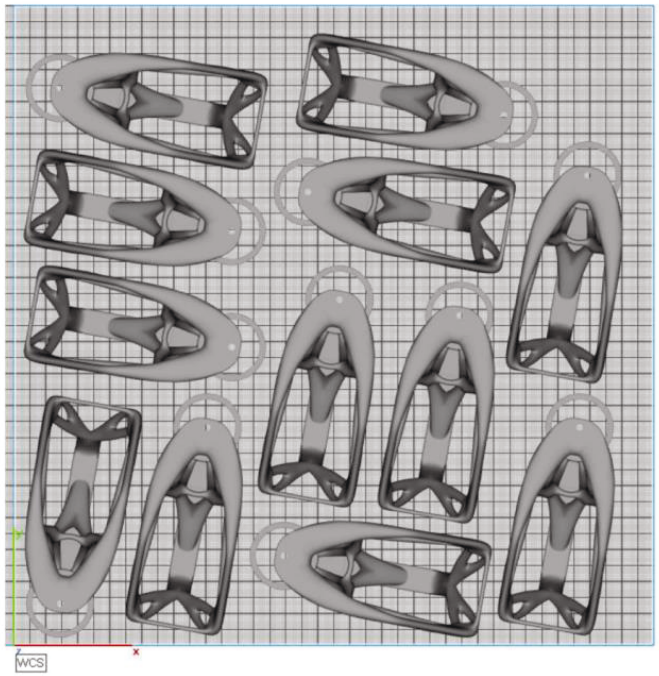




Original part Milling solution AM-solution

Evaluation

Cost scenario for serial production of the AM part



Higher part number in build chamber for scaled C-clamp

- Cost prediction for 2023
  - ↗ build rates
  - ↗ machine cost
  - ↘ material cost
  - ↘ post-processing effort

  1255 €

- Scaled C-clamp (50%)
  - ↘ part height
  - ↗ number of parts per job

  258 €

C-Frame design optimization for selective laser melting

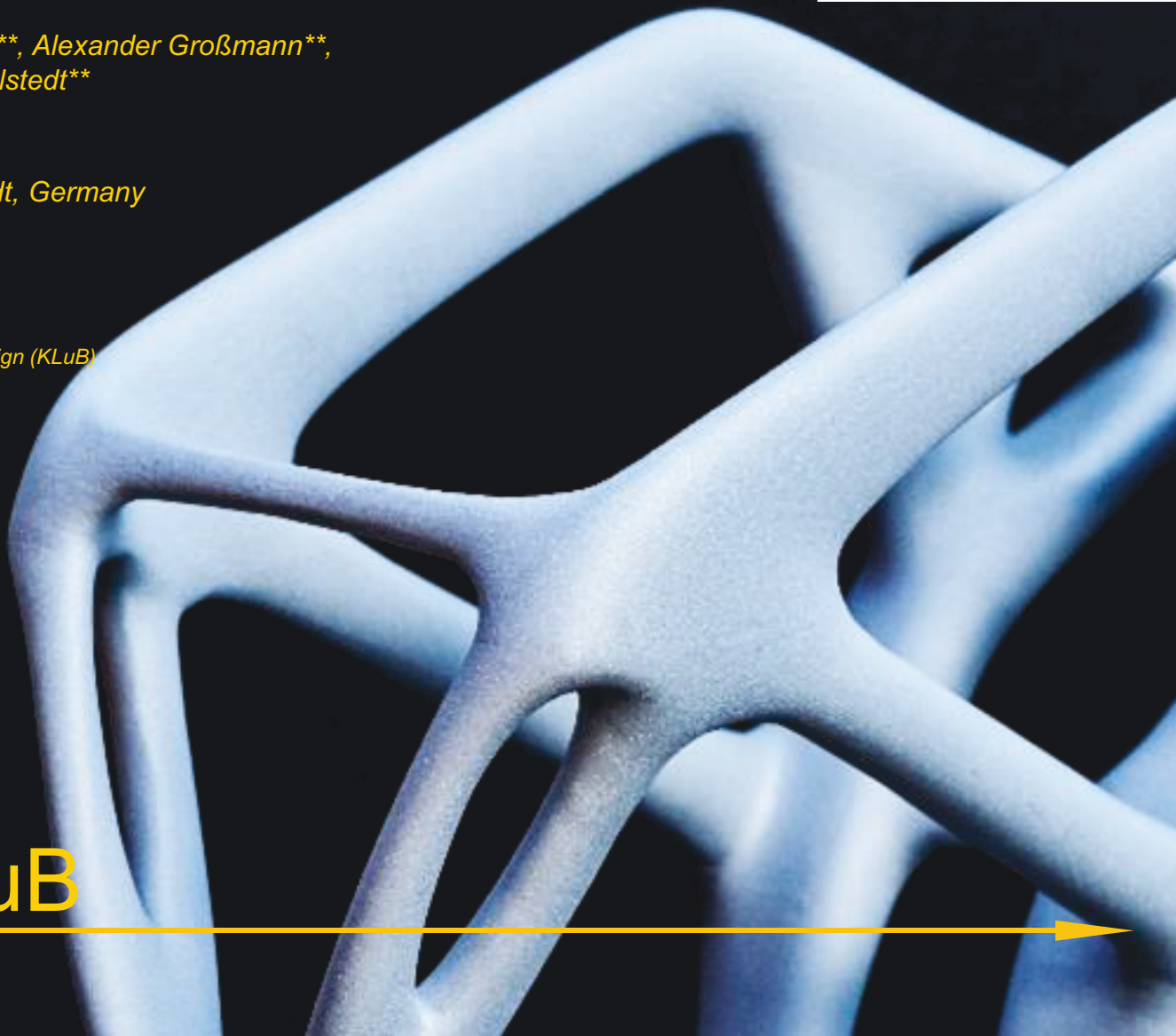
Guillaume Meyer **, Patrick Weis**, Alexander Großmann**,*
*Christof Clemen***, Christian Mittelstedt***

DLRK

30 Sept. – 02 Okt. 2019, Darmstadt, Germany

**) Corresponding author:*
guillaume.meyer@klub.tu-darmstadt.de
***) Technische Universität Darmstadt*
Institute for Lightweight Construction and Design (KLuB)
Otto-Berndt-Str. 2, 64287 Darmstadt
****) Stanley Engineered Fastening*
Max-Eyth-Str. 1, D-35394 Giessen, Germany

TECHNISCHE UNIVERSITÄT DARMSTADT



MASCHINENBAU
We engineer future KLuB

A. Literature

TECHNISCHE UNIVERSITÄT DARMSTADT

[1] Acc. to Richard et al., Additive Fertigung von Bauteilen und Strukturen, Springer-Verlag Wiesbaden, 2017.

[2] http://www.seilnacht.com/Minerale/Seeigel.htm

[3] STANLEY Engineered Fastening: Mechanisches Fügen von TUCKER. Stanznieten und Clinchen in einem System. Broschüre (2018).

[4] ALTAIR HyperWorks: Logo Altair HyperWorks.
URL: https://resources.altair.com/altairadmin/images/resource_library/graphics-en-US/Altair_HyperWorks_RGB_vertical.png
Stand: 01.08.2018

[5] TARGA TECH AG: Fräsen.
URL: http://targa-tech.ch/fraesen/
Stand: 01.08.2018

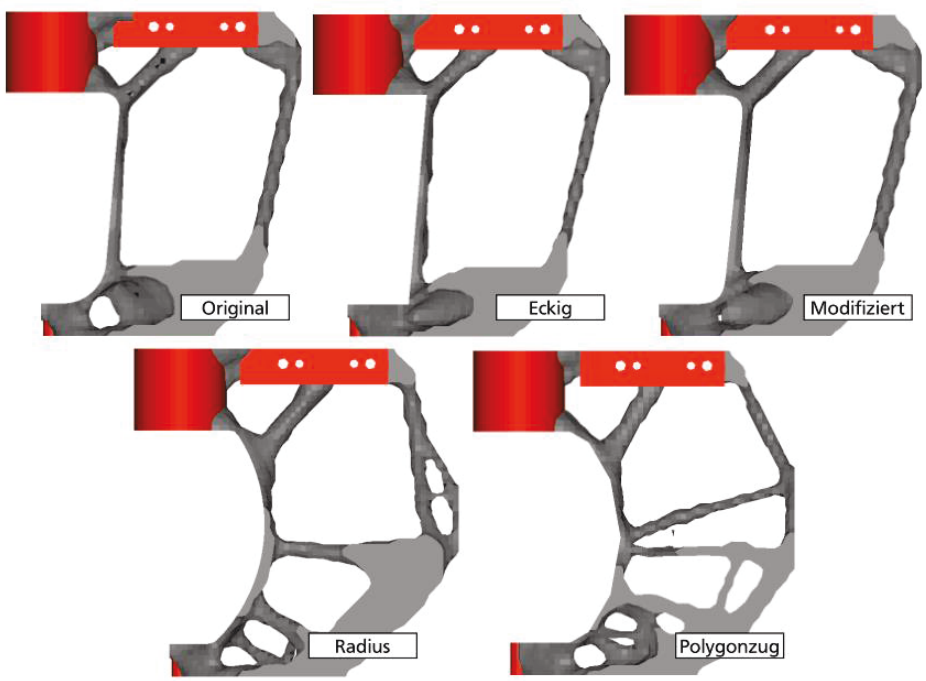
[6] DMG MORI: New method of manufacturing using powder bed: Additive Manufacturing with Selective Laser Melting.
URL: https://www.youtube.com/watch?v=te9OaSZ0kf8
Stand: 01.08.2018

[7] Kranz: Methodik und Richtlinien für die Konstruktion von laseradditiv gefertigten Leichtbaustrukturen. Springer-Verlag Vieweg, 2017.

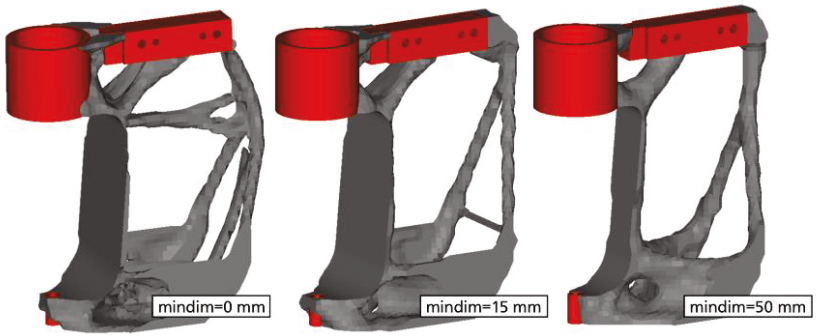
Backup

Preliminary studies

TECHNISCHE UNIVERSITÄT DARMSTADT



Design space



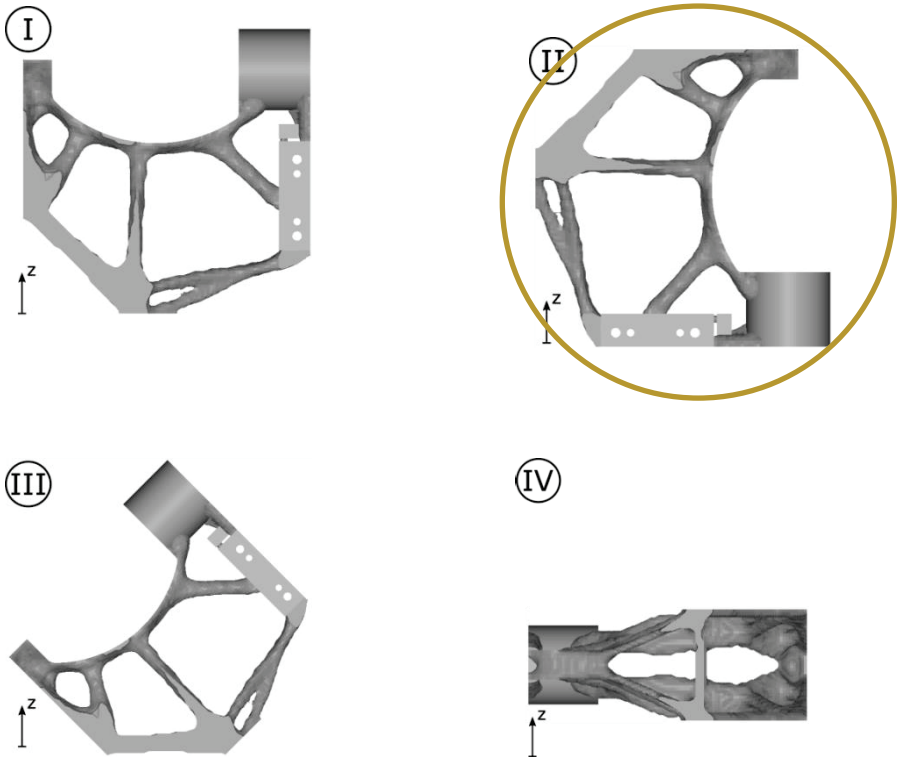
Element minimal dimension

Manufacturing constraints

Backup

Build strategy

TECHNISCHE UNIVERSITÄT DARMSTADT

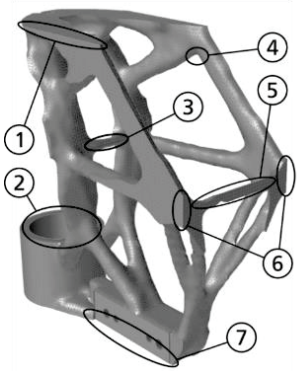


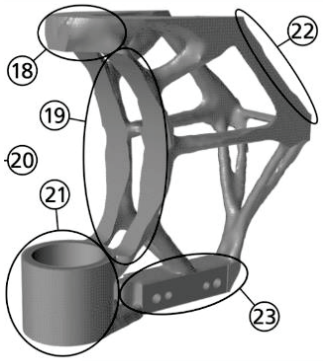
Wirtschaftliche Bewertung				
	ABS I	**ABS II**	**ABS III**	**ABS IV**
Prozesskosten				
Aufbauhöhe	1	1	0	2
Supportvolumen	1	1	2	0
Ausnutzung Bauplattform	1	1	1	1
Nachbearbeitungsaufwand				
Downskin-Flächen	1	2	0	1
Supportvolumen	1	1	2	0
Abtrennaufwand	2	1	1	0
Aufwand Supportentfernung	0	2	0	0
Technische Bewertung				
	ABS I	**ABS II**	**ABS III**	**ABS IV**
Verzug				
Horizontale Flächen	2	1	2	0
Zusammenwachsende Strukturen	0	1	1	2
Bauteilqualität				
Downskin-Flächen	1	2	0	1
Fertigungsbedingte Anisotropie	1	0	1	2
Gesamtpunkte	**11**	**13**	**10**	**9**

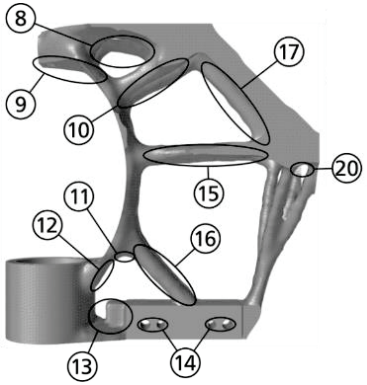
Backup

Critical areas for re-design

TECHNISCHE UNIVERSITÄT DARMSTADT





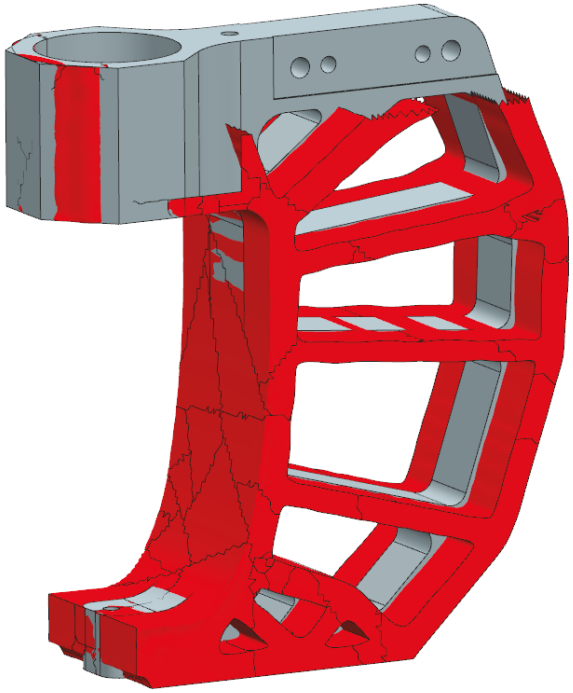


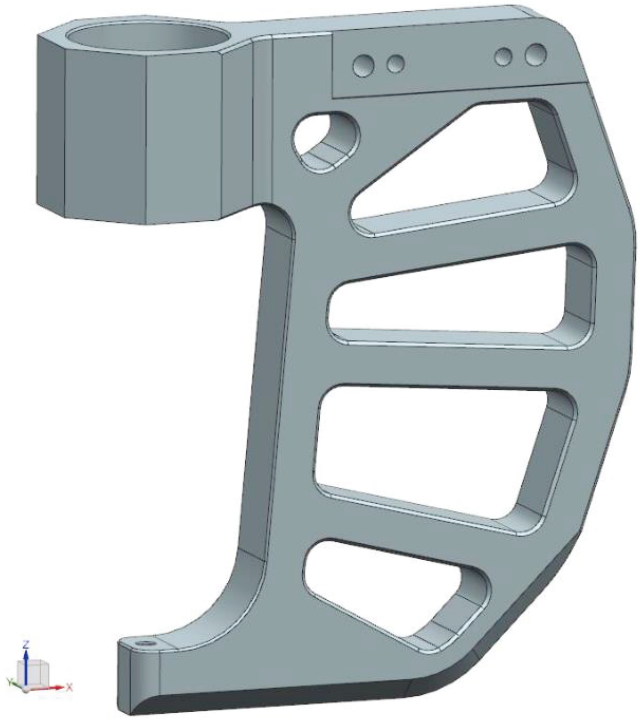
No.	Issue	Comment / Measures
1	Sharp-edged junction	Round off
2	Sharp-edged junction	Round off
3	Horizontal strut	Adjust or employ support structures
4	Maximum diameter exceeded	Decrease diameter
5	Horizontal strut	Adjust or employ support structures
6	Sharp-edged junction	Round off
7	Sharp-edged junction	Round off
8	Threshold angle not complied with	Adjust angle, employ vertical strut
9	Threshold angle not complied with, functional area	Post-processing required, employ oversize, employ support structures
10	Threshold angle not complied with	Adjust angle
11	Maximum diameter exceeded	Decrease diameter
12	Threshold angle not complied with	Adjust angle
13	Sharp-edged junction	Round off, fill gap
14	Horizontal boreholes	Employ support structures, post-processing required
15	Horizontal strut	Not adjustable, employ support structures
16	Threshold angle not complied with	Adjust angle
17	Threshold angle not complied with	Adjust angle
18	Material accumulation	Remove material
19	Critical areas	Post-processing required
20	Maximum diameter exceeded	Decrease diameter
21	Functional areas	Post-processing required, employ oversize
22	Sharp-edged junction	Round off
23	Functional areas and material accumulations	Post-processing required, employ oversize, remove material

Backup

Re-design of the milling solution

TECHNISCHE UNIVERSITÄT DARMSTADT





Backup

Structural analysis – Material data

TECHNISCHE UNIVERSITÄT DARMSTADT

Stainless steel alloy 316L

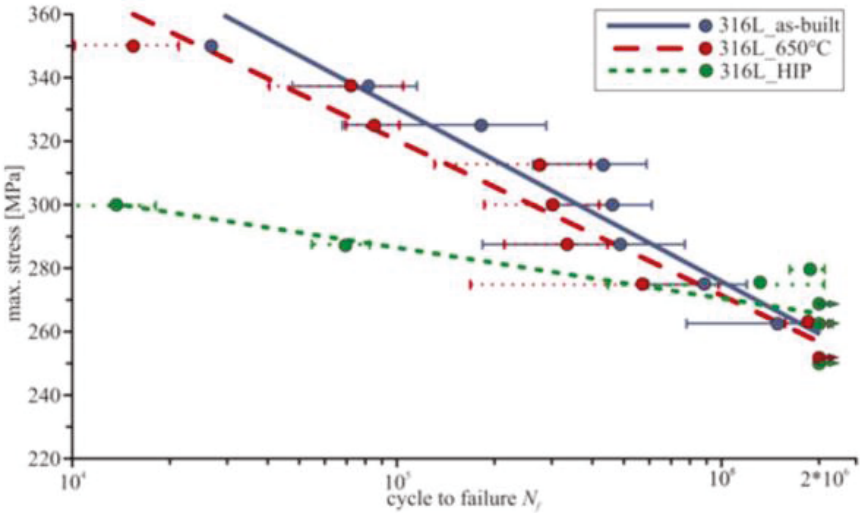
- E = 190GPa
- ν = 0.3

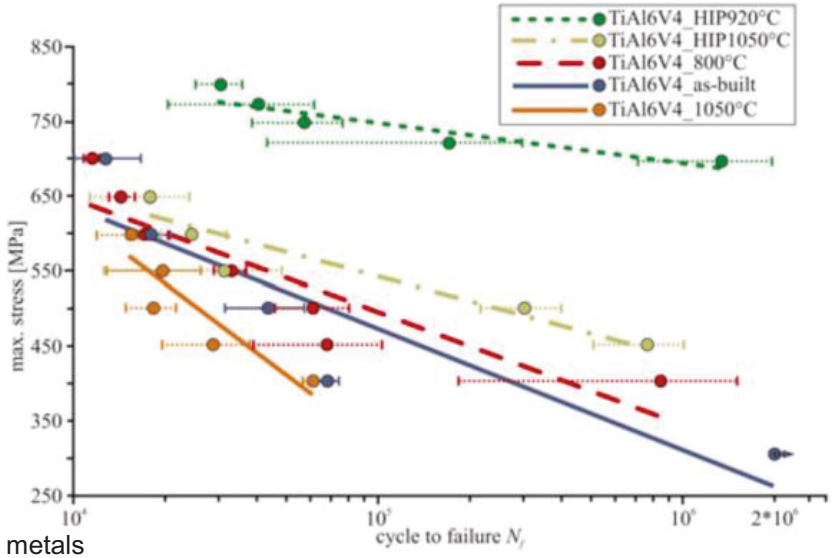
E-Modul (in GPa)	Quelle	Kommentar
184 ± 20	*SLM Solutions* [dat18a]	Ohne Nachbehandlung
$193,1 \pm 4,1$	ZHANG [ZDC13]	Ohne Nachbehandlung
$207,2 \pm 6,85$	MARBURY [Mar17]	Spannungsarmglühen
190 ± 10	*Renishaw* [dat17c]	In Aufbaurichtung, 316L-0407 (Kohlenstoffarme Legierung)
200	*Concept Laser GmbH* [dat17a]	Spannungsarmglühen

Backup

Fatigue assessment for AM parts

- **316L**
  - Post treatment not necessary
- **TiAl6V4**
  - HIP @920 °C
- **AlSi10Mg**
  - Build platform temperature 300 °C
  - Heat treatment
- **Inconel 939**
  - Post treatment not necessary



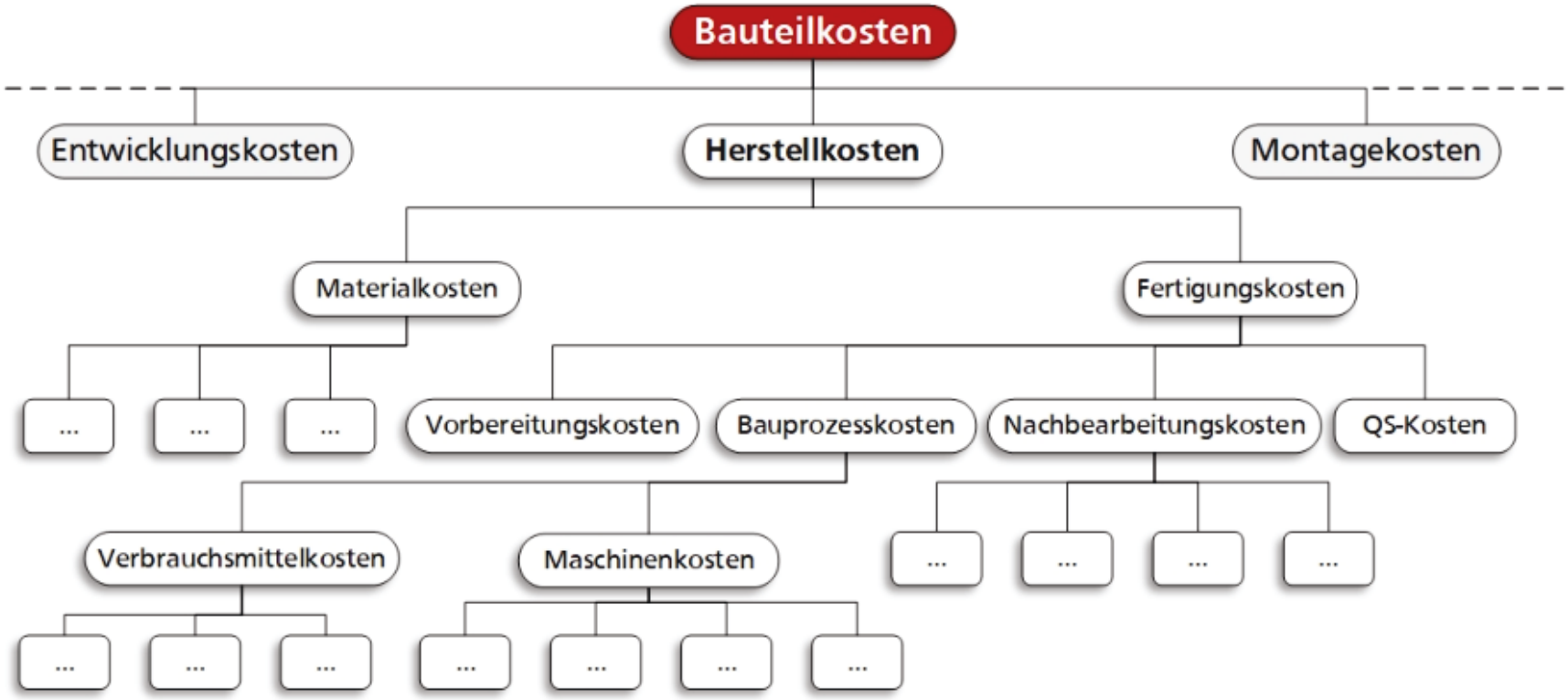


Source: LEUDERS; LAMMERS; TRÖSTER; NIENDORF: On the fatigue properties of metals manufactured by selective laser melting. In: *Materials Research Society* (2014)

Backup

Costs estimation – Principle

TECHNISCHE UNIVERSITÄT DARMSTADT



[7]

Backup

Costs estimation – Milling solution

TECHNISCHE UNIVERSITÄT DARMSTADT

Parameter	Value	Unit
Volume of half-finished part	7446112	mm^3
Density	7.83	g/cm^3
Material price	7.20	€/kg
Material costs *M*	419.78	€
Part volume *V*	1191141	mm^3
Part surface	170359	mm^2
Ablation rate roughing	228	cm^3/min
Removal volume roughing	6084612	mm^3
Oversize	1	mm
Milling time roughing	27	min
Ablation rate smoothing	7000	mm^3/min
Removal volume smoothing	139775	mm^3
Milling time smoothing	24	min
Percentage of functional areas	24	%
Ablation rate finishing	5000	mm^2/min
Cutting depth finishing	0.1	mm
Finishing area	33546	mm^2
Milling time finishing	8.2	min
Hourly machinery rate	40	€/h
Duration reclamping operations	80	min
Machine costs	92.8	€
Tooling costs	100.00	€
Labour costs	25	€/h
Setup time	90	min
Total personnel costs	70,84	€
Tooling costs surcharge	5	%
Personnel costs surcharge	200	%
Overhead costs	162.67	€
Manufacturing costs	**846.09**	**€**

Backup

Costs estimation – AM solution

TECHNISCHE UNIVERSITÄT DARMSTADT

Parameter	Value	Unit
Material costs P_{316L}	89	€/kg
Part volume V_{SLM}	1094	cm^3
Support volume V_S	91	cm^3
Material volume V	1185	cm^3
Material density ρ_{316L}	7.9	g/cm^3
Number of parts	3	-
Material costs M_{SLM} (N=1)	833.17	€
Material costs M_{SLM} (N=3)	2499.51	€
Preparation time t_{prep}	0.5	h
Labour costs P_{lab}	25	€/h
Preparatory costs P_{prep}	12.50	€
Part height H	301	mm
Coating time per layer t_c	12	s
Layer thickness h	40	µm
Volume rate R_V	50	cm^3/h
Build time t_{build} (N=1)	48.8	h
Build time t_{build} (N=3)	96.2	h
Machine utilization rate U	4320	h/year
Acquisition costs P_A	500000	€
Service life t_S	8	years
Maintenance costs P_{main}	24000	€/year
Consumables costs P_{cons}	3000	€/year
Energy costs P_E	10000	€/year
Rental costs P_R	3640	€/year
Build process costs P_{build} (N=1)	1165.10	€
Build process costs P_{build} (N=3)	2296.78	€
Postprocessing effort t_{post}	1.52	h/kg
Postprocessing costs P_{Post} (N=1)	355.74	€
Postprocessing costs P_{Post} (N=3)	1067.21	€
Quality assurance costs P_{qual} (N=1)	61.00	€
Quality assurance costs P_{qual} (N=3)	120.25	€
Production costs P_{SLM} (N=1)	1594.34	€
Production costs P_{SLM} (N=3)	3496.74	€
Manufacturing costs c_{SLM} (N=1)	**2427.51**	**€**
Manufacturing costs c_{SLM} (N=3)	**1998.75**	**€**

Backup

Costs estimation – AM solution

TECHNISCHE UNIVERSITÄT DARMSTADT

Downscaled

Parameter	Value	Unit
Part volume V_{SLM}	135	cm^3
Support volume V_S	18	cm^3
Material volume V	153	cm^3
Number of parts per batch N	12	-
Material costs M_{SLM} (N=1)	107.57	€
Material costs M_{SLM} (N=12)	1290.89	€
Preparatory costs P_{prep}	12.50	€
Part height H	150	mm
Build time t_{build} (N=1)	15.56	h
Build time t_{build} (N=12)	49.22	h
Build process costs P_{build} (N=1)	371.50	€
Build process costs P_{build} (N=12)	1175.13	€
Postprocessing costs P_{Post} (N=1)	45.93	€
Postprocessing costs P_{Post} (N=12)	551.17	€
Quality assurance costs (N=1)	19.45	€
Quality assurance costs (N=12)	61.53	€
Production costs P_{SLM} (N=1)	449.38	€
Production costs P_{SLM} (N=12)	1800.33	€
Manufacturing costs c_{SLM} (N=1)	**556.95**	**€**
Manufacturing costs c_{SLM} (N=12)	**257.60**	**€**

Downscaled 2023

Parameter	Value	Unit
Material costs P_{316L}	30	€/kg
Material costs M_{SLM} (N=1)	280.85	€
Material costs M_{SLM} (N=3)	842.54	€
Preparatory costs P_{prep}	12.50	€
Volume rate R_V	80	cm^3/h
Build time t_{build} (N=1)	39.9	h
Build time t_{build} (N=3)	69.5	h
Acquisition costs P_A	800000	€
Build process costs P_{build} (N=1)	1298.97	€
Build process costs P_{build} (N=3)	2262.62	€
Postprocessing effort t_{post}	0.96	h/kg
Postprocessing costs P_{Post} (N=1)	224.68	€
Postprocessing costs P_{Post} (N=3)	647.03	€
Production costs P_{SLM} (N=1)	1536.15	€
Production costs P_{SLM} (N=3)	2922.15	€
Manufacturing costs c_{SLM} (N=1)	**1817.00**	**€**
Manufacturing costs c_{SLM} (N=3)	**1254.90**	**€**