PERMAS USERS‘ Conference
12.04.2018 – 13.04.2018

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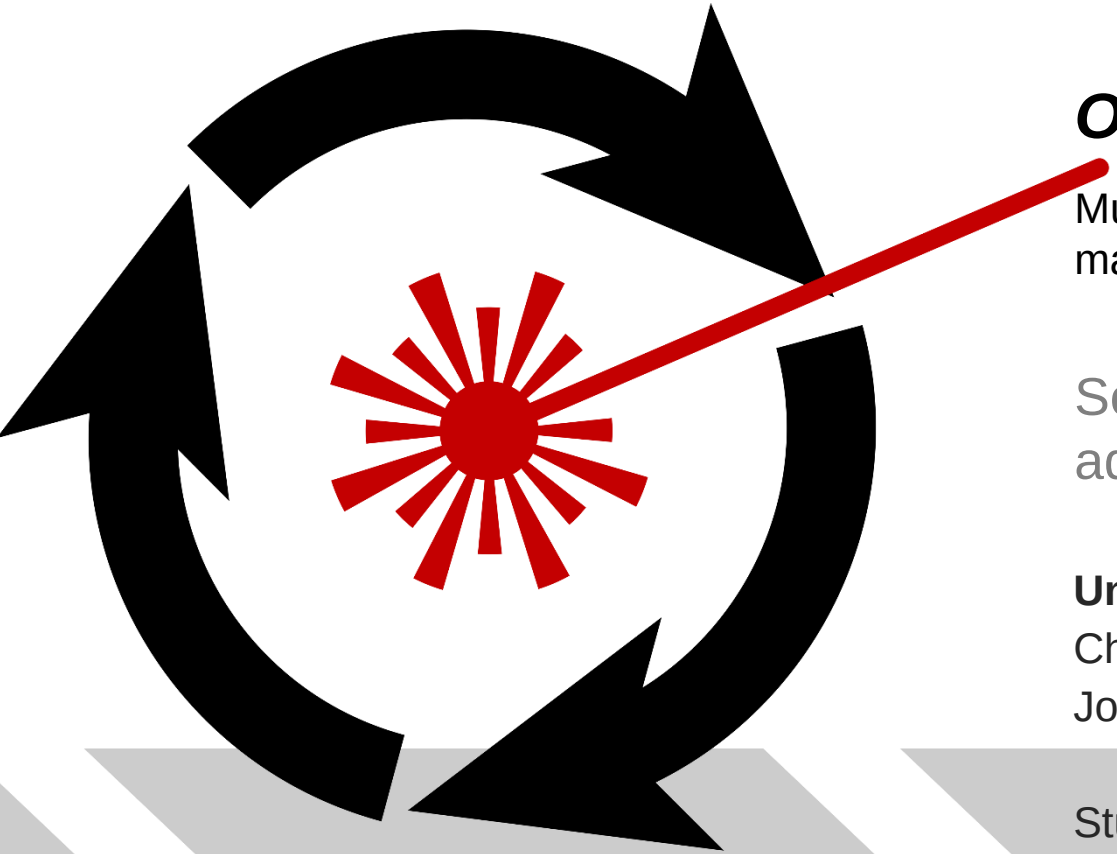
Stuttgart 2018



OptiAMix

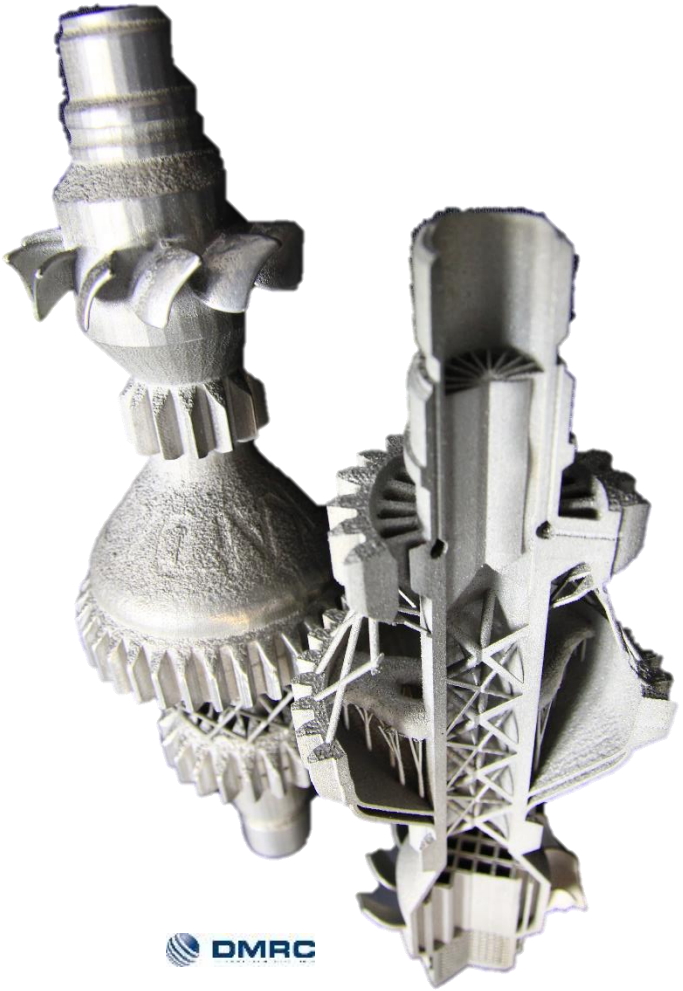
Multi-target-optimized product design for additive manufacturing

Software-assisted design check of additive manufactured components

University of Paderborn
Chair for Design and Drive Technology // DMRC
Johannes Tominski

Stuttgart

Agenda



- Additive Manufacturing
- Design-Guidelines for Additive Manufacturing
- Identification of standard-elements
- Database for reference values
- Procedure for checking the component shape
- Summary

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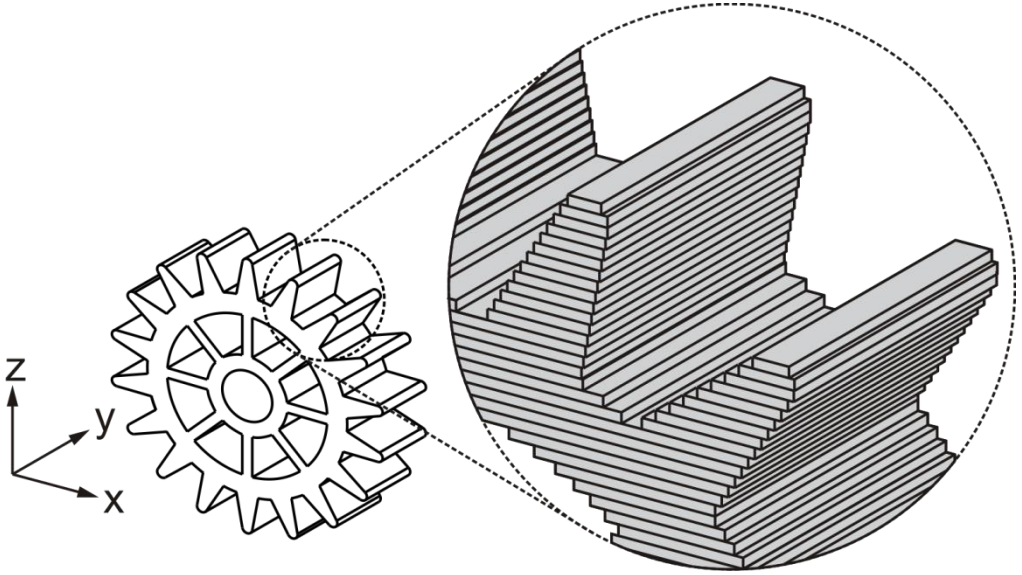
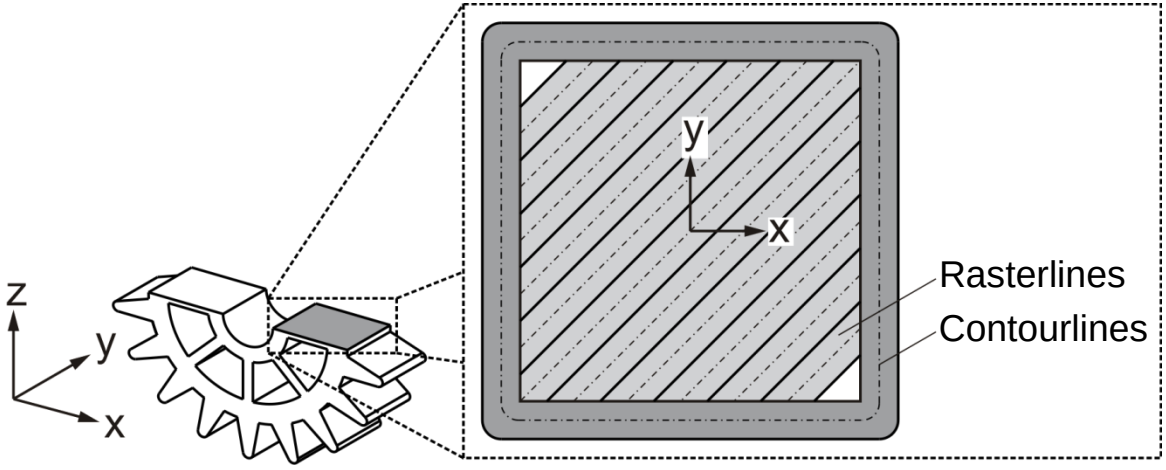
Structure of components

- Components are build layer-by-layer
- Layers are oriented in x-y-direction
- Joining layers in z-direction

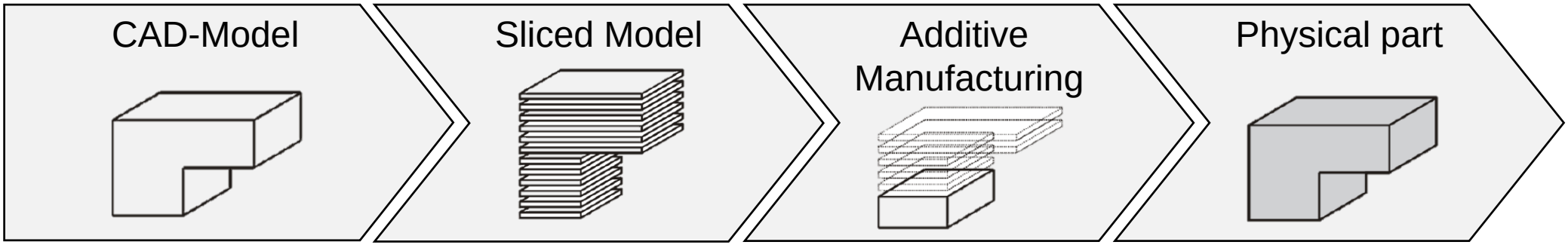


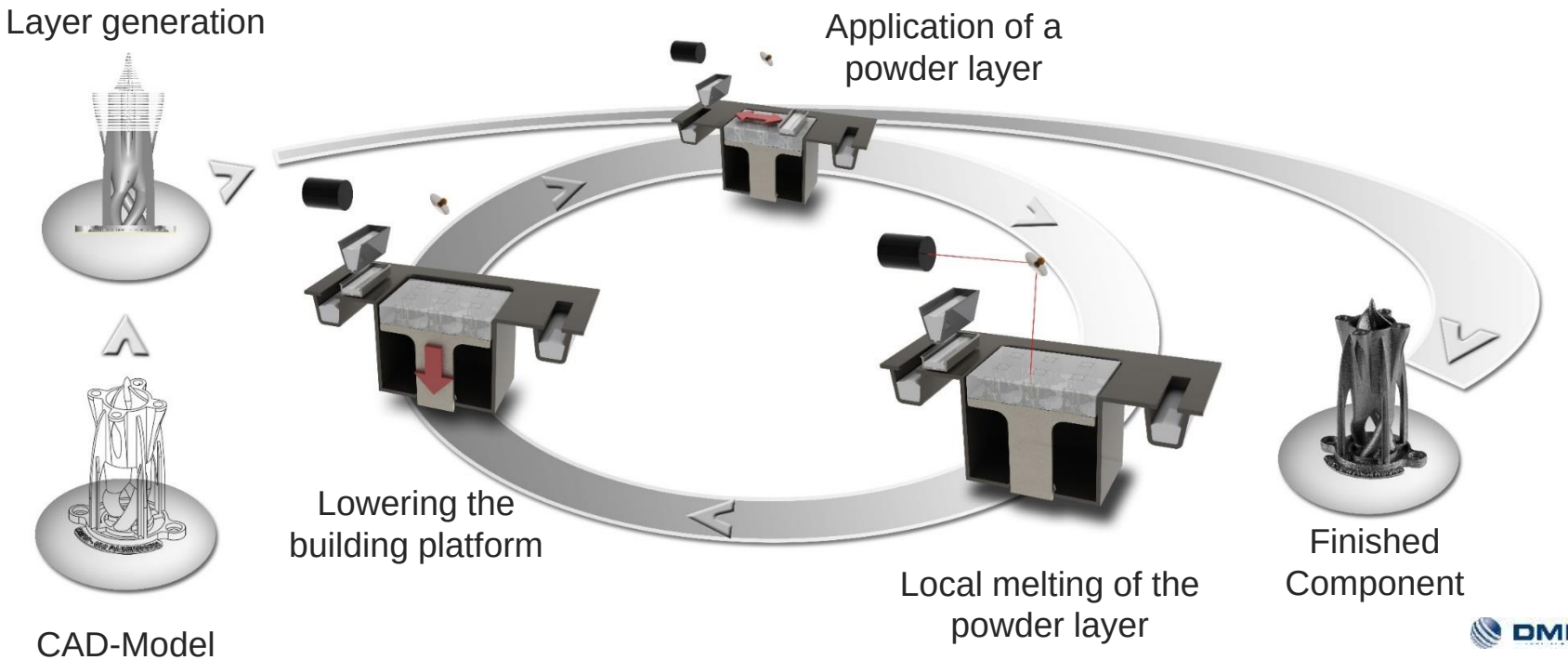
Structure of component-layers

- Contourlines:
  Limitation of the outer expansion
- Rasterlines:
  Filling of the Areas between the contourlines



[Ada13]


CAD-Model
Sliced Model
Additive Manufacturing
Physical part


Layer generation
Application of a powder layer
Lowering the building platform
Local melting of the powder layer
Finished Component
CAD-Model
DMRC

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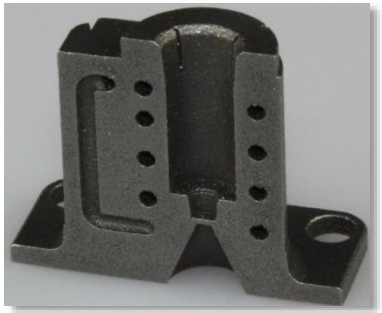
Undercuts

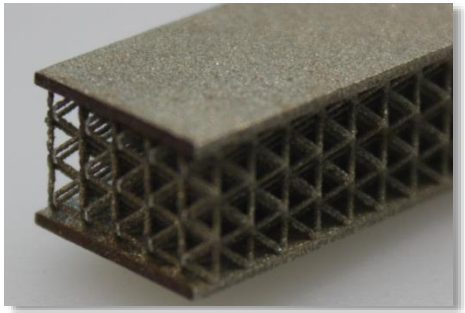
- Accessibility for tools is not required
- Undercuts arise in
  - layer direction
  - building direction

[LAL+15]

Internal structures

- Example: conformal cooling





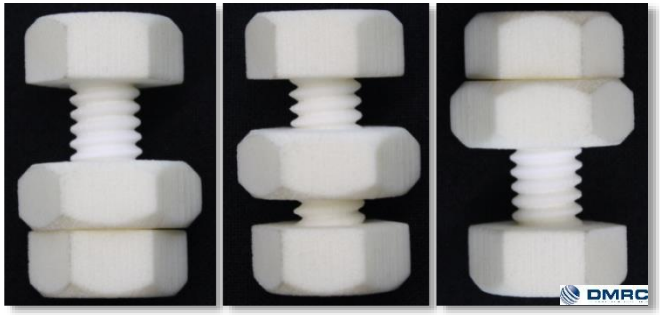
[LAL+15]

Truss structures

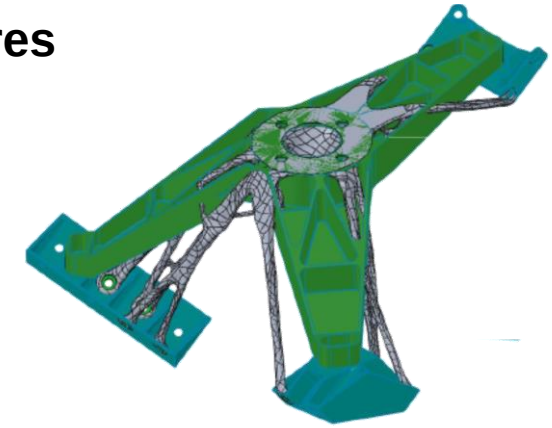
- Complex arrangements of beams and bars

Manufacturing of form fitted elements

- Production without mounting



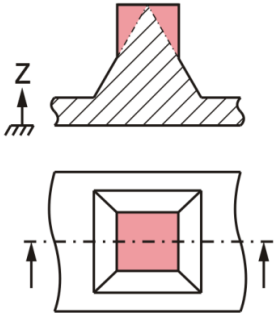
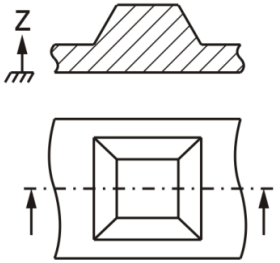
Topology optimized structures



	Milling	Additive	Change
weight	1114g	456g	- 60%
max. deformation	0,076mm	0,048mm	- 37%
1. eigenfrequency	180 Hz	216 Hz	+ 20%
number of parts	4	2	- 50%
buy-to-fly-ratio	56 kg	0,84 kg	- 97%
production time (4 brackets)	180 h	120h	- 33%
costs	8000 €	3800€	- 53%

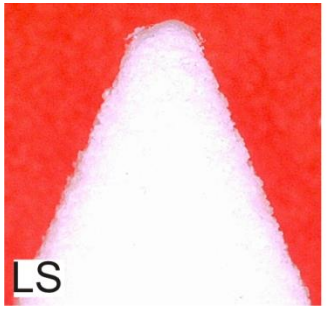
[Rei15]

Design-guideline example: Corners

Regular description / Specific description	Unsuitable design	Suitable design	LS	LM	FDM
Corners that form an vertical extreme point should be blunted parallel to the building plane. The dimensions of the blunted area should be larger than the thickness of a wall.			X	X	X

- Minimal dimensions limited by the size of the lines of the part layer.
- Thickenings arise at the corners
- Avoid the thickenings due to chamfers
- Chamfers can be manufactured more easily if they are parallel to the building plane.

Corners with sharp nominal shapes:



[ZA13]

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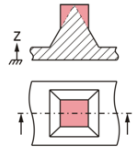
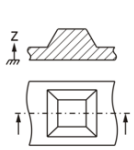
Actual design-guidelines

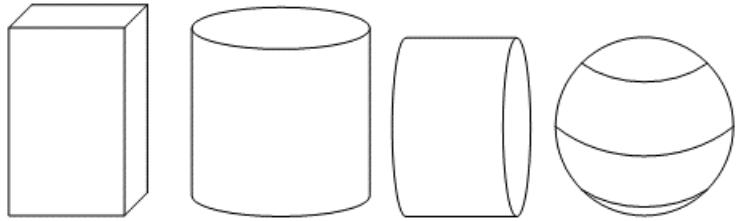
- The design-guidelines are addressed to the designer
- Guidelines refer to standard elements

Regular description / Specific description	Unsuitable design	Suitable design	LS	LM	FDM
Corners that form an vertical extreme point should be blunted parallel to the building plane. The dimensions of the blunted area should be larger than the thickness of a wall.			X	X	X

[ZA13]

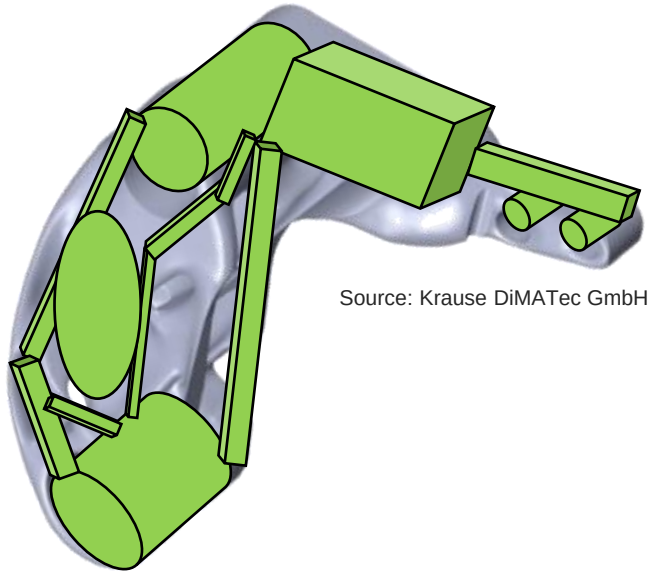
Standard-geometries in design

In the design process, standard elements are geometric elements that are frequently used in recurring form.



⇨ Difficult identification of design-standard-geometries, especially at topology-optimized structures

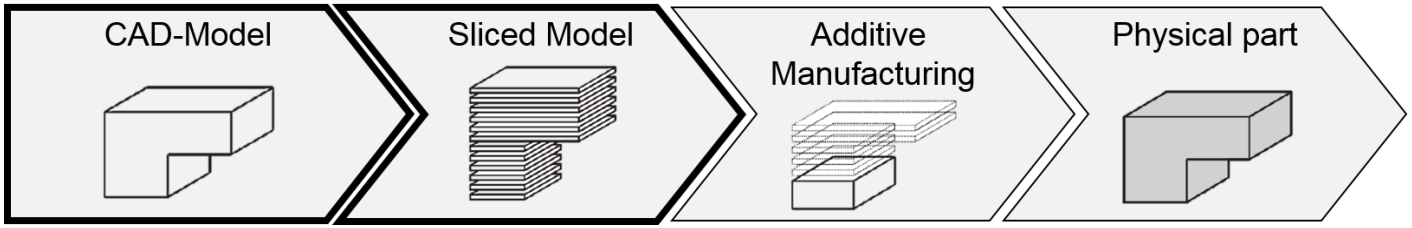
⇨ Redefintion of standard-elements for the software-based, automatic component description is necessary

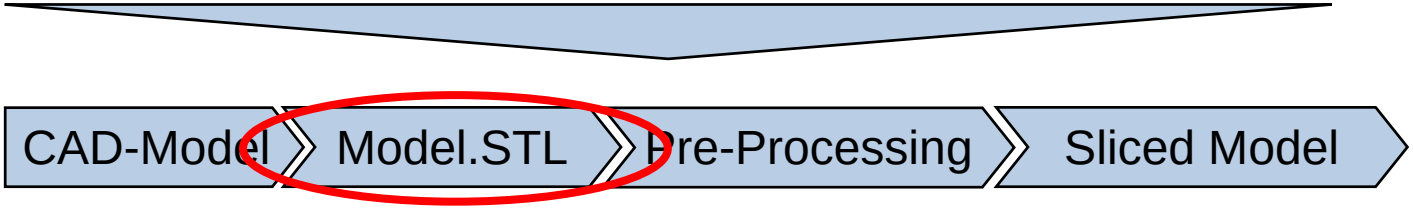


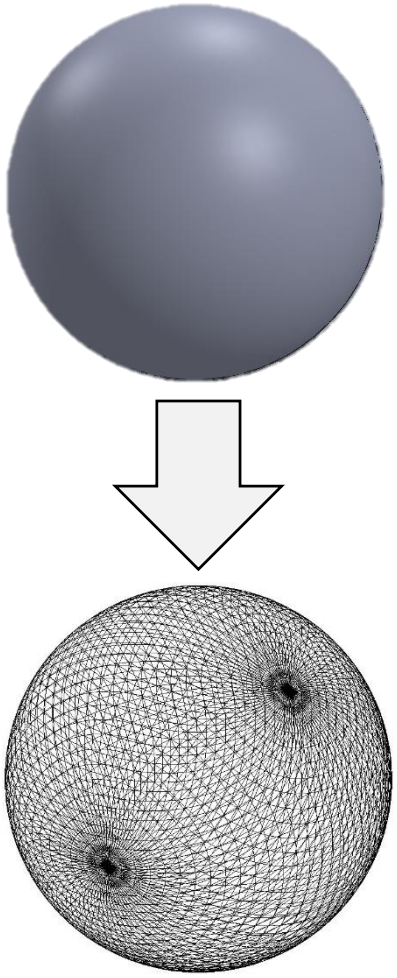
Source: Krause DiMATec GmbH

Requirements for standard-elements

- Geometric attributes limit the additive manufacturing
- Design-guidelines consider these procedure-specific limits
- A method needed to identify the geometric attributes that limit the feasibility
- Method must be independent of specific CAD- and pre-processing-software
- Use of the STL-fileformat that exists between CAD and manufacturing machine







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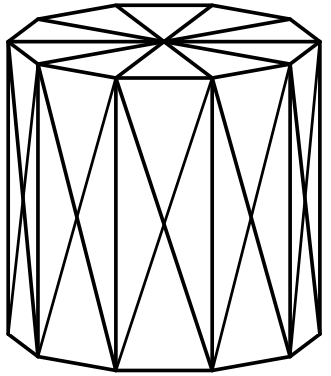
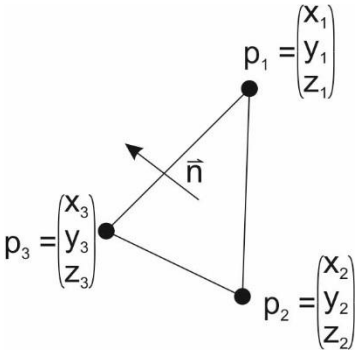
Standard-elements in STL-Format

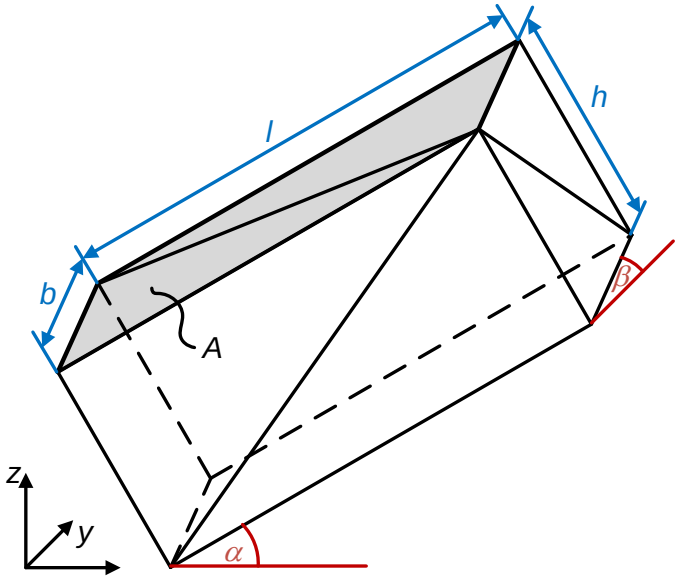
The triangles in STL-format contain information about the position in space and the orientation of body surfaces.



Core attributes:

- Position of triangles
- Orientation





Derived attributes:

- Distance (e.g., wall thickness, gaps, length)
- Angle (e.g., orientation of area in the building-room)
- Areas (e.g., cross sectional area in the building-area)

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General requirements for a database

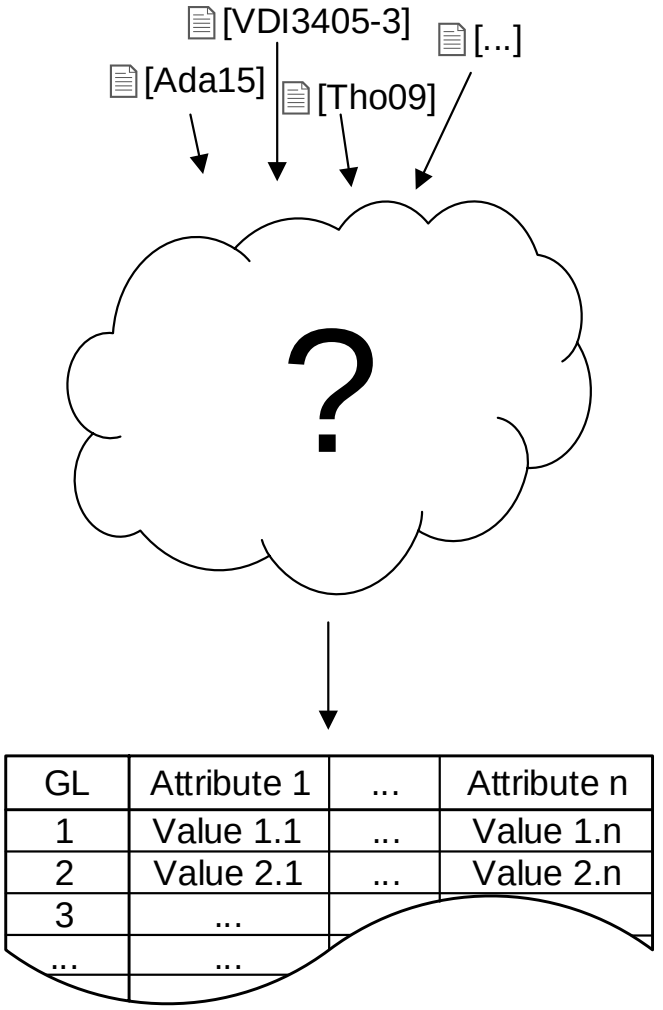
- Design-guidelines contain the limiting geometries with the attributes of STL-triangles
- Include the permissible attribute values for best possible additive manufacturing
- Electronically processable

Design-guidelines (z.B. [Ada15], [VDI3405])

- During the design process, the values serve as orientation for the designer
- Specified, quantitative values are machine- and material-dependent
- Description based on standard-geometries or example parts

Conclusion

- Actual guidelines must be brought to a uniform format
- Consideration of machine and material parameters necessary



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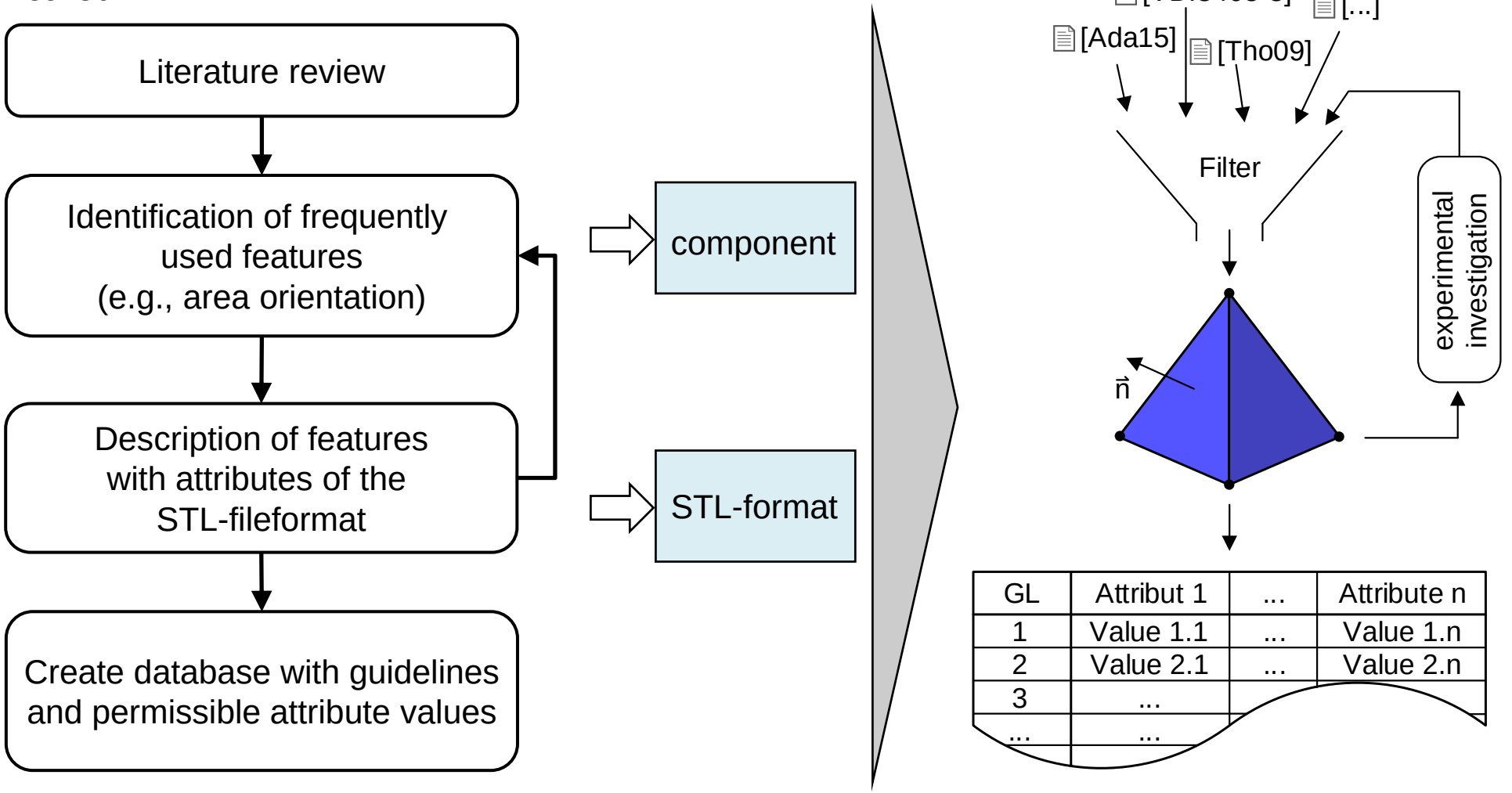
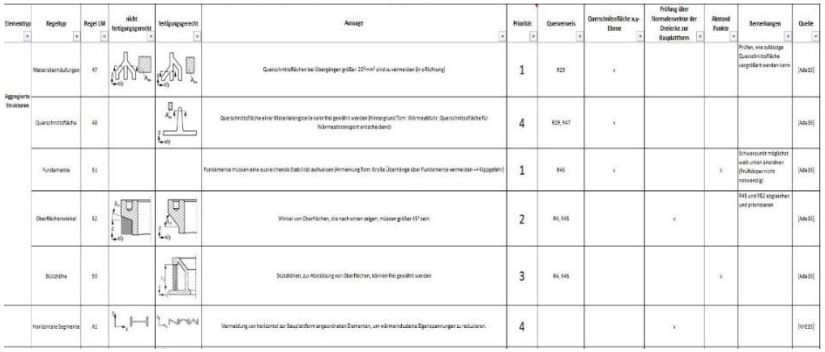
Method



Database for reference values

Research und priorization

- List of existing design-guidelines (about 100)
- Reduction of criteria through combination and priorization of the design-guidelines



Priorization of design-guidelines

Priority	*Definition*
1	Risks for the manufacturing process
2	Loss of component quality
3	Determination by the user / no influence on manufacturability or quality
4	Contained in other guidelines

About 20 guidelines,

that, if not respected,

risk the robust manufacturing process or lead to

losses of component quality

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Experimental investigation / Abstraction

- Examination of further similarities / same causes of deviation in form
- Check of validity to other geometries
- Creation of further guidelines, that are of a more general character

9 guidelines,

for a

software-based check

of the component geometry

Considered attributes

- Minimum wallthickness
- Minimum gap
- Minimum innerradius
- Maximum innerradius (without support)
- Minimum outerradius
- Variation of cross sectional area in building direction
- Maximum cross sectional area
- Minimum overhang angle (without support)
- Criterion of stability while manufacturing process

Guideline-Nr.	Name	Attribute	Unit	Priority
1	wall thickness - minimum	$t_{w0,lim}$	mm	1
2	gap - minimum	$w_{g90,lim}$	mm	1
3	Innerradius - minimum	$r_{i,0,lim}$	mm	1
4	innerradius - support	$r_{i,s}$	mm	2
5	outerradius - minimum	$r_{o,90,min}$	mm	1
6	variation of cross section	f_A	-	2
7	cross sectional area - maximum (rectangular)	$A_{c,lim}$	mm²	1
8	overhang - support	$l_{0,lim}$	mm	2
9	Stability	-	-	1

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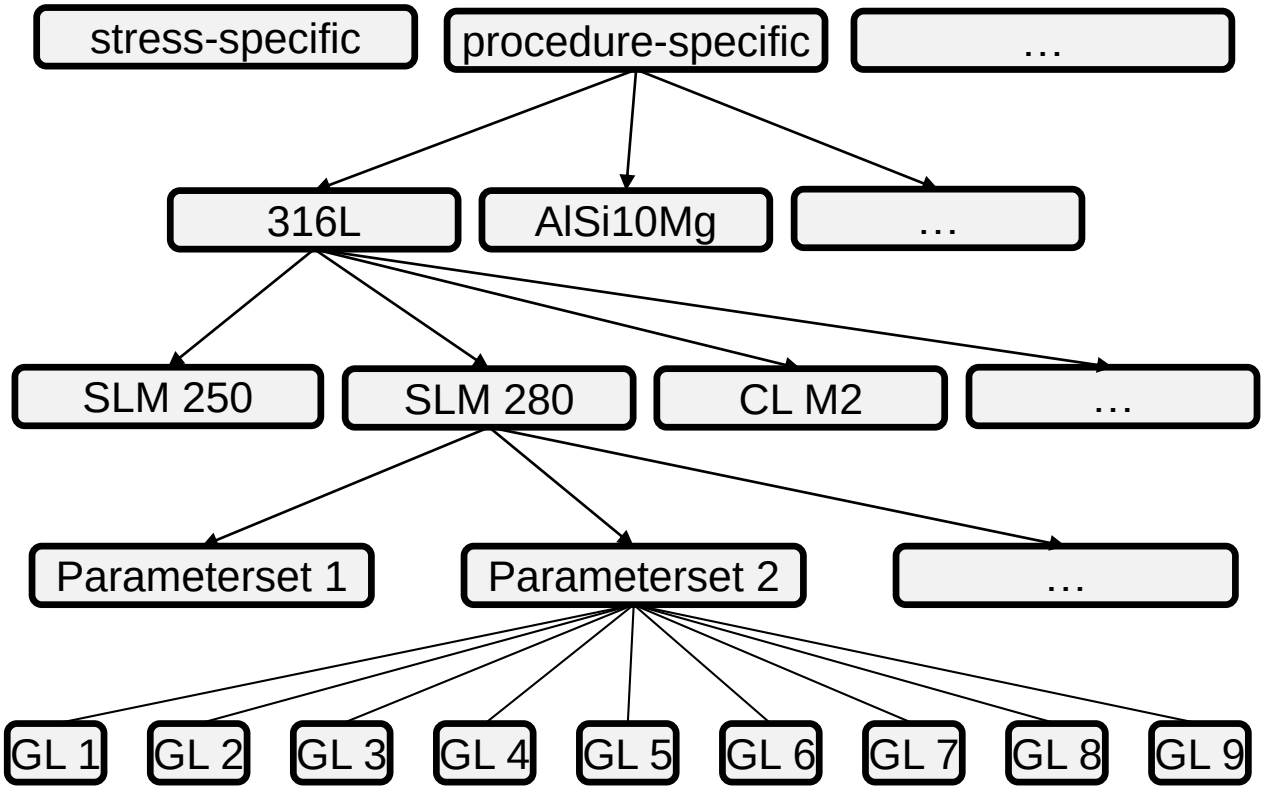
Structure of the database

The database has to distinguish between different boundary conditions:

- Type of guideline (1. level)
- Material (2. level)
- Production machine (3. level)
- Parameter set (4. level)



Benefits:

- Expandable on all levels
- Implementation in MS Excel possible

Procedure for checking the component shape

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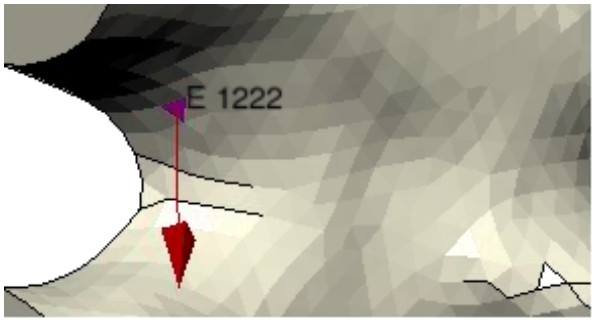
Angle

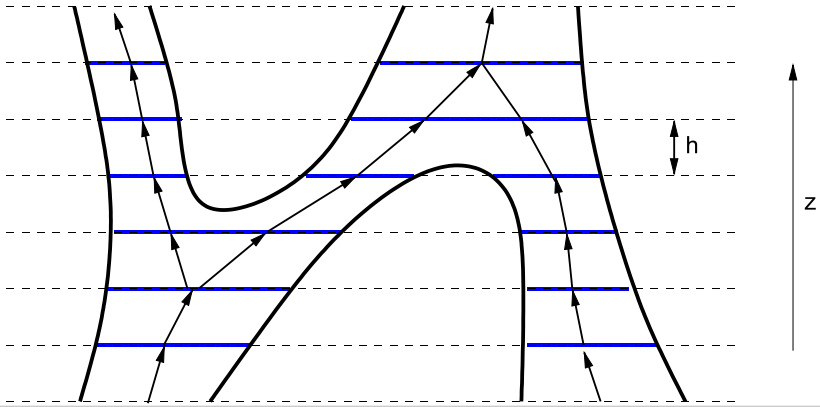
- Permissible overhang angle without support
- Directly available from the surface orientation of the triangles

Areas

- Cross sectional areas and their change in building direction
- Discretization in building direction (*z*-direction) with discretization parameter: h: $A(z) \approx A(i \cdot h)$
- Extraction of closed polylines (plane polygones) from intersection of plane $z = i \cdot h$ and 3D triangular mesh of the surface (i.e., area calculation analytically possible)
- Linking of connected* patches in *z*-direction via directed graph

*Non-empty intersection of two directly superimposed subareas





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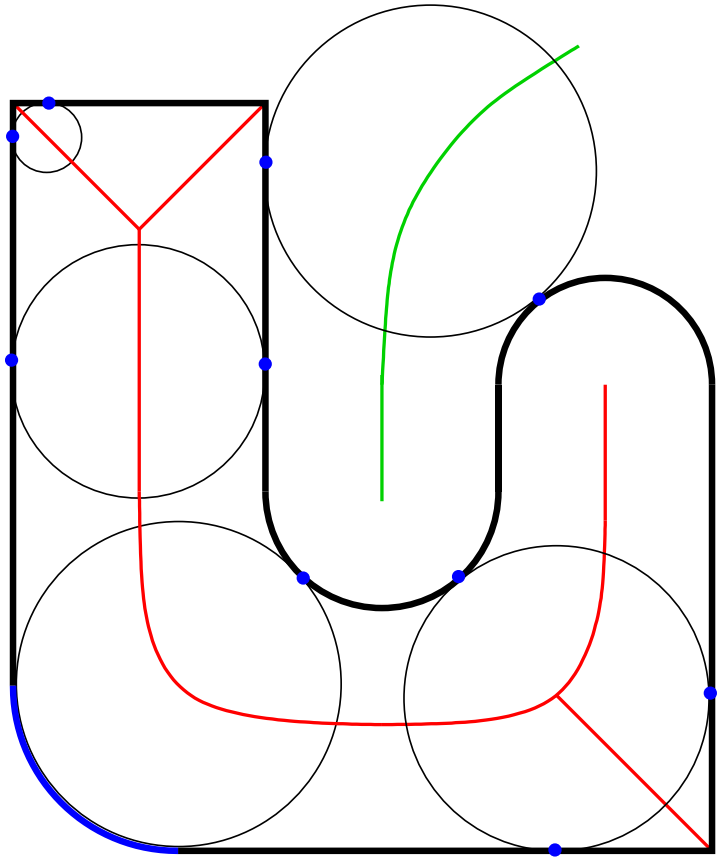
Distances

- Inner- and outerradii, wall thickness, gaps, etc.
- Basis: *Media Axes Transformation*
  - Maximale circles: circles that are completely in one area and that are not covered by any othe circle that is also completely within the area
    (3D: maximum great ball in the volume)
  - Media Axes: The set of centers of all maximum circles (3D: medial area)
- The radii of the maximum circles are the attributes to be measured and *tangetially* touch the edge or the surface at two points
- Also for the measurement of cavaties (e.g., gaps)



Maximum circles with 2,3 or infitely many points of contact and medial axes inside or outside

Distances

- Shortest distance d_R to the edge (2D) or to the surface (3D) as a distance field by solving the

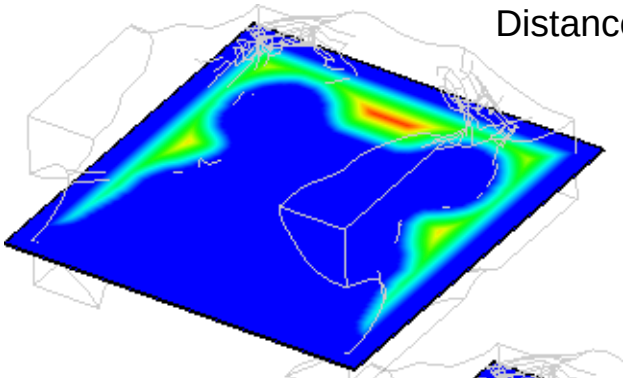
  $$\textit{Eikonal equation}: ||\nabla d_R|| = 1$$

  With the boundary condition $d_R = 0$ at the edge or at the surface (corresponds to wave expansion with velocity ’1’)

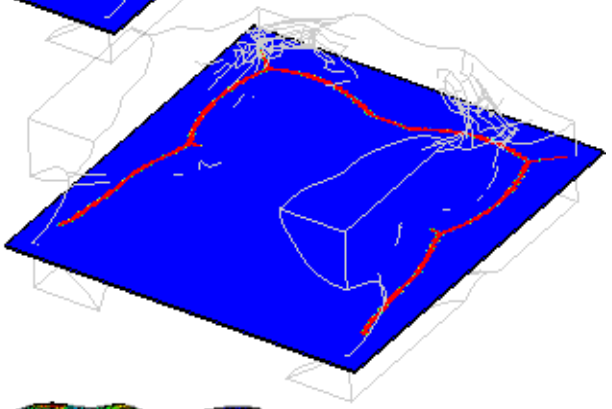
- Numerical solution on rectangular grid and extraction of the medial axis / area of *singularities* (coincidence of waves of different directions)

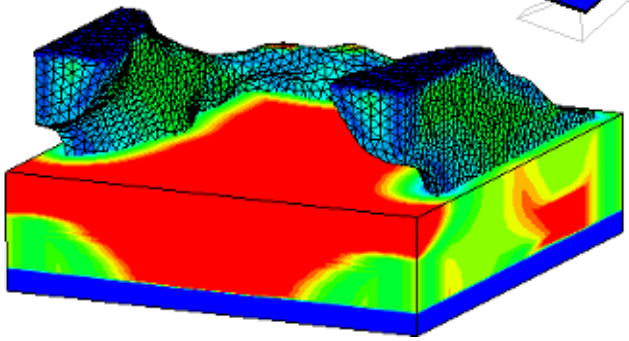
- Calculation of the shortest distances d_M to the medial axis or surface by solving the Eikonal equation again with boudary condition $d_M = 0$ on the medial axis / area and evaluation on edge or surface

Distance d_R to the edge



Medial axis





Distance d_M to the medial axis

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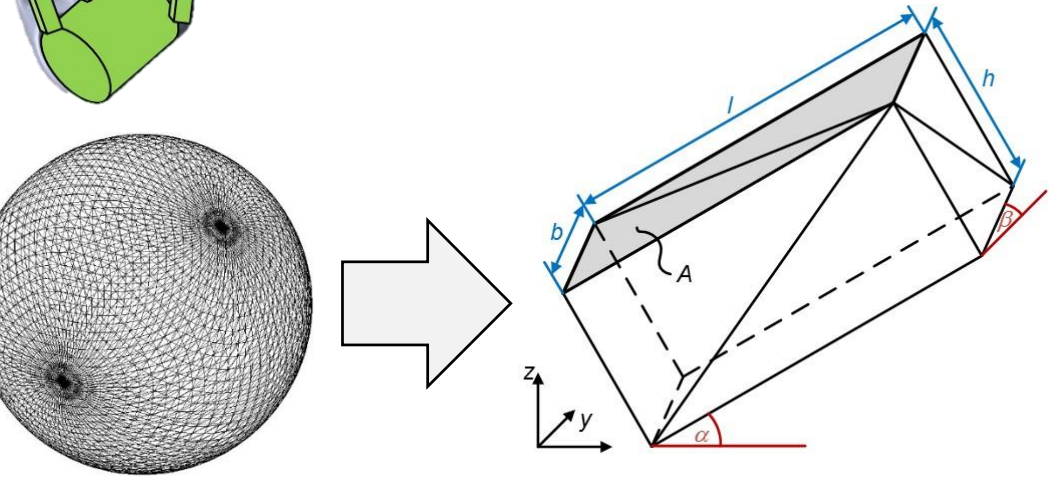
Additive Manufacturing

offers the potential to produce structures that are difficult or impossible to produce using conventional manufacturing methods.

Actual design guidelines for additive manufacturing

are addressed to the designer and refer to standard geometries that are difficult to identify especially at high complex structures.



The STL-Format

usually exists between CAD and production machine. It offers the possibility to identify different geometric attributes by systematically linking the triangles.

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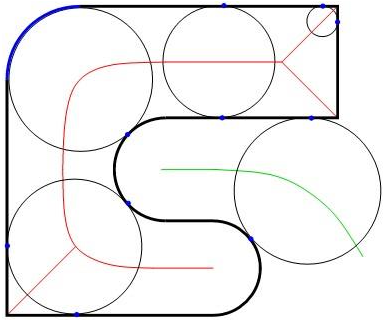
The Database

includes reference values that are necessary for a robust manufacturing. There is a distinction between different rules, machines, materials and parameter sets.

Guideline-Nr.	Name	Attribute	Unit	Priority
1	wall thickness - minimum	$t_{w0,lim}$	mm	1
2	gap - minimum	$w_{g90,lim}$	mm	1
3	Innerradius - minimum	$r_{i,0,lim}$	mm	1
4	innerradius - support	$r_{i,s}$	mm	2
5	outerradius - minimum	$r_{o,90,min}$	mm	1
6	variation of cross section	f_A	-	2
7	cross sectional area - maximum (rectangular)	$A_{c,lim}$	mm²	1
8	overhang - support	$l_{0,lim}$	mm	2
9	Stability	-	-	1

The automated design check

can be realized by different methods to get all necessary geometric attributes that have an influence on manufacturing quality.



Conclusion

By reducing the number of design guidelines and identifying the restrictive geometric sizes in a STL format, it is *possible to test a design for manufacturability and manufacturing quality before production*.

A special additional benefit arises from the *check of complex structures*, such as topology-optimized structures, which is not possible with previous methods.

Thank you for your attention

[Ada13] ADAM, G. A. O.: *Die Potentiale additiver Fertigung nutzen – Praktische Hinweise für eine optimale Konstruktion.* Vortrag, 12. Rapid Prototyping Fachtagung, Hamburg, 19.04.2013

[Ada15] ADAM, G. A. O.: *Systematische Erarbeitung von Konstruktionsregeln für die additiven Fertigungsverfahren Lasersintern, Laserschmelzen und Fused Deposition Modeling*. Dissertation, Universität Paderborn, 2015

[LAL+15] LIENEKE, T.; ET AL: *Entwicklung einer Methode zur systematischen Erarbeitung von Maßtoleranzen für additive Fertigungsverfahren*. Vortrag, Rapid.Tech Konferenz, Erfurt, 11.06.2015

[Rei15] REIHER, T: *FE-optimization and design of additive manufactured structural metallic parts for telecommunication satellites*. Vortrag, Paris Space Week, Paris, 05.02.2015

[Tho09] THOMAS, D.: *The Development of Design Rules for Selective Laser Melting*. Dissertation, University of Wales Institute, Cardiff, 2009

[VDI3405-3] VEREIN DEUTSCHER INGENIEURE E.V.: *VDI 3405 Blatt 3: Additive Fertigungsverfahren – Konstruktionsempfehlungen für die Bauteilfertigung mit Laser-Sintern und Laser-Strahlschmelzen.* Beuth Verlag, Berlin, 2015

[ZA13] ZIMMER, D.; ADAM, G.A.O.: *Konstruktionsregeln für Additive Fertigungsverfahren*. Zeitschrift Konstruktion, Ausgabe 07/08, Springer Verlag, S.77-82, 2013

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