Constructive Generative Design for Additive Manufacturing

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Outline

1. **Lab & Research Introduction**

2. **Design for AM**

3. **Constructive Generative Design for AM**
   - ➢ **Top-down method**
   - ➢ **Bottom-up method**

4. **Conclusion & Perspectives**

❖ Personal information

Position:

Associate Professor (Maitre de conference, since 2017), HDR (research habilitation, since 2021) at the Department of Design & Mechanical Engineering of UTBM (since 2017).

Teaching (@ UTBM):
CAX; PLM/PSS;
Additive Manufacturing(UTBM & UTSEUS)

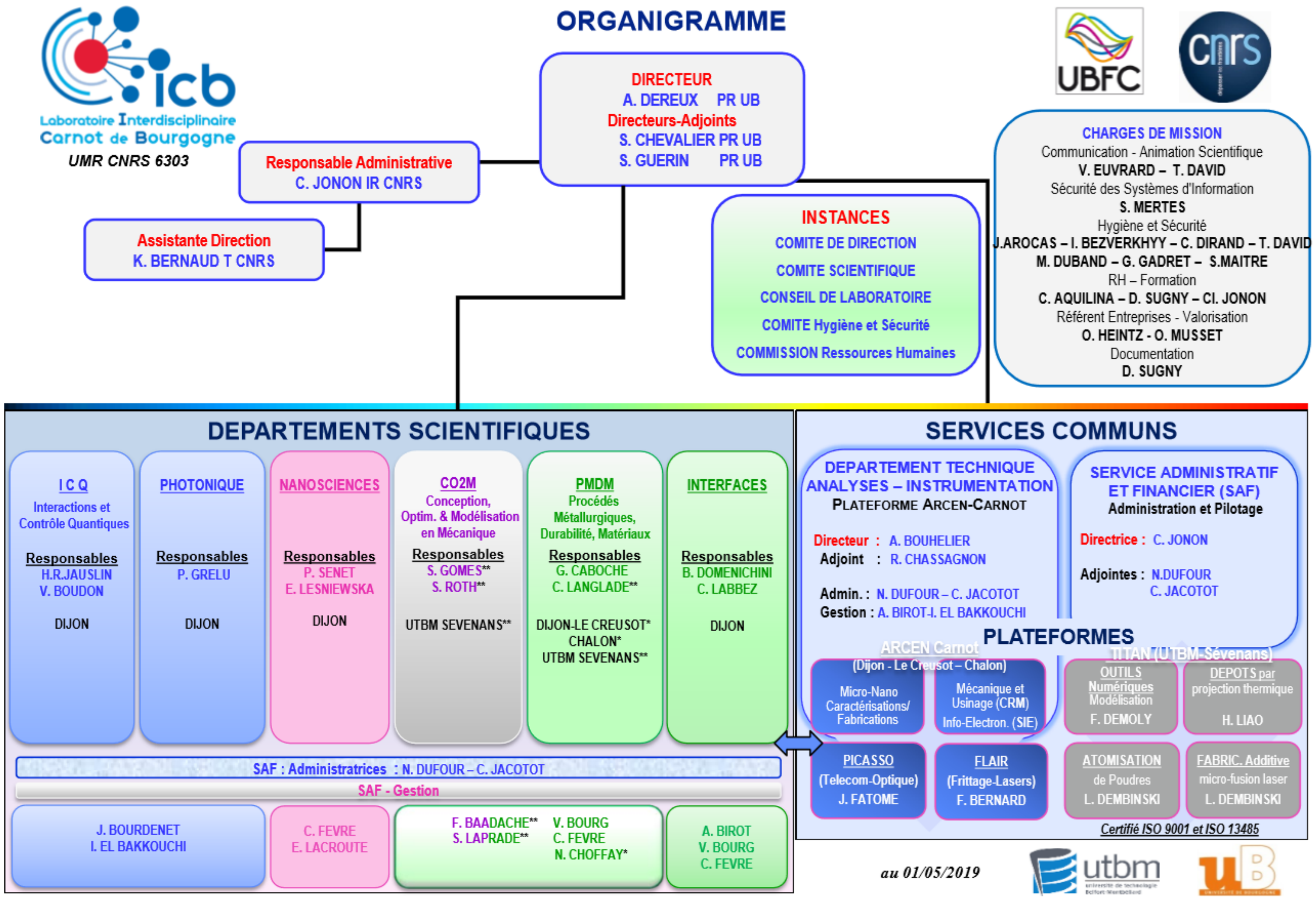
Research (@ CNRS):
CAX; PSS; Additive Manufacturing; Intelligent Manufacturing Systems; Expert System; Decision Making & Optimization

❖ Lab information

UTBM: **University of Technology @ Belfort-Montbeliard**
'Grandes Ecoles' in France with 400+ Faculties & staff; 1600+ students; 150+ international partners

ICB: CNRS lab with 600+ researchers

❖ ICB-COMM, CNRS: National Lab of Interdisciplinary Research



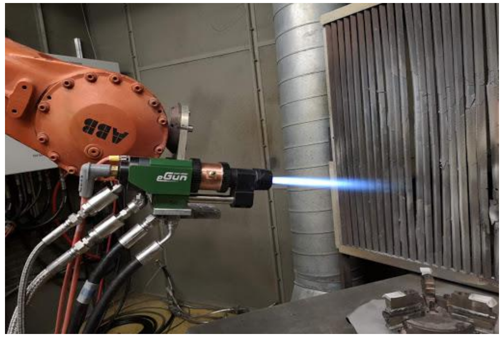
Design, Modeling & Optimization in Mechanics

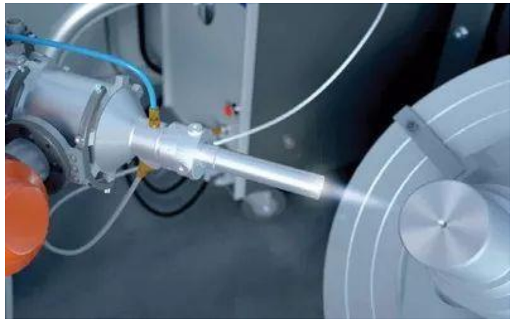
- 15 Academic members (CNU section 60 and 26):
  - 4 Full Professors,
  - 11 Associate Professors (including 2 HDR)
- 14 PhD Students
- 2 technical staff (BIATSS)

❖ ICB-COMM & PMDM AM facilities (TITAN Platform)

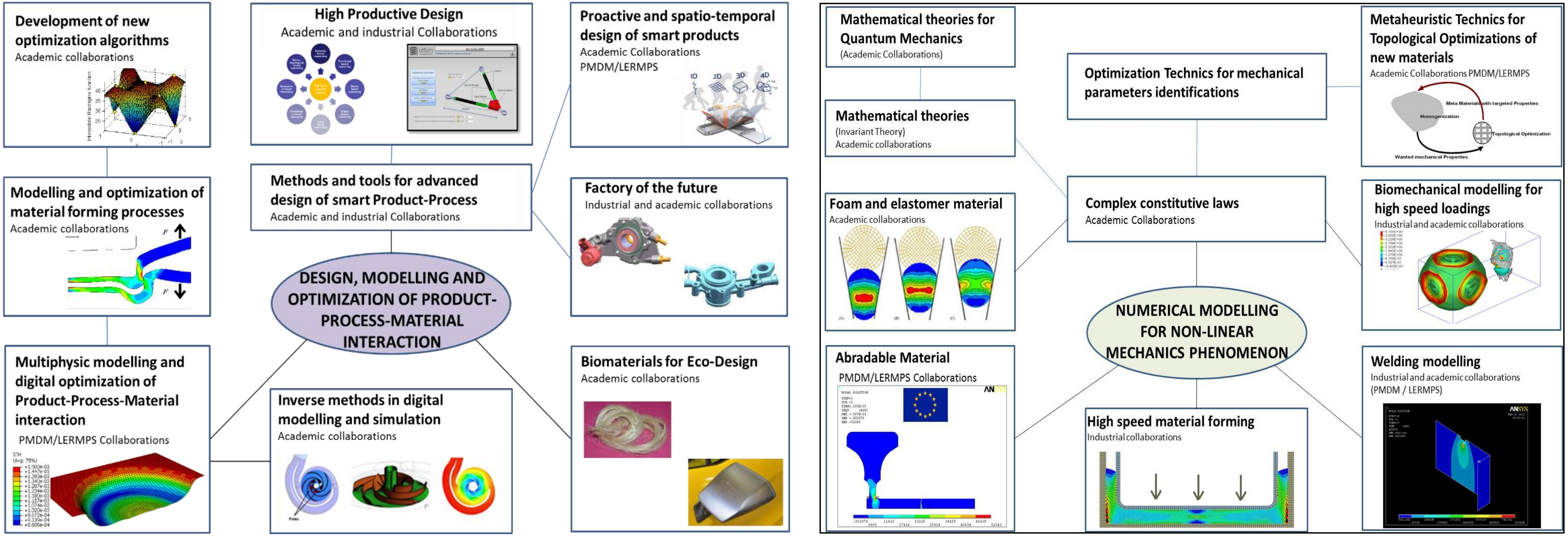
Facilities (share with PMDM, only mention AM related here):

5 SLM (4 EOS & Renishaw and 1 homemade) + 1 jetting (Stratasys) + 1 powder production system + 1 fiber FDM & 1 metal FDM (Markforged) + 5 spraying (cold & thermal) + 2 SLA (Object) + 45 FDM (DIY)…



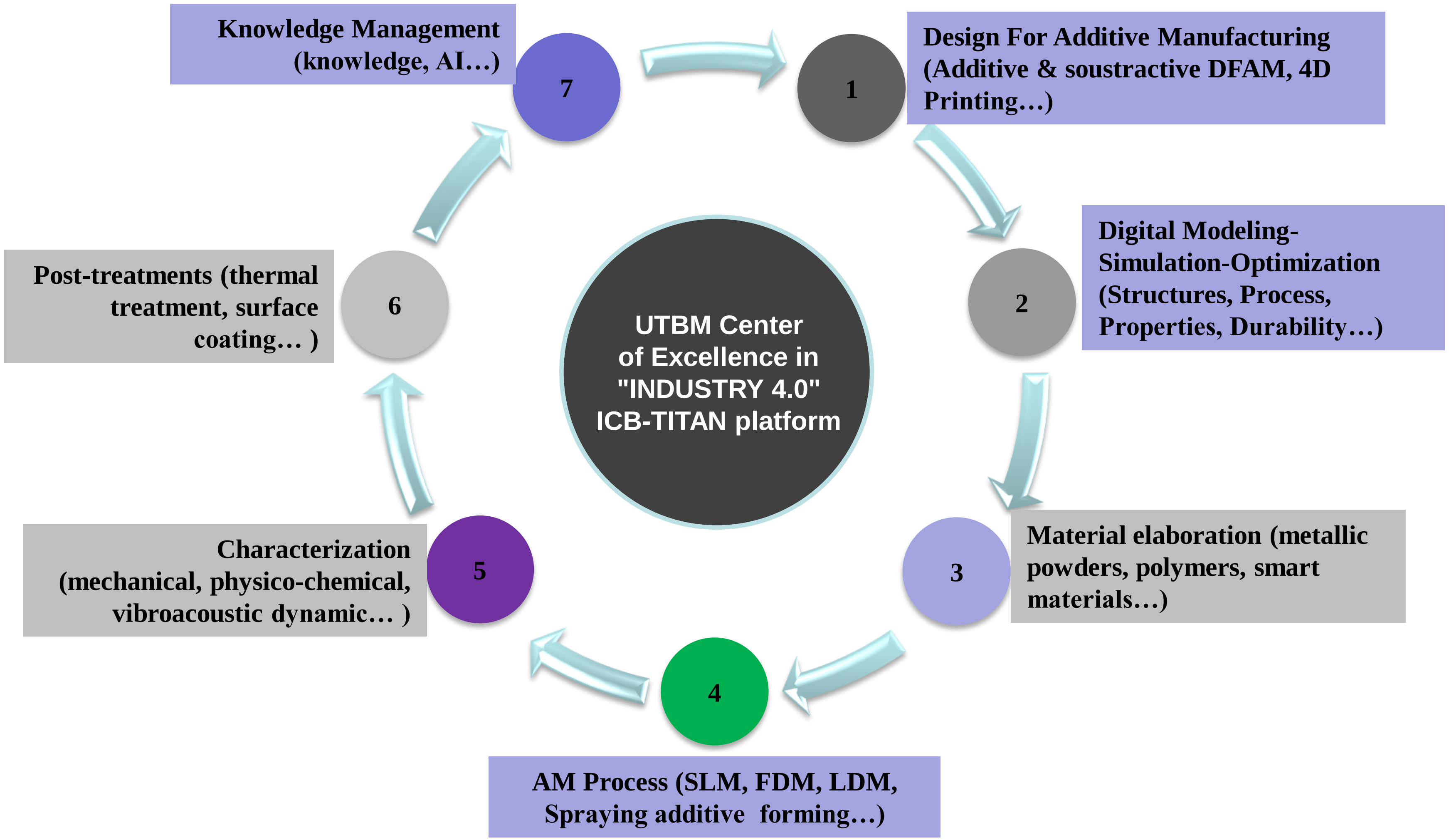


❖ ICB-COMM, CNRS: National Lab of Interdisciplinary Research



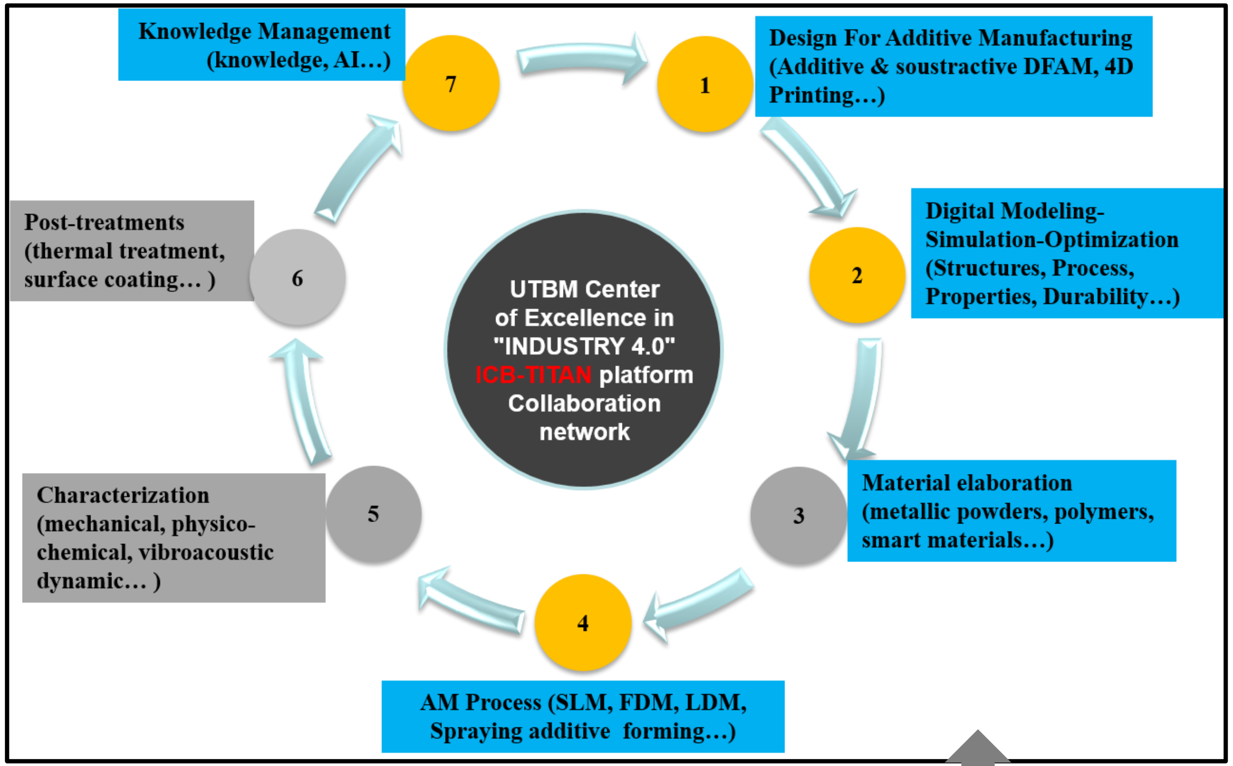
ICB-COMM research topics: design, simulation & optimization, etc.

❖ ICB-COMM, CNRS: National Lab of Interdisciplinary Research

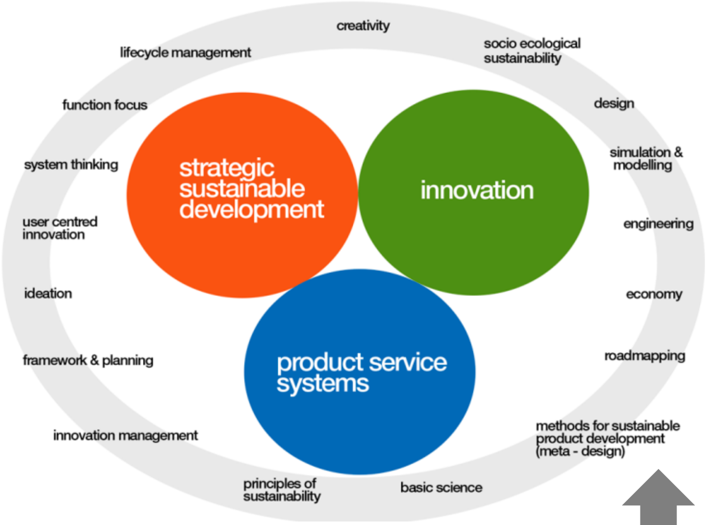


ICB-COMM AM research topics.

❖ Personal research focus

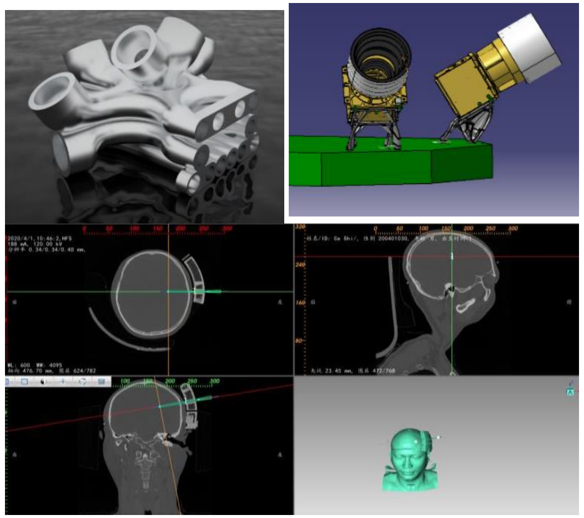


Guiding



Replying

Serving



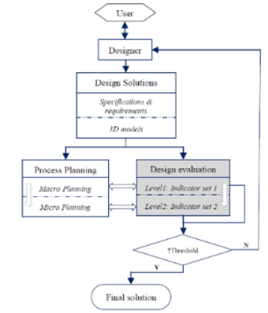
Personal research focus:

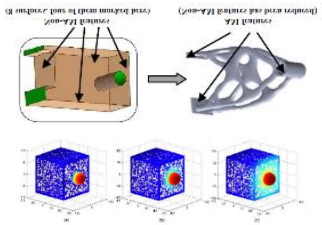
1. DFAM & planning for AM 2. Material-structure design (4D)

3. AM Process 4. KM for AM 5. AM application

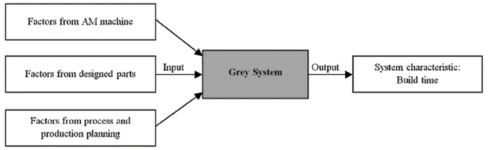
❖ Former research focus: CAPP/CAM for AM

$$C^* = \mu V_k + (1-\mu)\varepsilon_{p_0 k} = \mu \frac{1}{e^{\sum_{i=1}^{n}\omega_i |(P_i-\chi_i)/P_i|}} \times 100\% + (1-\mu)\frac{1+|s_{p_0}|+|s_k|}{1+|s_{p_0}|+|s_k|+|s_{p_0}-s_k|}$$

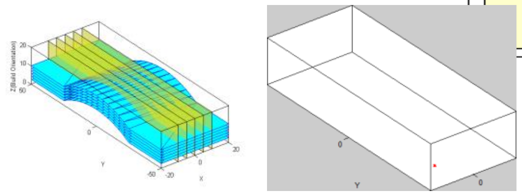




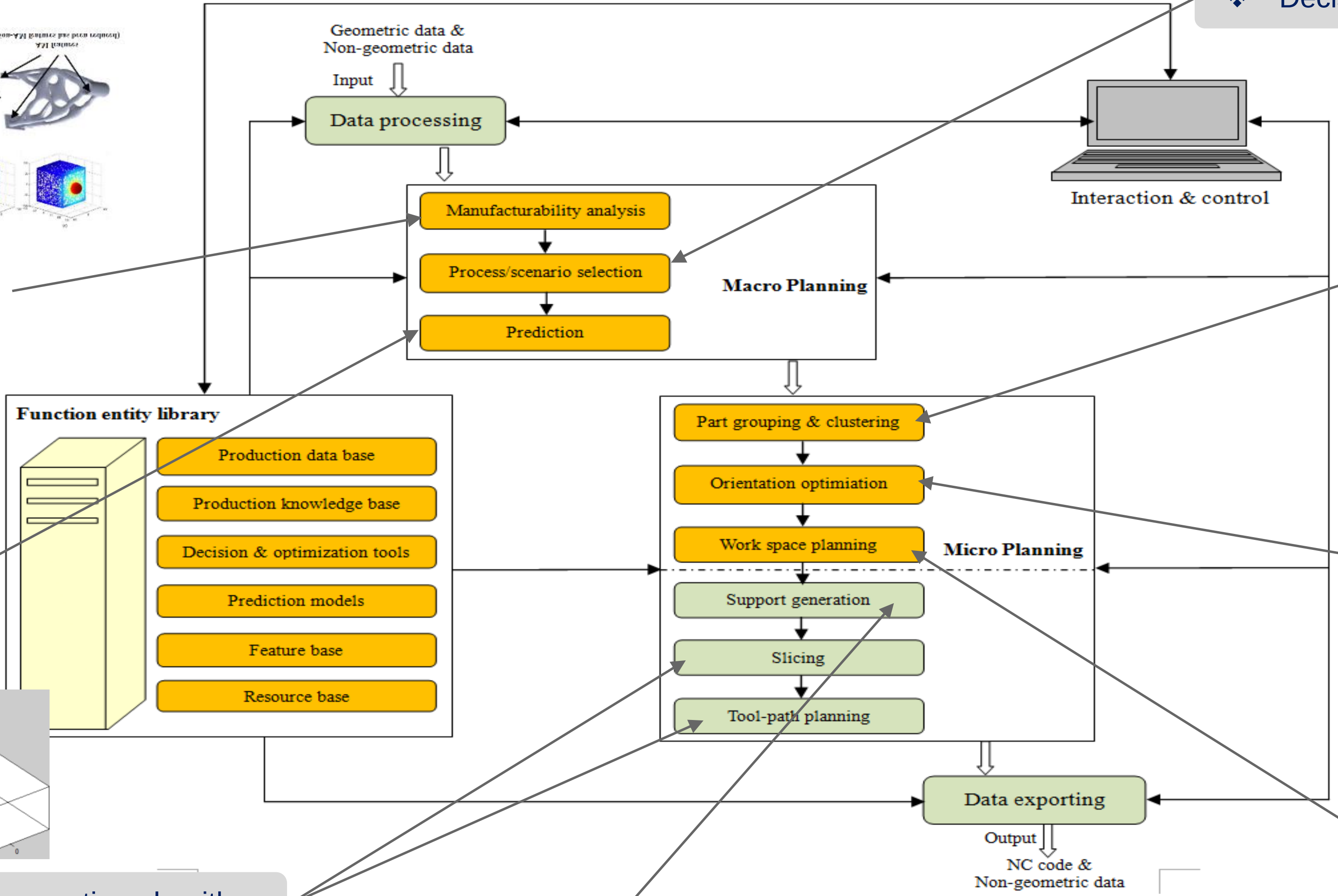
❖ Design Support Tool development



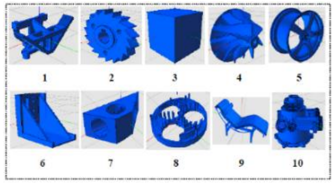
❖ AI based Prediction models



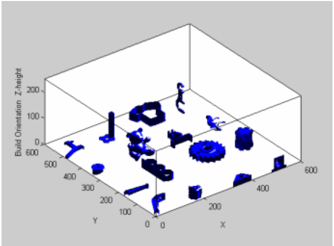
❖ Curved slicing & tool-path generation algorithm



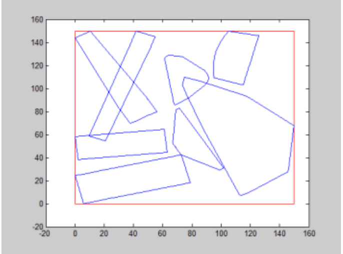
❖ Decision making models reasoning



❖ Part clustring

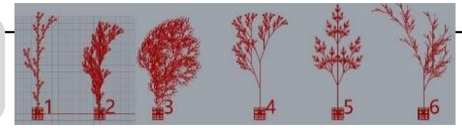


❖ Orientation optimization



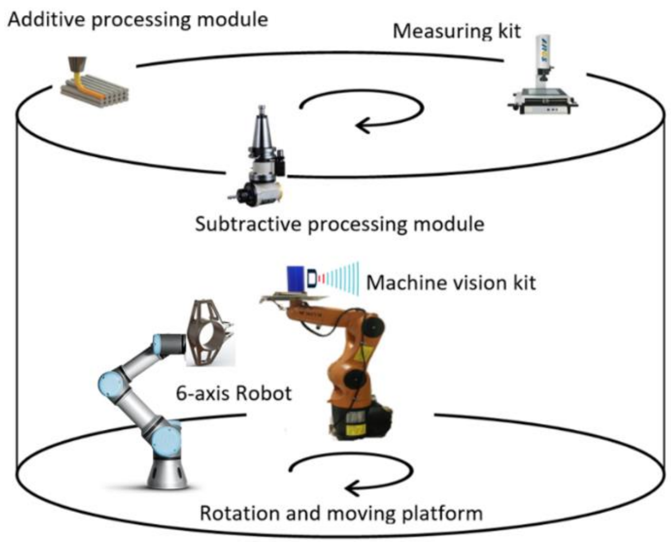
❖ Nesting & packing

❖ Bio-inspired support structure design



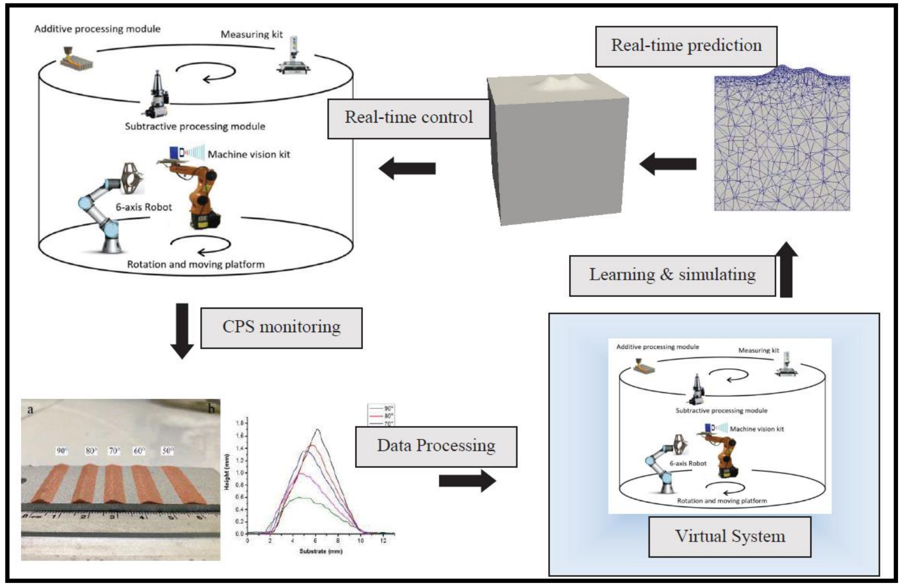
universités de technologie Belfort-Montbéliard Compiègne Troyes · icb · cnrs · UBFC UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ

❖ Current research focus: Robotic modular HAM development (4D printing smart metallic composite)



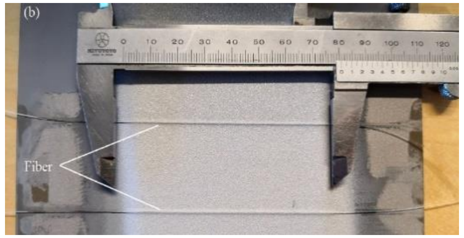
Knowledge base

modèle de prise de décision
modèle de prédiction
modèle de simulation
modèle d'optimisation
connaissance des matériaux et des procédés, etc...



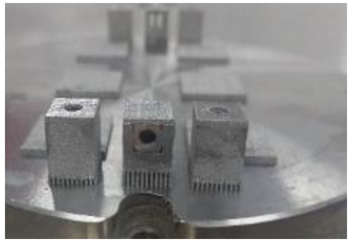
Collaborative robotic modular hybrid AM process platform & its digitalization concept

Some tentative application development

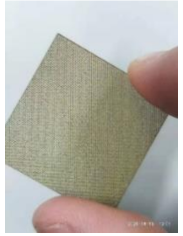


inc+aluminum+fiber sensor' (Lu, Zhang et al., IEEE Sensors, 2020)

'Copper + aluminum alloy'



'Copper with titanium alloy'



'Fine porous structures'

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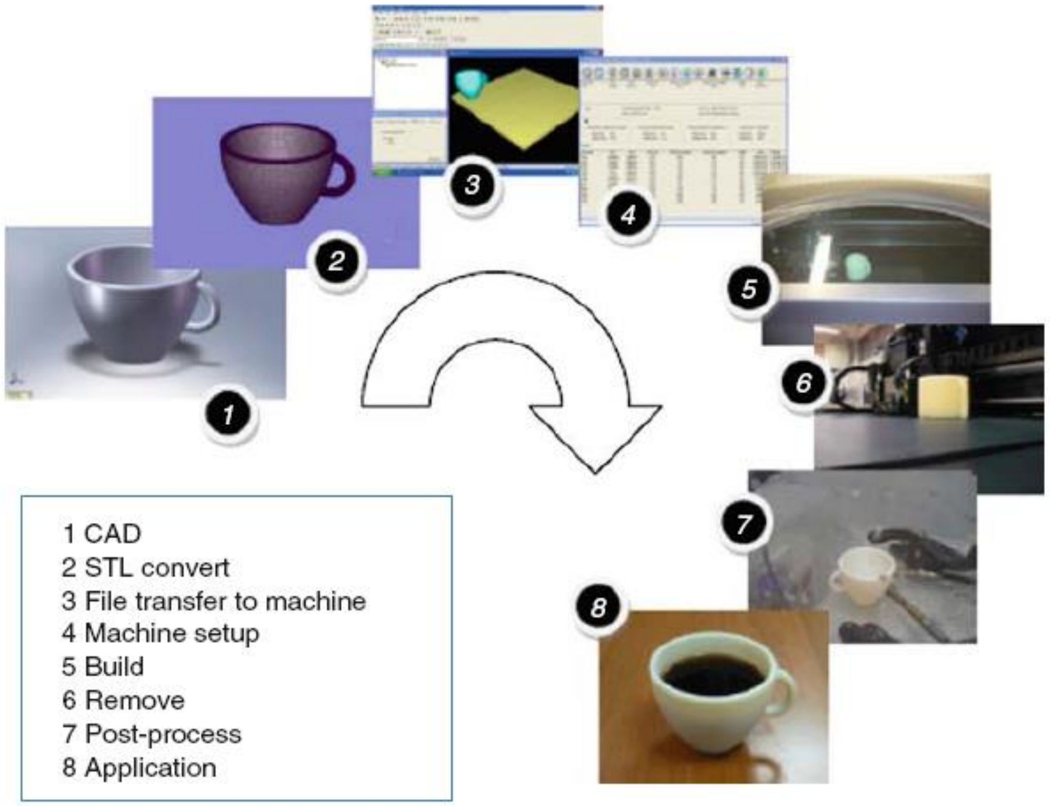
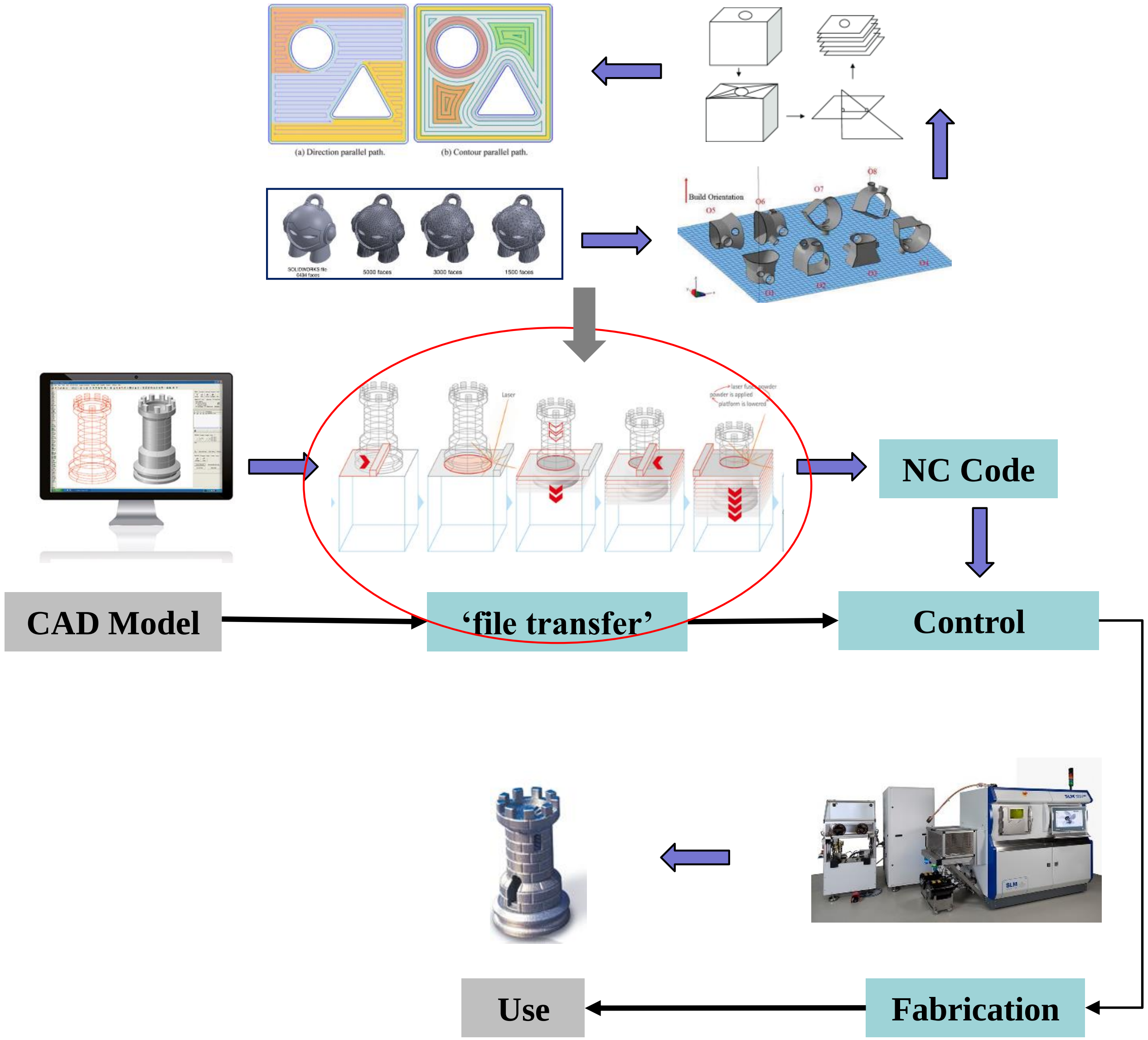
4. Conclusion & Perspectives

❖ What is AM?



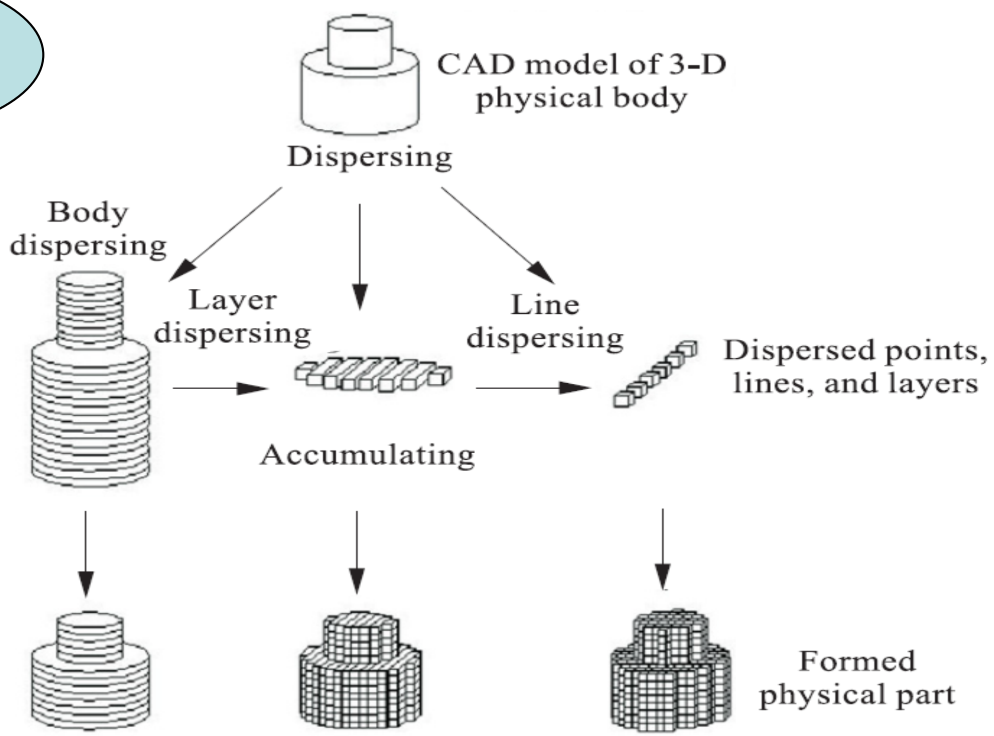
AM General Processing Chain (Ref.)



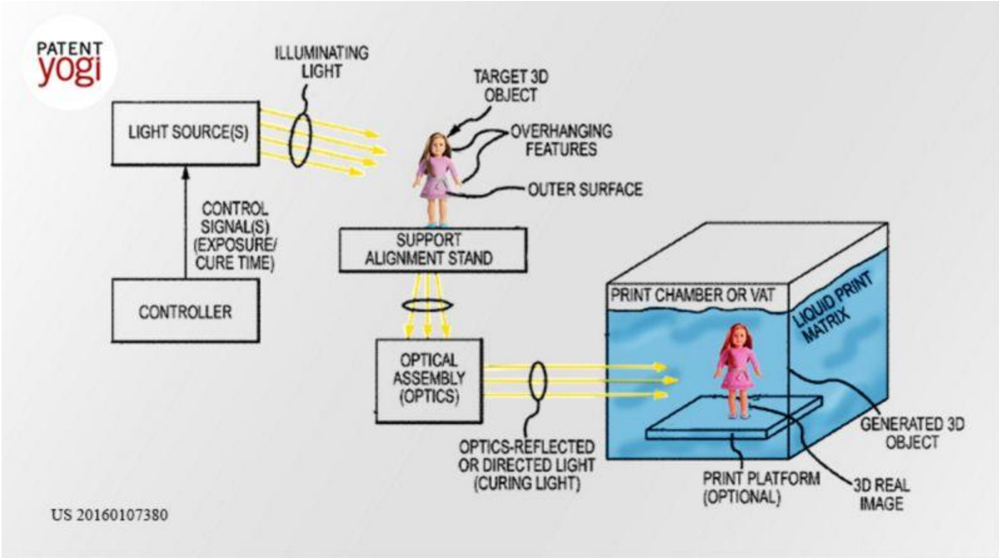
❖ What is AM?

Digital Decomposition

Physical Assembly



AM Principles (Ref.)

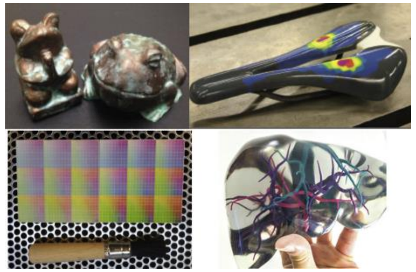


'3D' printing (Ref.)

Applying a kind of or several kinds of energy (laser, electronic beam, ultrasonic wave, binder, etc.) to join a kind or several kinds of materials (plastic, ceramic, metals, bio-cells, food, etc.) in an accumulative way (spot-by spot, line-by-line, layer-by-layer, or 3D at once/ instantaneous) to build 3D physical model from virtual CAD model.

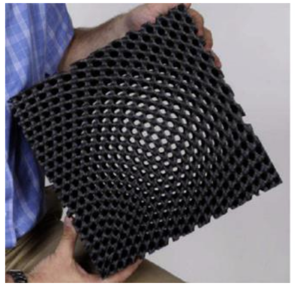
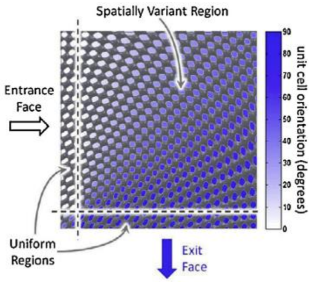
❖ What can AM do?

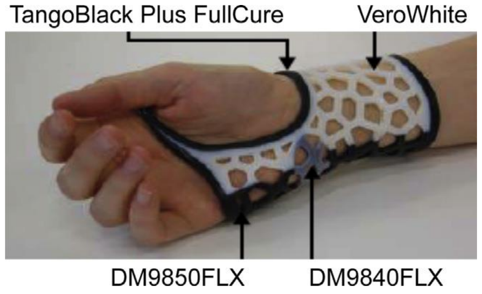
* Structure level in macro scale complexity



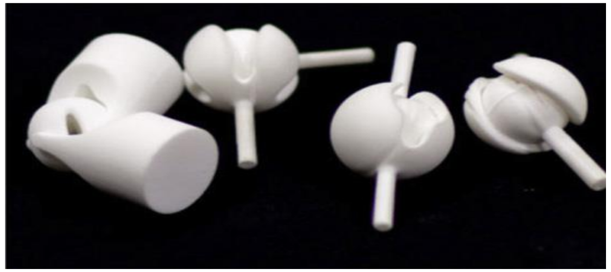


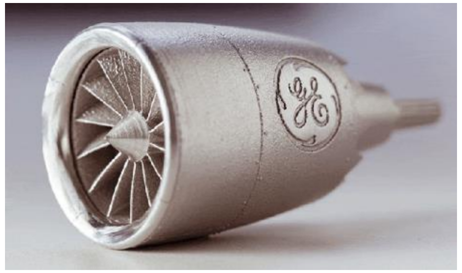

* Material level in micro scale complexity




* Product level in functional scale complexity

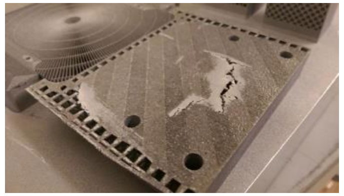




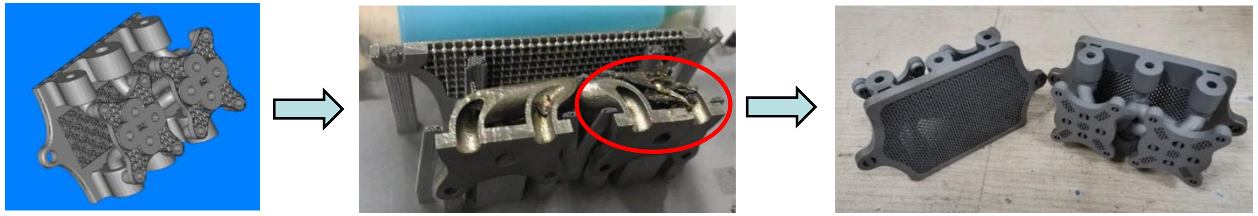
Complex AM components (Ref.)

❖ Sometimes, AM is still a lotto (even design is given)?





Defects are always unexpected (Ref.)



As designed = As printed? Never sure!

How to design?

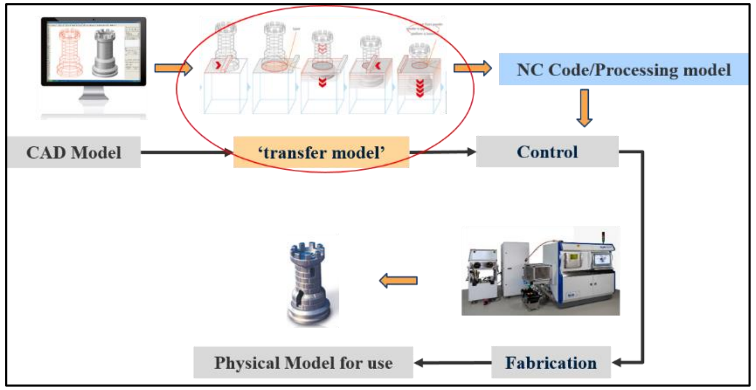
1. Complex geometry definition
2. Multi-material assignment
3. Complex structure simulation…

Why failed?

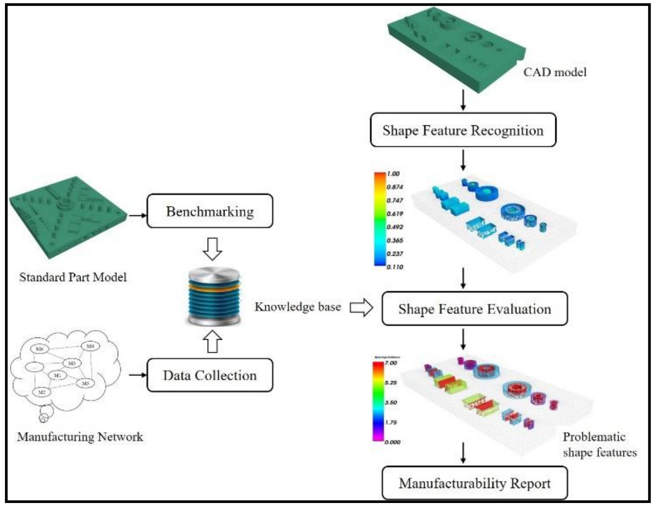
1. Material not right?
2. Design has problem?
3. Process is not stable?
4. Preparation work is wrong?

……

Accuracy loss in data transformation



Design not verified



❖ What is Design for AM?

Design for additive manufacturing (DFAM) is a set of decision making methods and computational tools to support the designer to generate, simulate and validate their design that is tailored for additive manufacturing with ensured manufacturability and quality).

*Why DFAM?

1. Avoid AM constraints
2. Harness the complexity ability of AM
3. Save time & cost
4. facilitate the AM processing, including pre-processing, layered building and post-processing

Try to get more benefits of AM and meanwhile avoid constraints of AM!

Current methods

- Group 1: **case/rule based methods**

Use design case or design rule to represent design knowledge to guide design process.

- Group 2: **computation based methods**

Use mathematical computation/simulation methods to automatically determine and define geometric elements for design solutions.

- Croup 3: **hybrid methods**

Combine the two kinds of methods to define design solutions.

❖ Rule/feature-based Design for AM

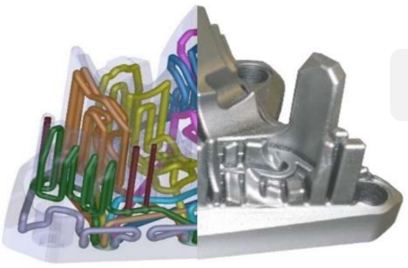
Definition of standard geometric unit shapes

Send to different AM machines for fabrication

Measure & evaluate manufacturing results

Structure design guidelines & rules

Why use simple shapes for benchmarking?



Shape decomposition

Law:

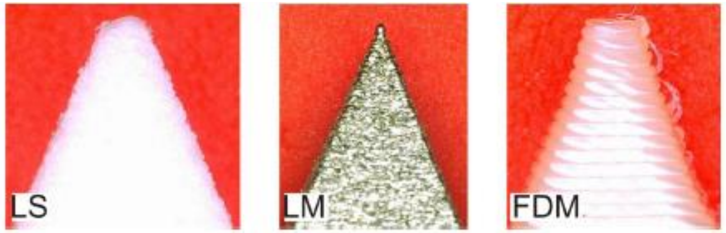
If

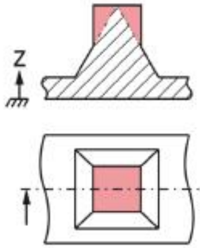
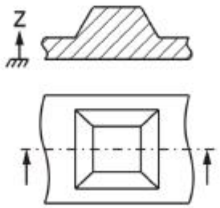
a simple shape has production problem

Then

a complex shape that contains the simple shape also has problem

❖ Rule/feature-based Design for AM



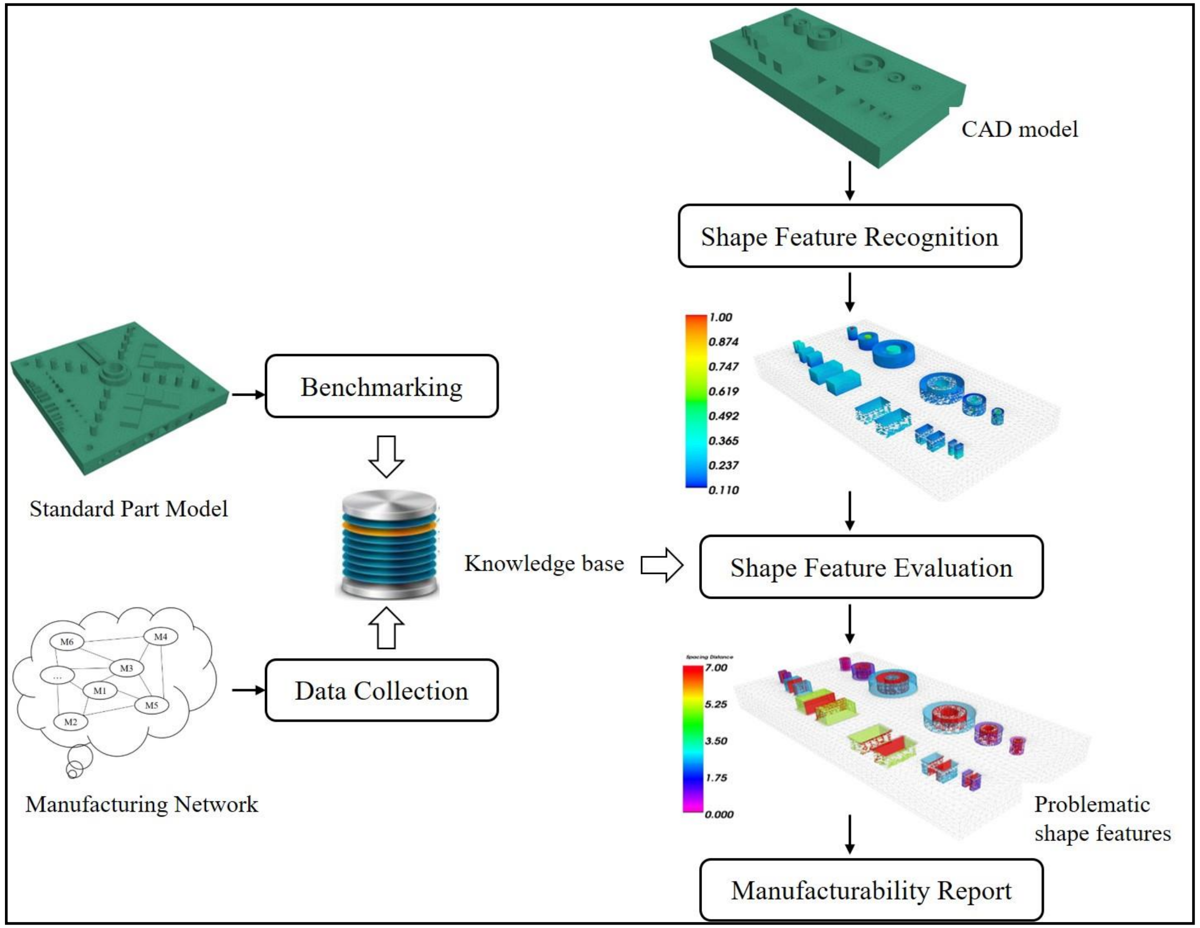
Regular description / Specific description	Unsuitable design	Suitable design	LS	LM	FDM
Corners that form an vertical extreme point should be blunted parallel to the building plane. The dimensions of the blunted area should be larger than the thickness of a wall.			X	X	X

- 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.

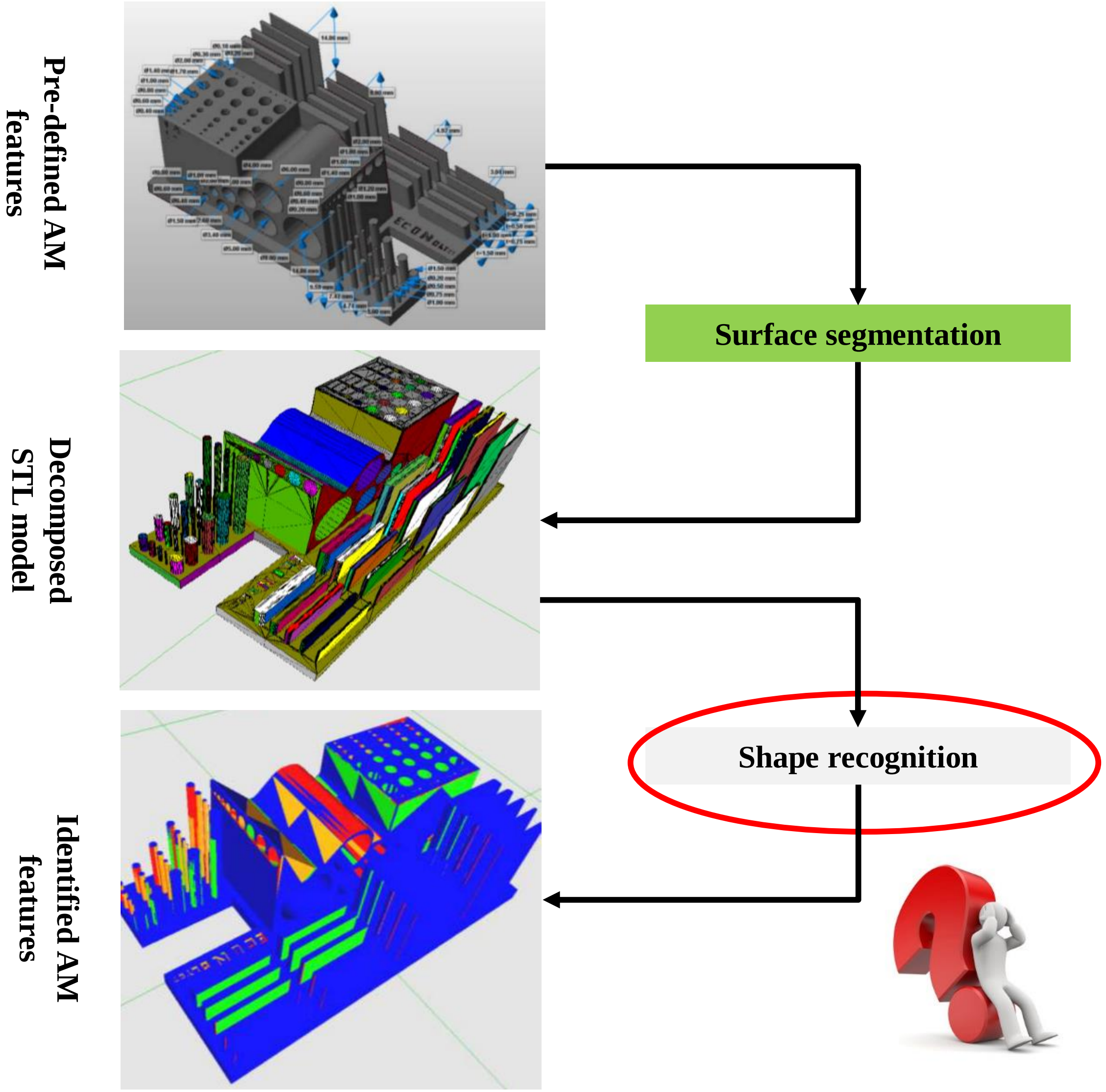
Corners with sharp nominal shapes:

Feature-based AM design knowledge/guide line structuring (Ref.)

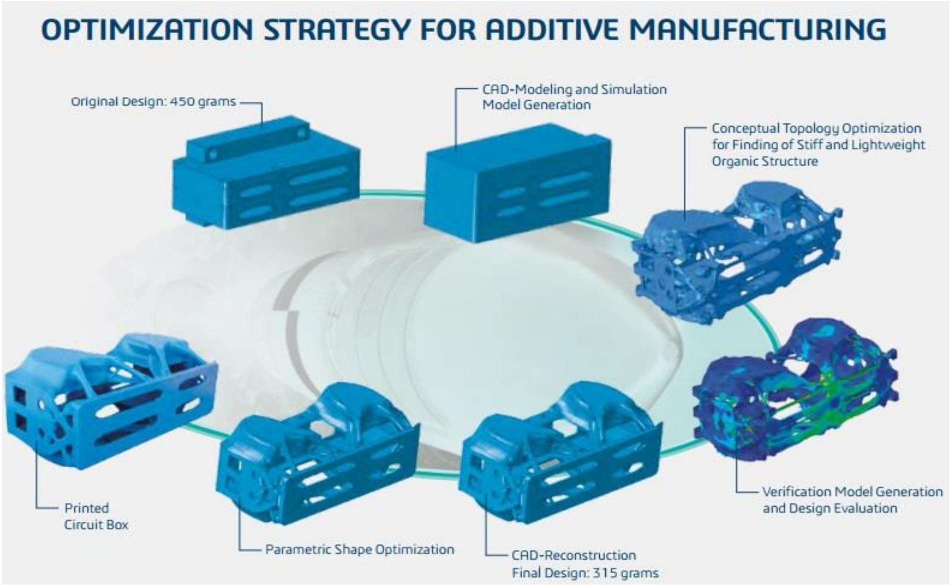
❖ Rule/feature-based Design for AM

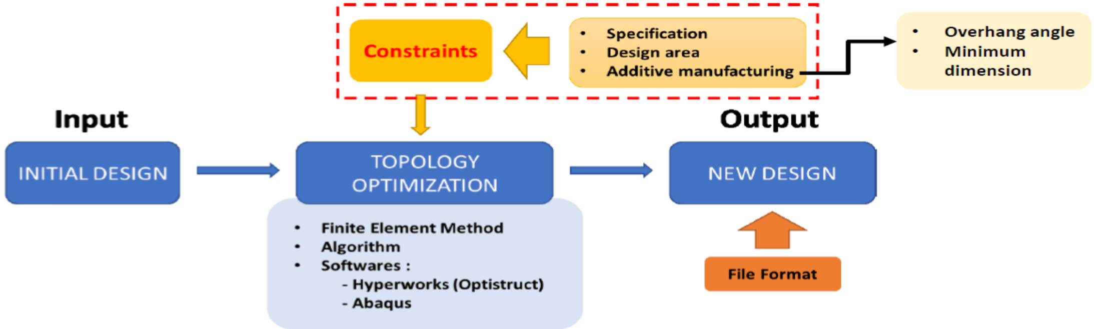


Feature-based design evalution (Zhang, Y et Bernard A, 2018, Shi Y, Zhang Y et al., 2018 & 2019)

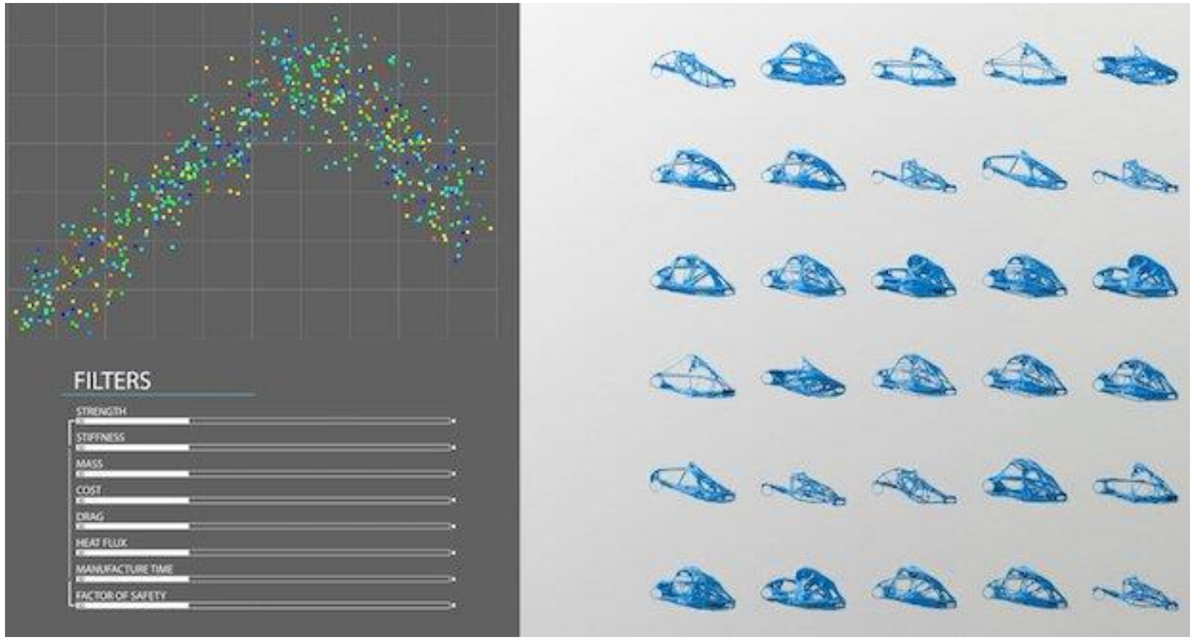


❖ Computation based methods: TO and TO-based generative design





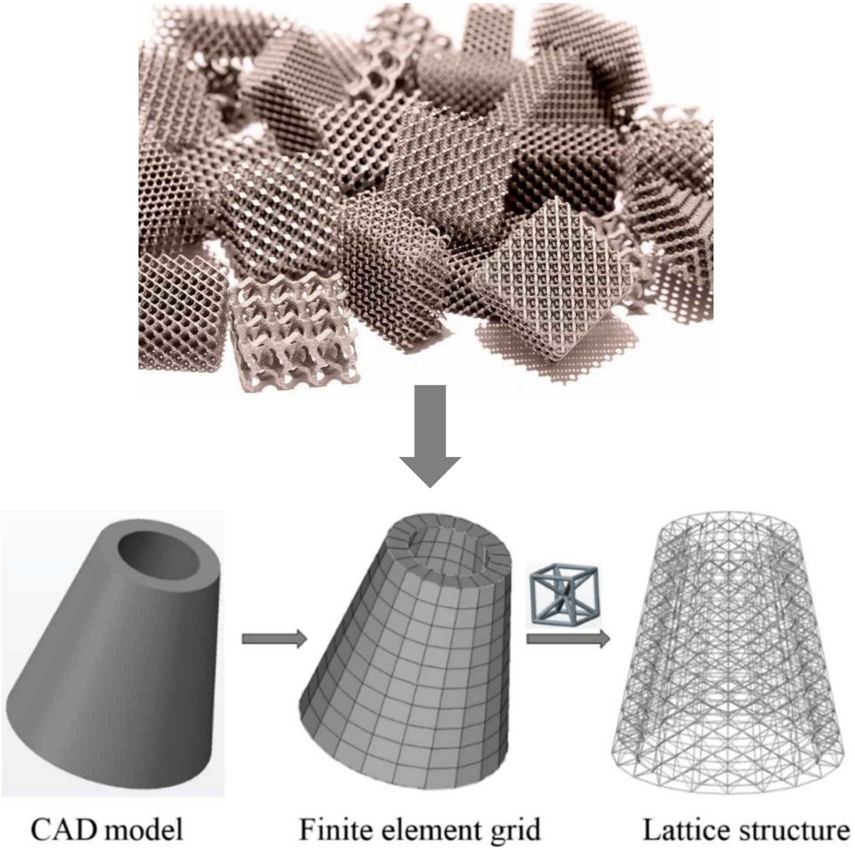
TO with AM constraints embedding



TO-based generative design (Ref.)

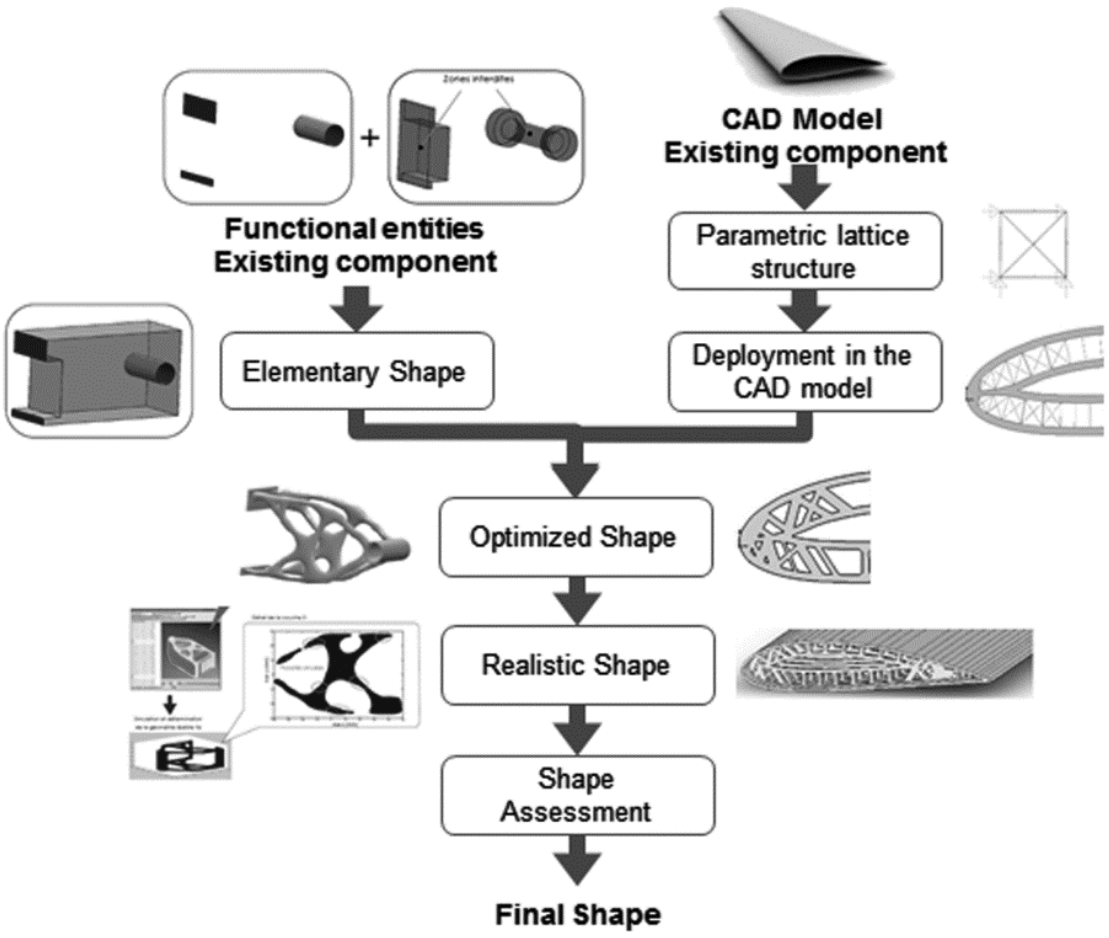
❖ **Computation based methods: geometric function-based control and generation & lattice filling**

Implicit mathematical function controlled shape generation (Ref.)

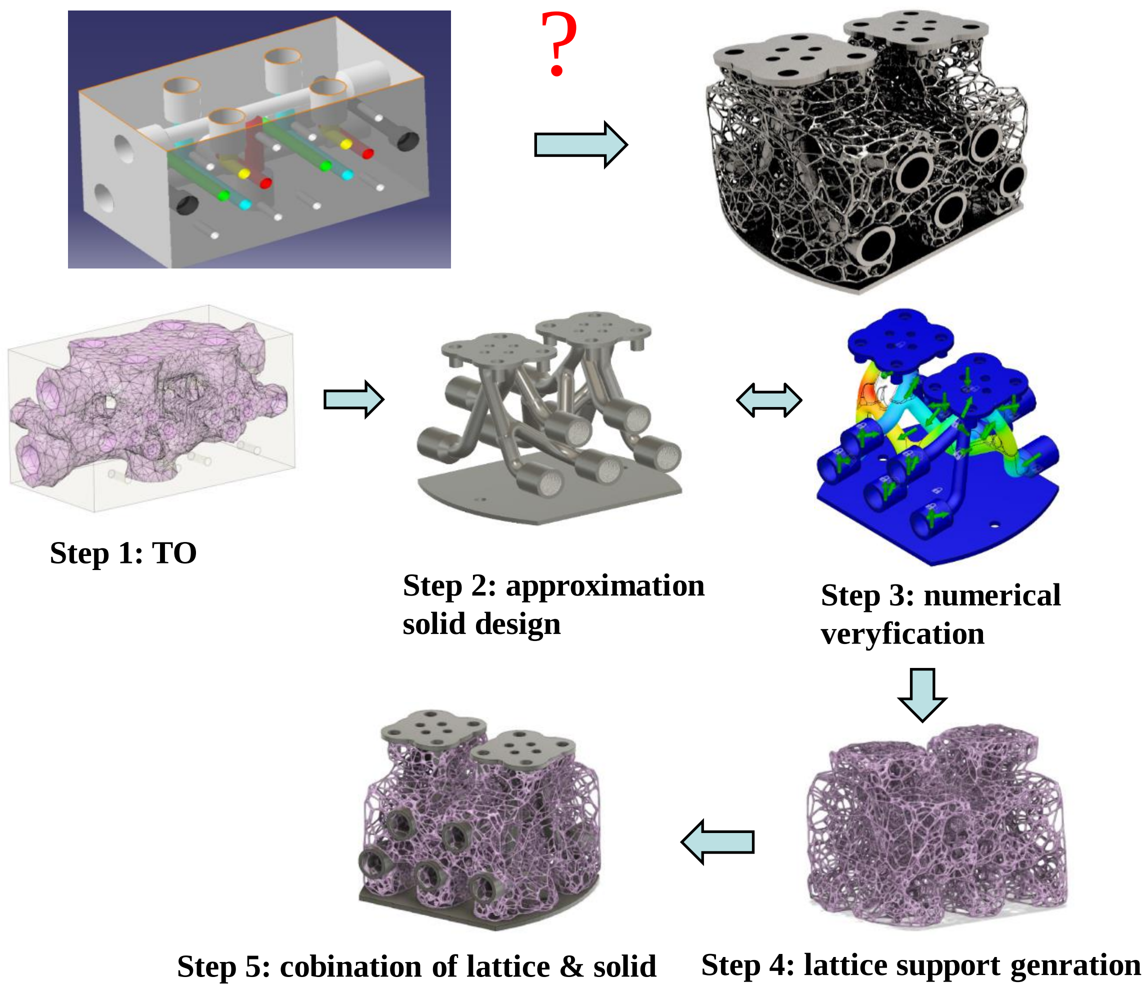


Periodic unit cell/lattice cell filling (Ref.)

❖ Hybrid methods



Hybrid DFAM (Ref.)



A practical redesign for AM method (Zhang et al,, 2021)

❖ Summary & strategy to current DFAM methods

Current DFAM roadmap

1. Subtractive way to define the geometry topology (e.g. TO)
2. Focus only on AM but neglect other process
3. Get used to ‘DFX’ but hardly to think about ‘XFD’
4. Focus more on structure design but less on system design

Proposals to extend the roadmap

1. Generative way to define the geometry topology
2. Hybrid method to consider the collaboration with other processes
3. Inversed implicit design method for manufactability
4. System design method to get benefits of both AM and non-AM

More perspectives on DFAM can be found in a CIRP Keynote paper (Vaneker, T., Bernard, A., Moroni, G., Gibson, I., & Zhang, Y. *Design for additive manufacturing: Framework and methodology*.)

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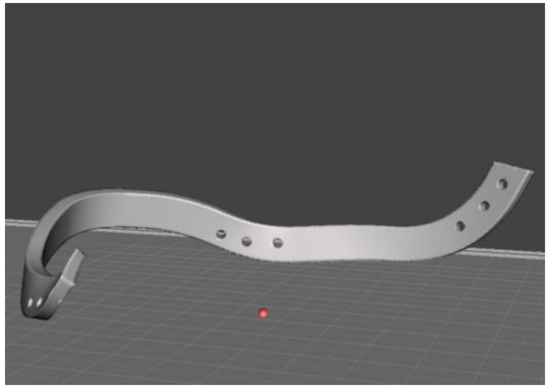
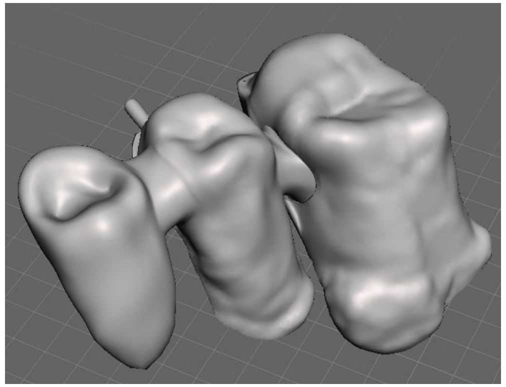
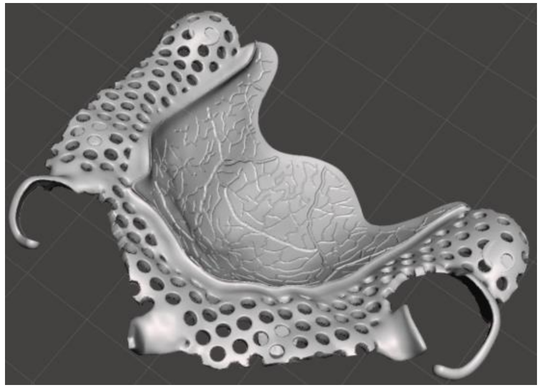
❖ **Top-down constructive generative DFAM: Bio-inspired generative design for support structure design**

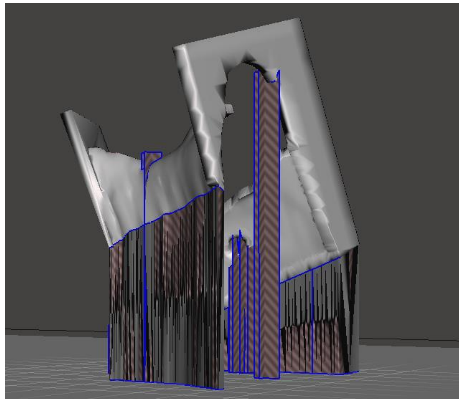






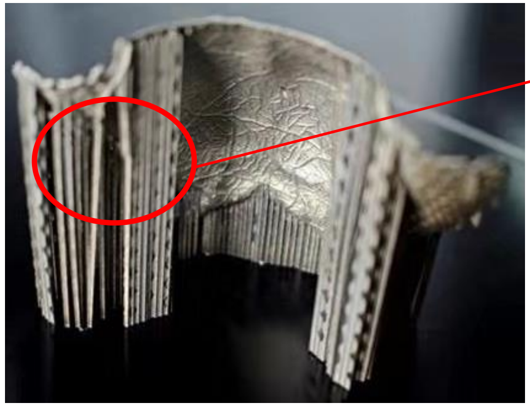
Complex dental components in AM

AM is suitable for customized and complex components.



Example from Autodesk

Example from Magics



Example from Profeta

Suppport deformation

Many materials wasted! More than 50%! (support volume VS component Volume)

❖ **Top-down constructive generative DFAM: Bio-inspired generative design for support structure design**

Fragile thin wall parts, hard for mannual post-processing

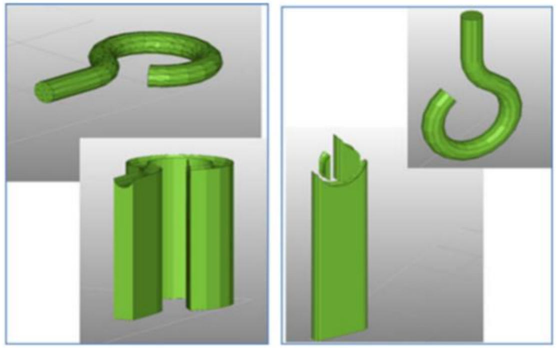
<u>As-is situation</u>: >50% material wasted; support structure is not verified; long post-processing time

<u>To be situation</u>: Ensure support quality, reduce material time & cost

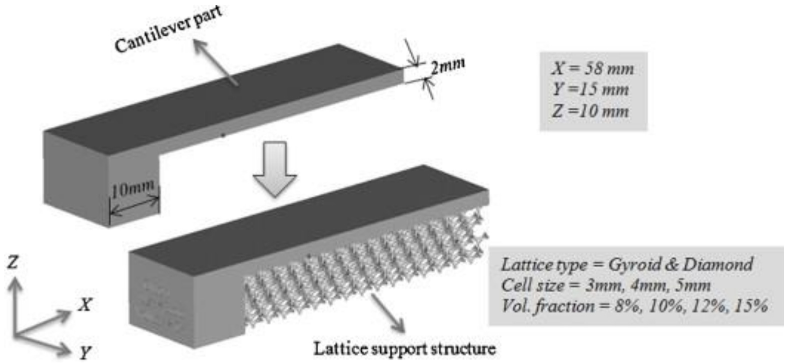
Industrial Needs: Automatic generation & optimization; ensured support quality; easy for post-processing

<u>Save material, post-processing time and improve the support quality</u>

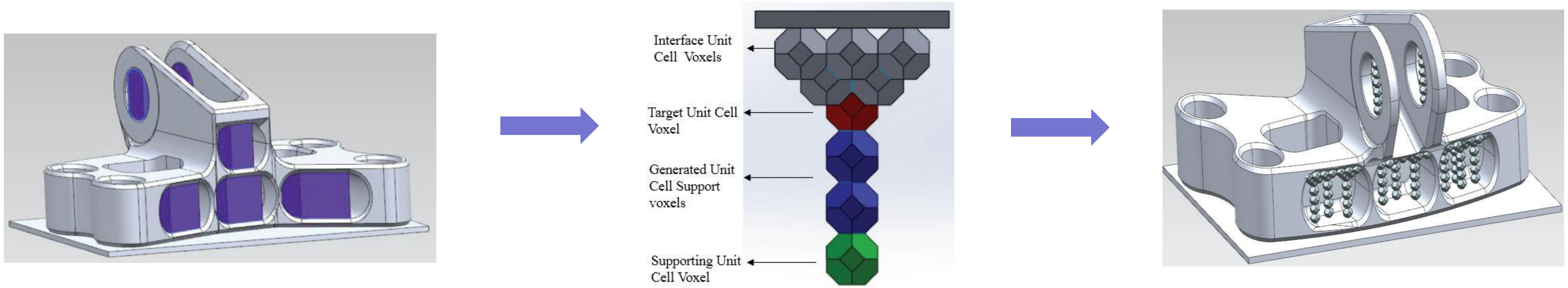
❖ **Top-down constructive generative DFAM: Bio-inspired generative design for support structure design**



Filling projection area with solid walls (G. Strano et al., 2013)

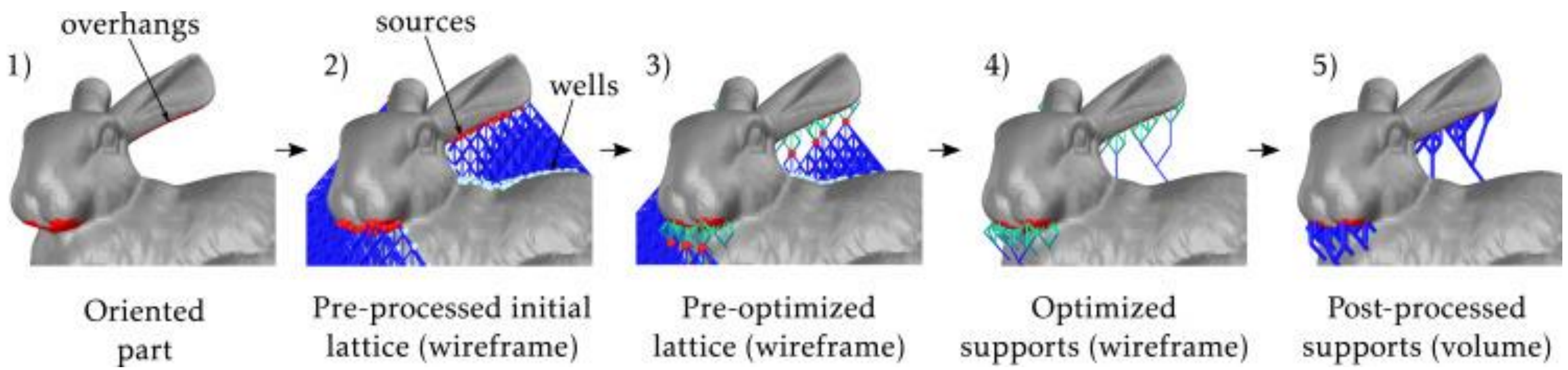


Filling projection area with porous walls (A. Houssein et al., 2013)

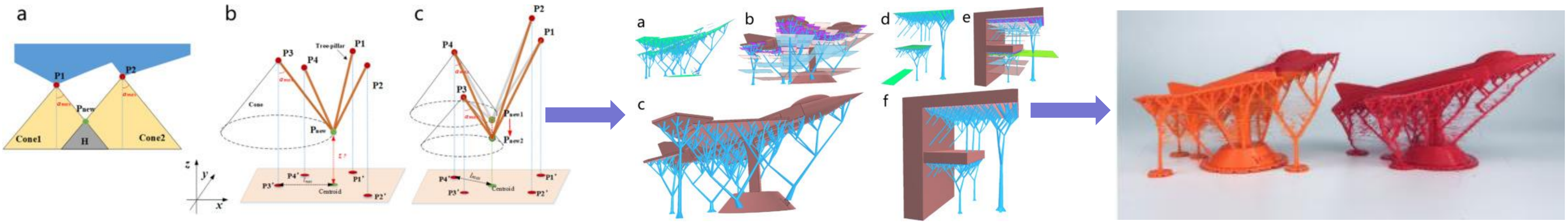


Sparsely filling with cellular structures (Rohan Vaidya and Sam Anand, 2016)

❖ Top-down constructive generative DFAM: Bio-inspired generative design for support structure design



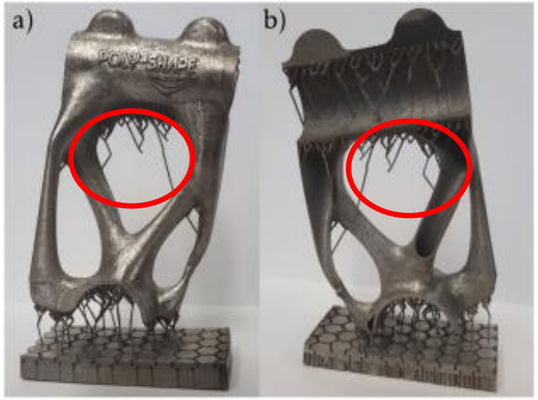
Sparsely filling with cellular structures (B. Vaissier et al., 2019)



supporting cone based tree or bridge shapes (J. Vanek et al., 2014)

- **Summary for the state-of-the-art**

  1) **Many limited to non-metallic AM processes with less consideration of metallic AM processes constraints**
  2) **Manufacturability and stability of the support structure itself are rarely considered, especially In metallic AM (e.g. strength, heat diffusion and the deformation of the support structure itself)**
  3) **Identifying the optimal support points on the overhang areas has never been investigated**
  4) **Complex demonstration examples at the industrial level are missing**

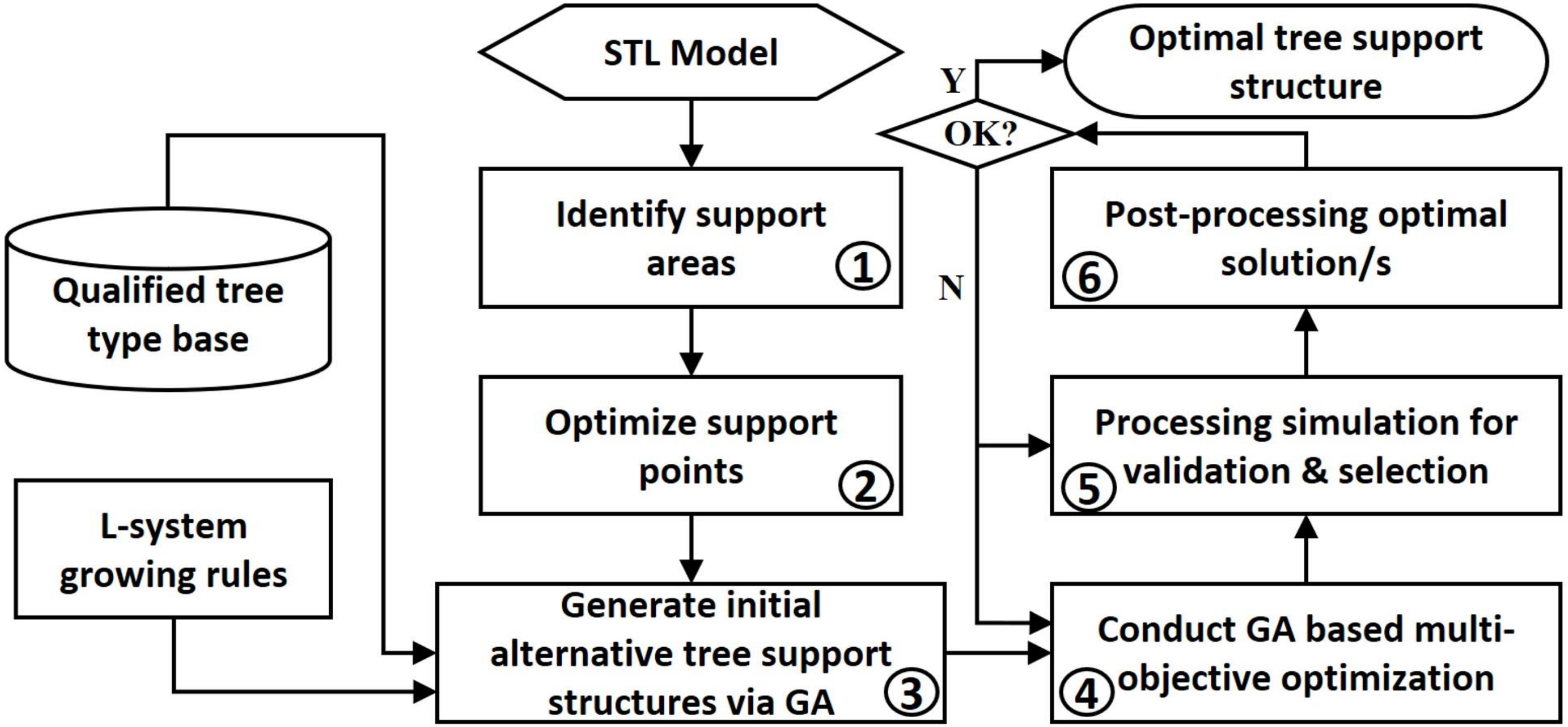


Broken of support structure in printing
(B. Vaissier et al., 2019)

- **Research objective**

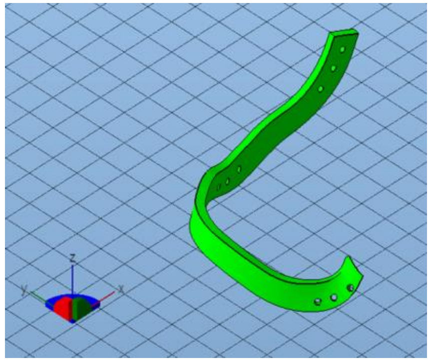
  1) **Optimize with consideration of metallic AM constraints**
  2) **Simulate the printing process to ensure the support quality**
  3) **Reuse predefined and qualified support shape for efficiency and stability**
  4) **Apply generative design for better multi-criteria decision making**

❖ **Top-down constructive generative DFAM: Bio-inspired generative design for support structure design**

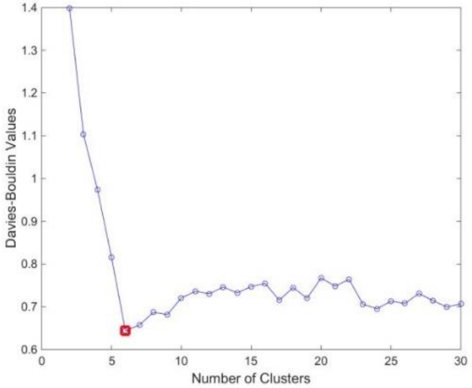


The main workflow of the proposed method

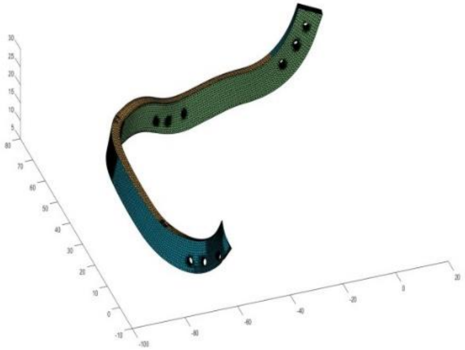
❖ Step 1: support area identification



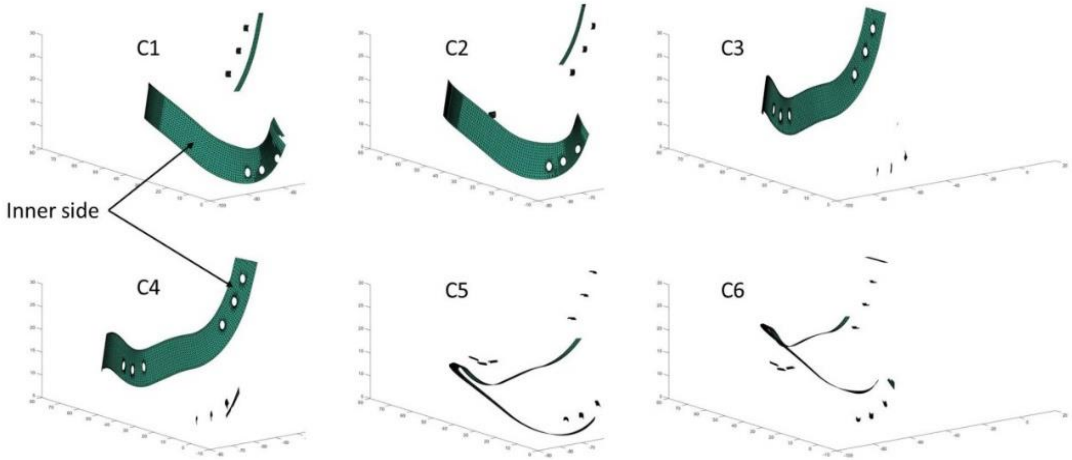
STL CAD model



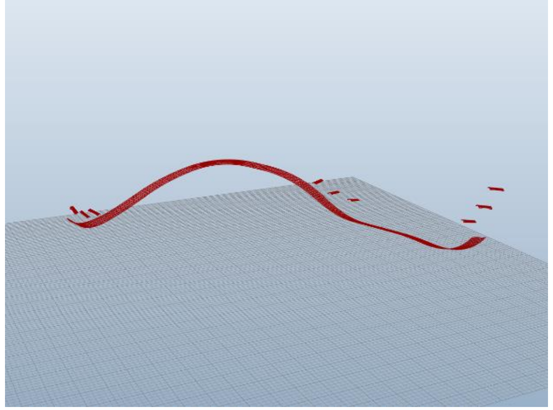
Facet clustering analysis



Model decomposition



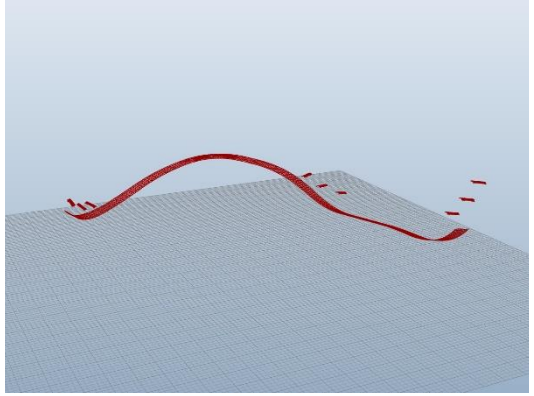
Alternative orientation generation

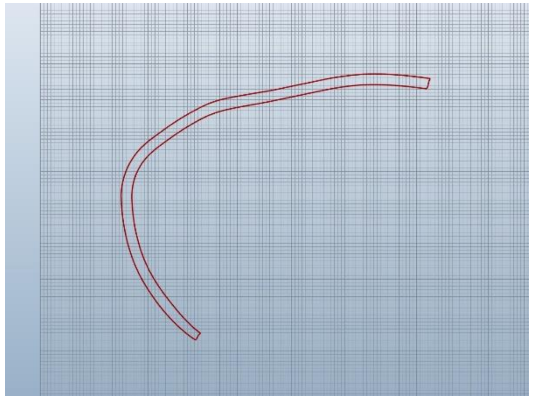


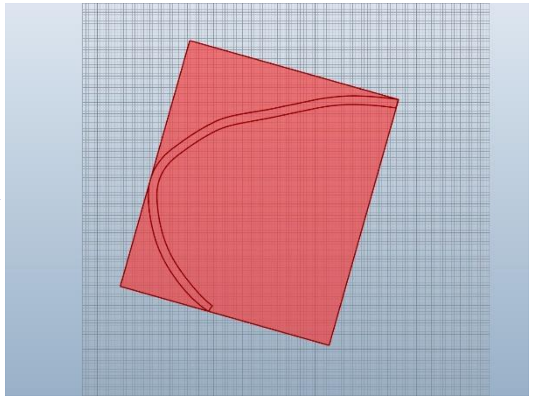
Support area determination

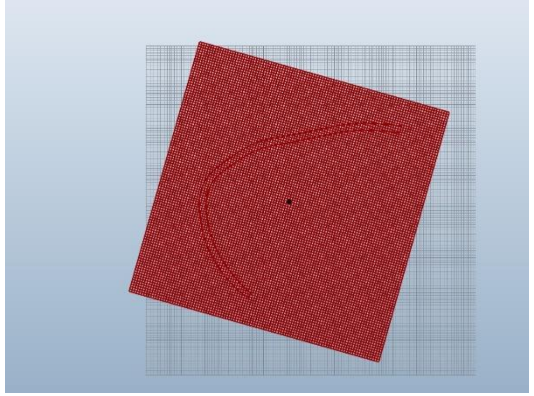
Statistic method for build orientation determination and support area identification (Y. Zhang et al., 2019)

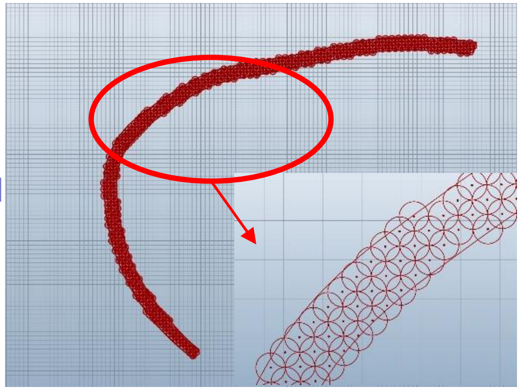
❖ Step 2: support point optimization

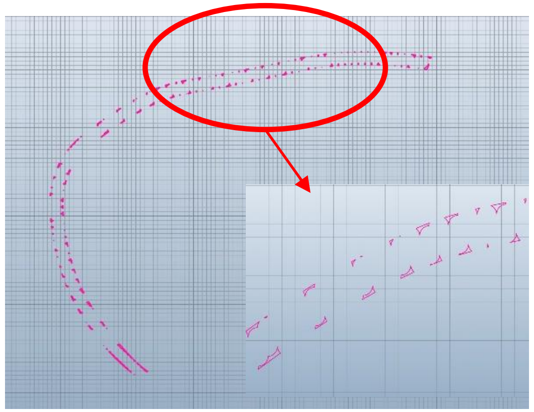

Support area identification

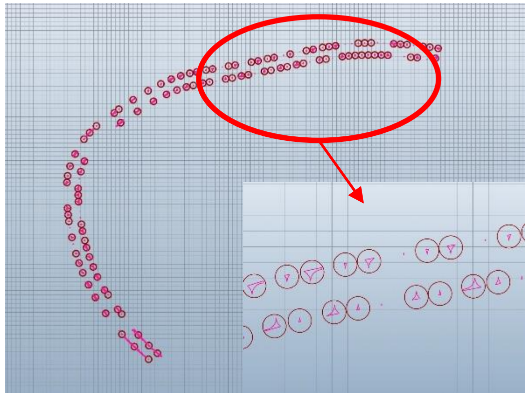

Support area projection

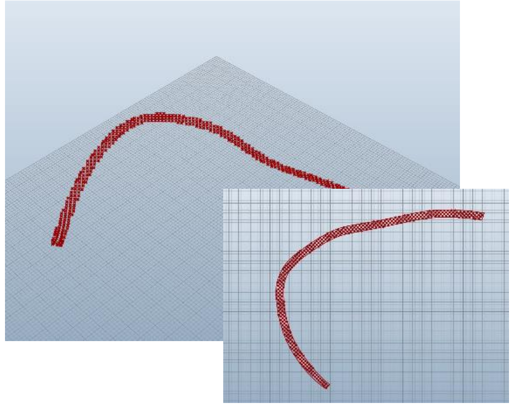

Bounding box generation


Seeding in bounding box


Overhang length circle generation

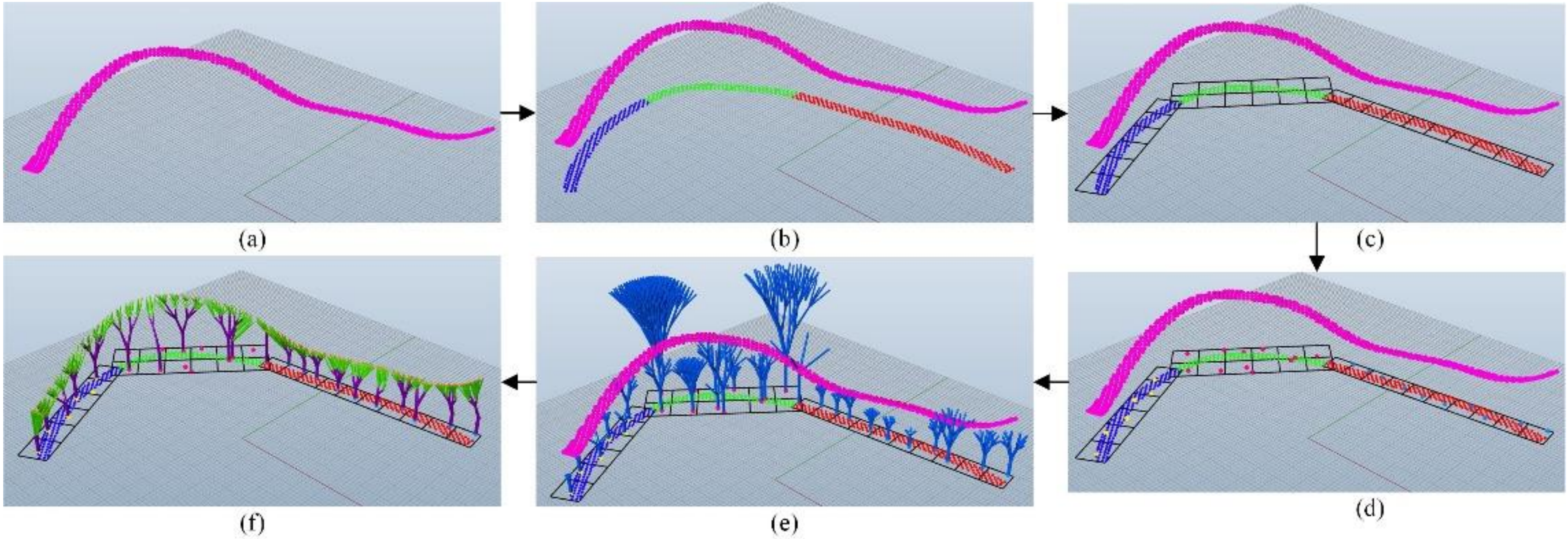

Boolean difference with boundary


Overhang length circles for boundary


Circle center re-projection onto support rarea

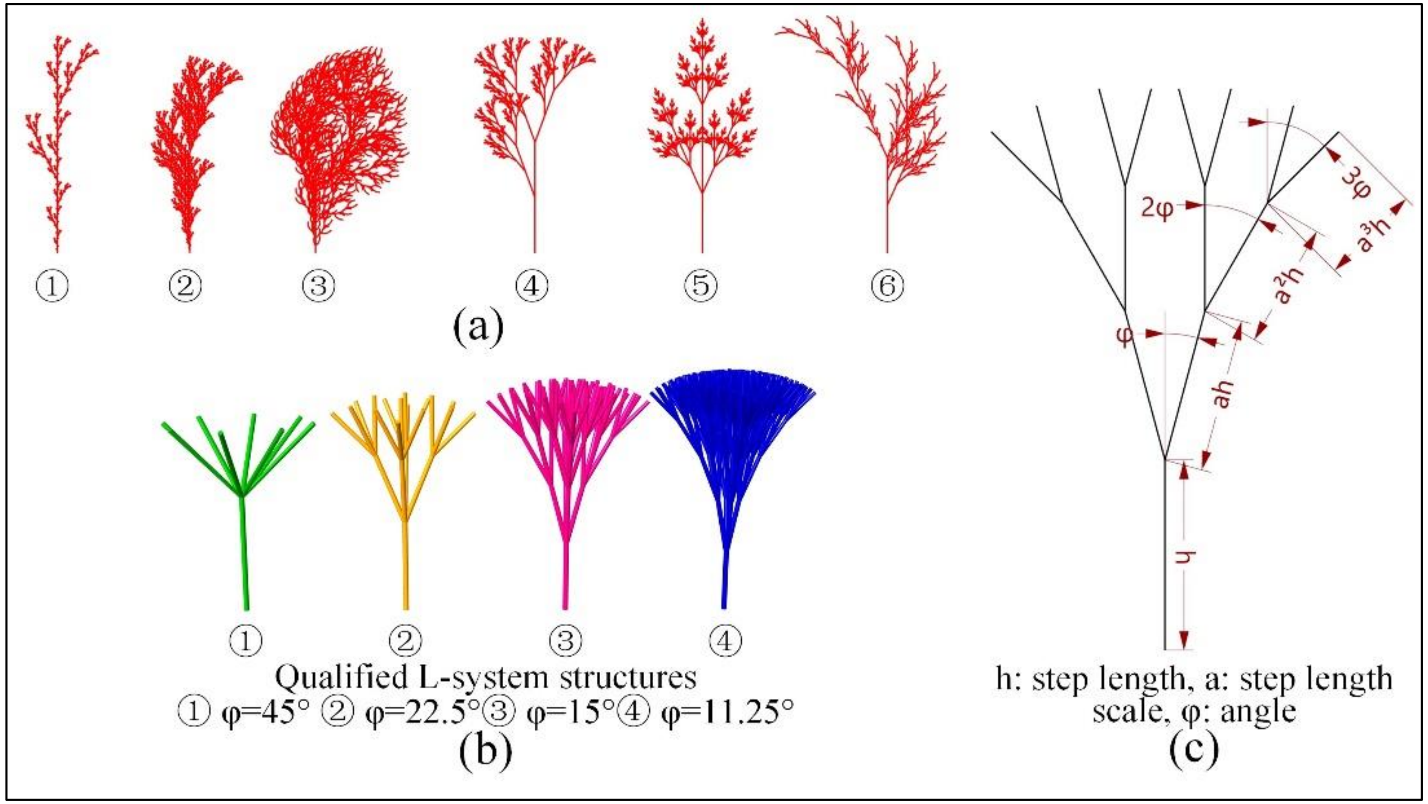
Yicha Zhang, et al, CIRP Annals 2020;Zhiping Wang, Yicha Zhang et al., Additive Manufacturing, 2021

❖ Step 3: tree structure generation via L-system



Tree structure generation procedure: a. support area; b. available overhang length circle centers; c. centers decomposition (depend on height and number of support points); d. randomly generate tree roots; e. L-system growing; f. tree pruning (shortest path rule)

❖ Step 4: GA encoding for optimization



Example predefined validated unit shapes/L-system structures

Objectives

- **Volume of support structures**: $F_1(x) = V = \sum_{i=1}^{n} v_i$ where v_i is the volume of i-th L-system, V is sum of volumes.
- **Number of collisions**: $F_2(x) = C = \sum_{j=1}^{n} c_j$ where c_j is the number of collisions between jth L-system and the part, C is sum of collisions.

Chromosome

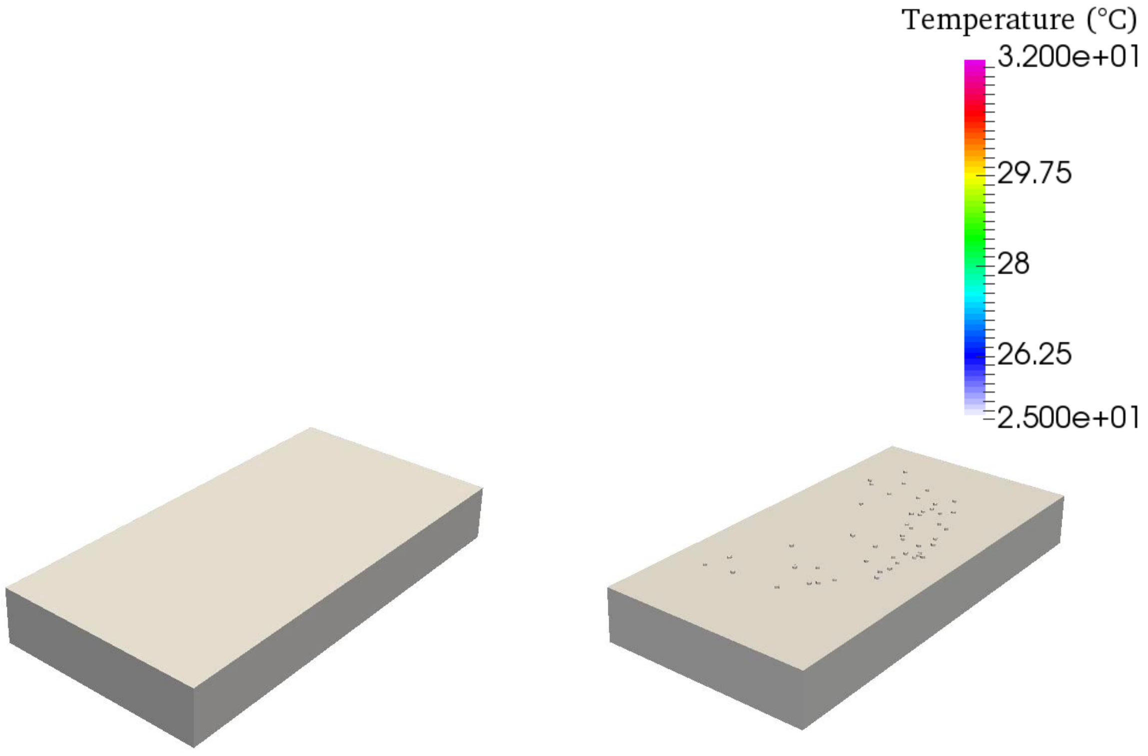
L_1	L_2	⋯	L_k	⋯	L_n	→ L_k is the k-th L-system structure
s_1	s_2	⋯	s_k	⋯	s_n	→ s_k is one of 4 kinds of L-system
h_1	h_2	⋯	h_k	⋯	h_n	→ h_k is step length
a_1	a_2	⋯	a_k	⋯	a_n	→ a_k is step length scale
p_1	p_2	⋯	p_k	⋯	p_n	→ p_k is initial position
α_1	α_2	⋯	α_k	⋯	α_n	→ α_k is initial orientation

❖ Step 5: process simulation for support growth

1. Non-exposed powder is considered for heat diffusion throughout the support branches

2. Two interfaces between support and non-exposed powder and between powder bed and gas are tracked by the level-set method to distinguish the different material domains

3. The interface for the deposited layer (between powder bed and gas, ψ^t) is updated by the deposited thickness Δz_l through $\psi^{(t+\Delta t)}=\psi^t-\Delta z_l$. The linear diffusion equation is used to improve computation efficiency for heat transfer analysis.

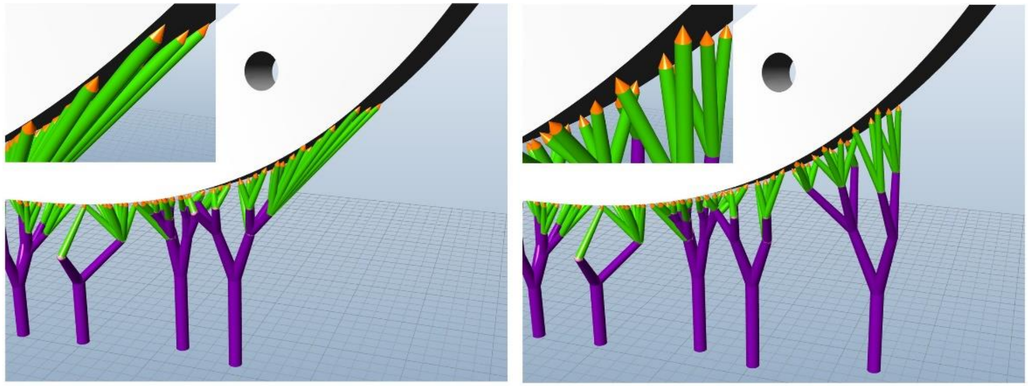


A simulation example for a L-system tree support

Macroscopic thermal finite element modeling of additive metal manufacturing by selective laser melting process (Y. Zhang et al., 2018)

❖ **Step 6: post-processing for support tips with contact point**

1. **Locate the collision areas**
2. **Adjust branch angle or further break the branch into the next sub-level and find the shortest child branch without collision**
3. **Construct conic shapes for the branch tips to connect with the contact points**



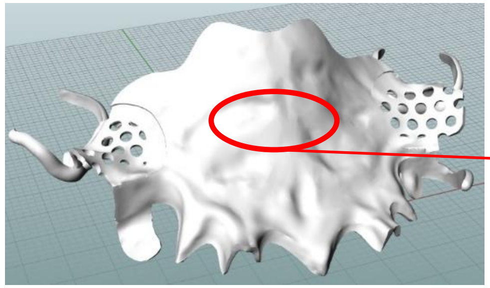
(a) Collision (b) No collision

❖ **Notes to the whole method:**

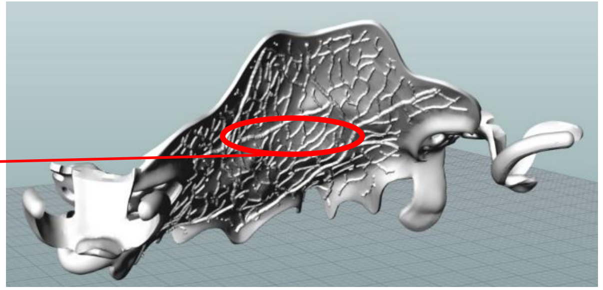
1. **Numerical simulation is used only for a set of limited solutions on the Pareto front**
2. **The setting of the L-system parameters depends on specific SLM process and can be set according to specific AM knowledge**
3. **The setting of GA optimization objective functions depends on the application objectives**

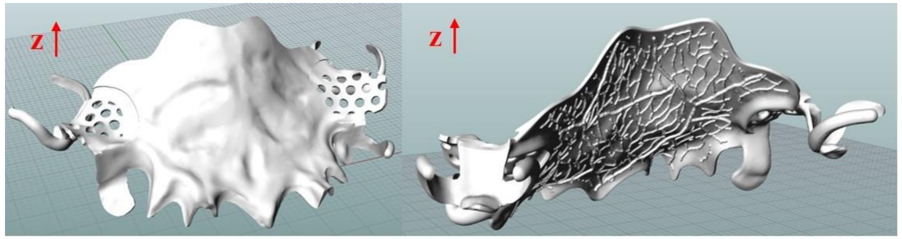
❖ Case study: introduction

A real dental component of a patient is selected for method validation. The component is also tested by three other popular industrial support generation tools (E-stage, Profeta and Meshmixer) for comparison study in this research.

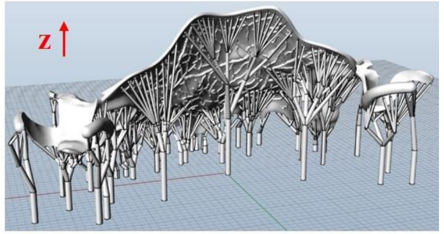


Application requirements: maximize the shape accuracy of the fine geometric features and minimize support contacts on these surfaces

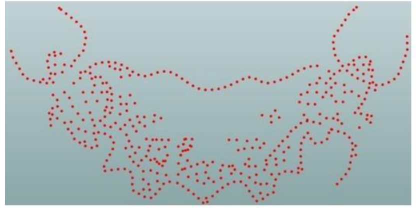




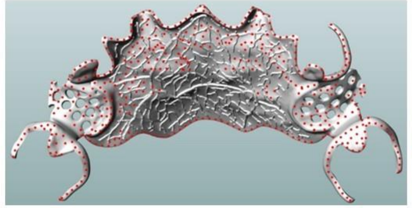
(a)



(d)



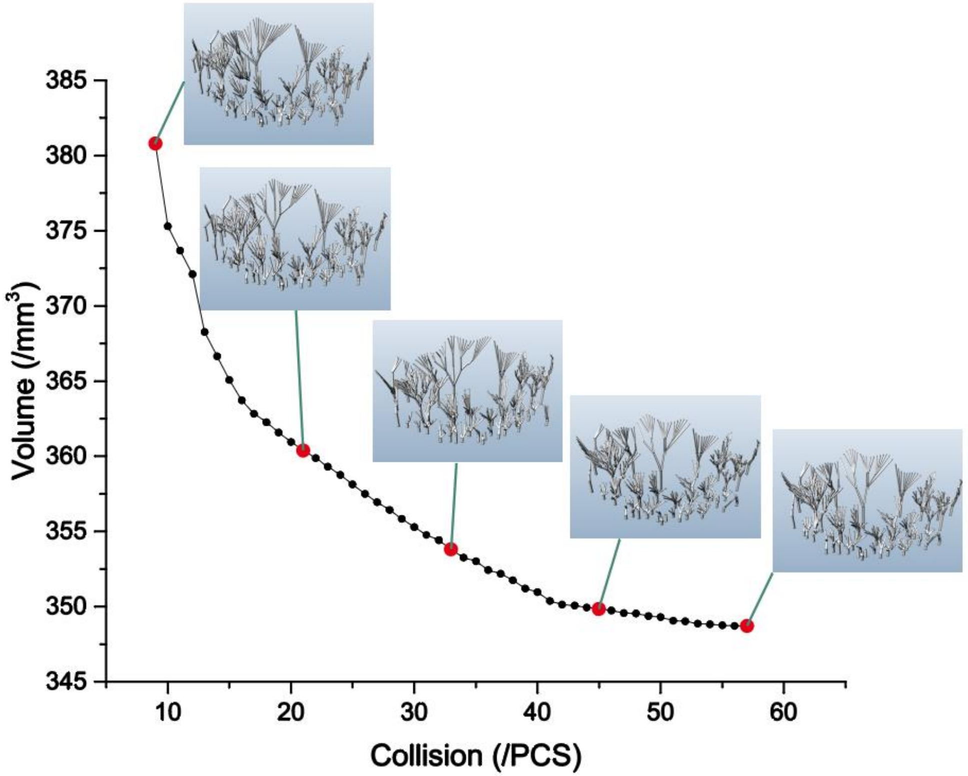
(b)



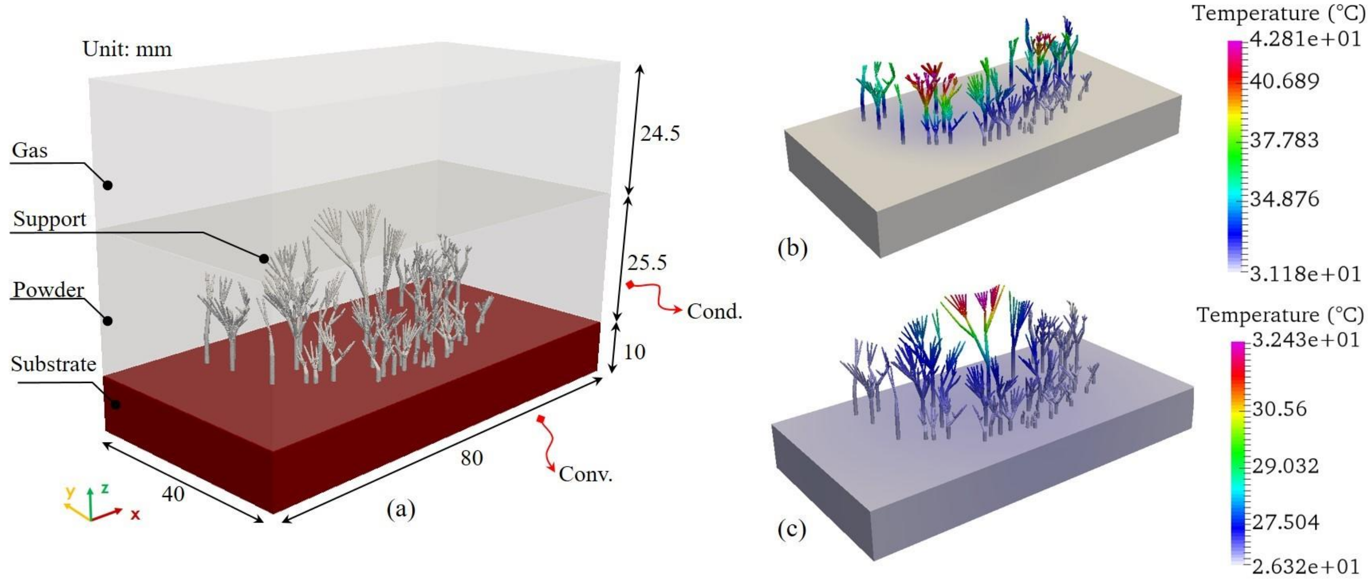
(c)

a. build orientation determination; b & c. optimized support points; d. an alternative tree structure generated via L-system rule

❖ Case study: GA optimization result and numerical simulation for solutions on the Pareto front

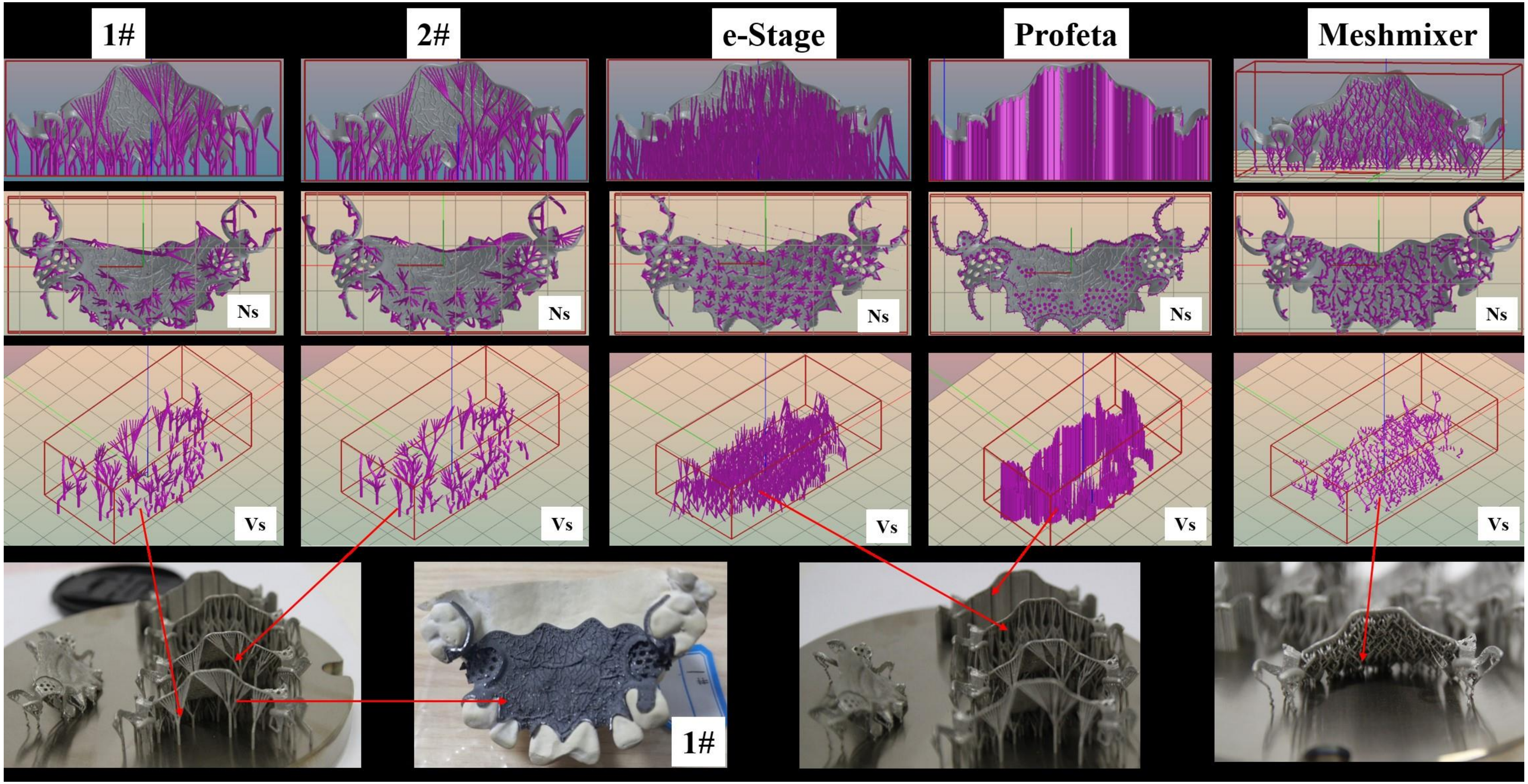


5 non-dominated solutions on the Pareto front



Example simulation: (a). tree structure growing simulation model; (b). temperature distribution in printing after dwell time (growing height of 12.6mm); (c). temperature distribution at the end of printing after dwell time (growing height of 25.5mm).

❖ Case study: result & comparison (2 L-system trees with 3 other industrial solutions)



Yicha Zhang, et al, CIRP Annals 2020

❖ Case study: result & comparison (2 L-system trees with 3 other industrial solutions)

Solution	1#	2#	E-stage	Profeta	Meshmixer
V_s(g)	2.06	1.99	3.29	6.93	2.16
N_s	Less	Less	Most	Medium	Most
R_a	Best	Best	Worse	Worse	Worst
P_t	less	less	more	more	most

V_s: support volume; **N_s**: number of support/contact points; **R_a**: surface roughness; **P_t**: post-processing time.

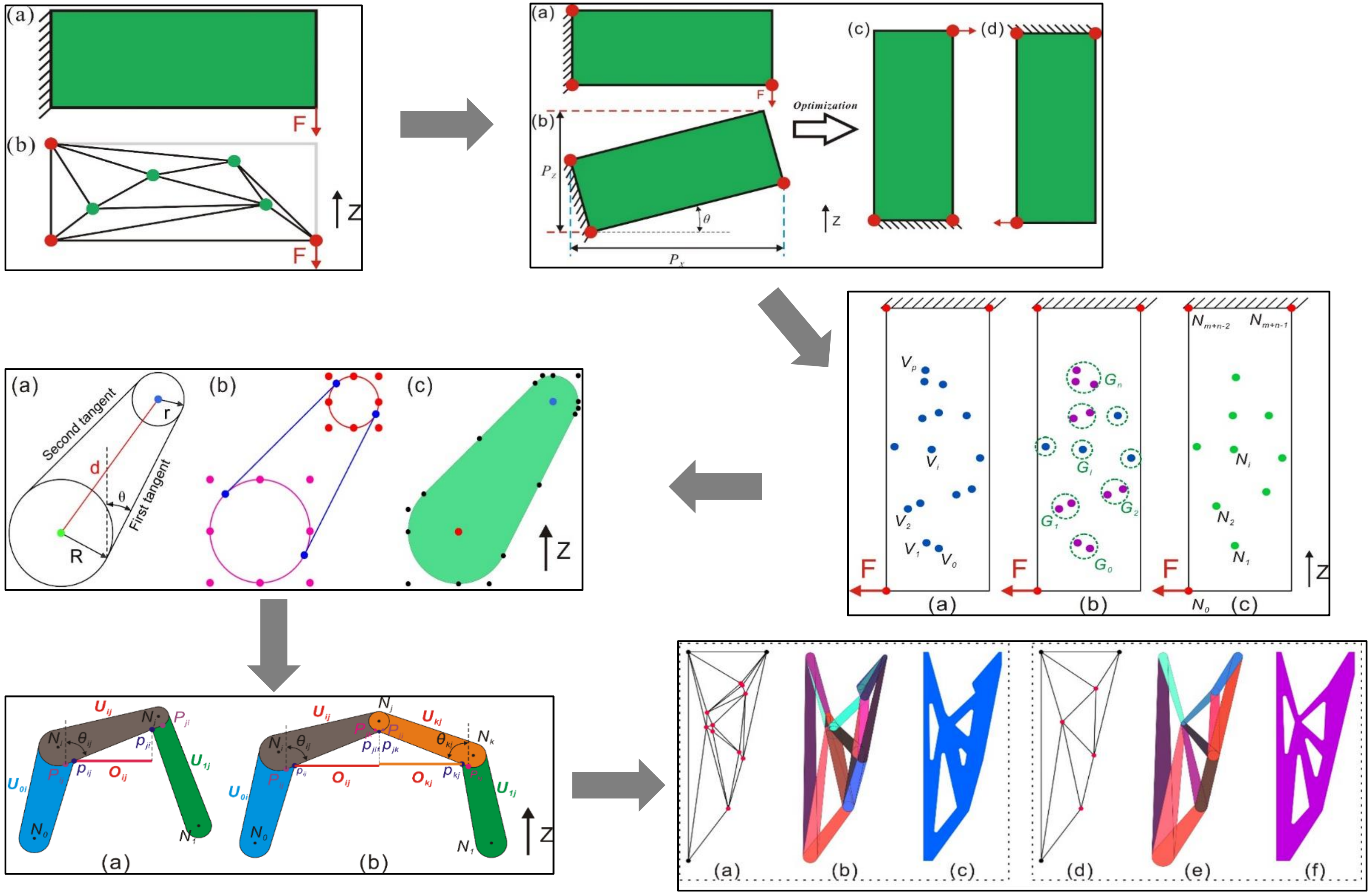
Shape accuracy checking (Meshmixer result cannot be assembled due to big deformation)

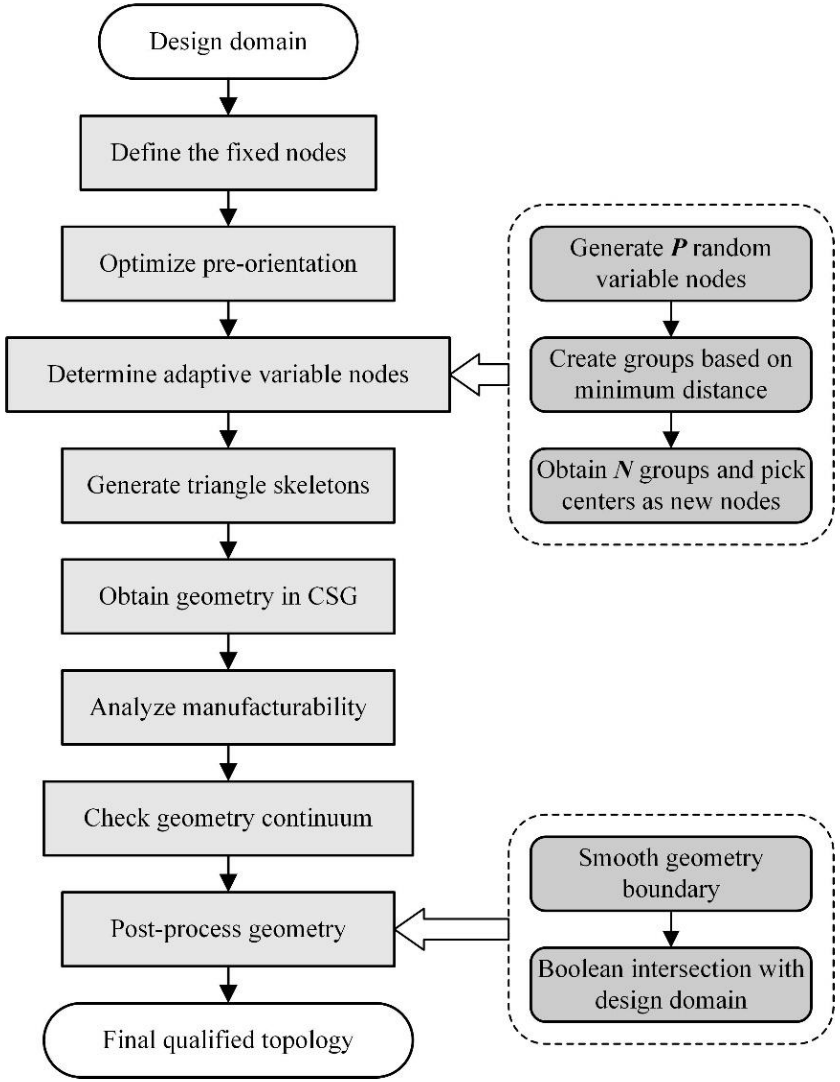
Note: component volume is 3.34 g.

Observations :

1) the tree structures can well support the complex overhang areas without any collapse;
2) Shape accuracy is very good since the printed part can be directly inserted into the assembly model without any adaptation;
3) Support points are greatly reduced as compared with others,
4) The support volume has been greatly reduced (40%-60% in average);
5) Post-processing time reduced much;
6) Parametric control is better for design operation.

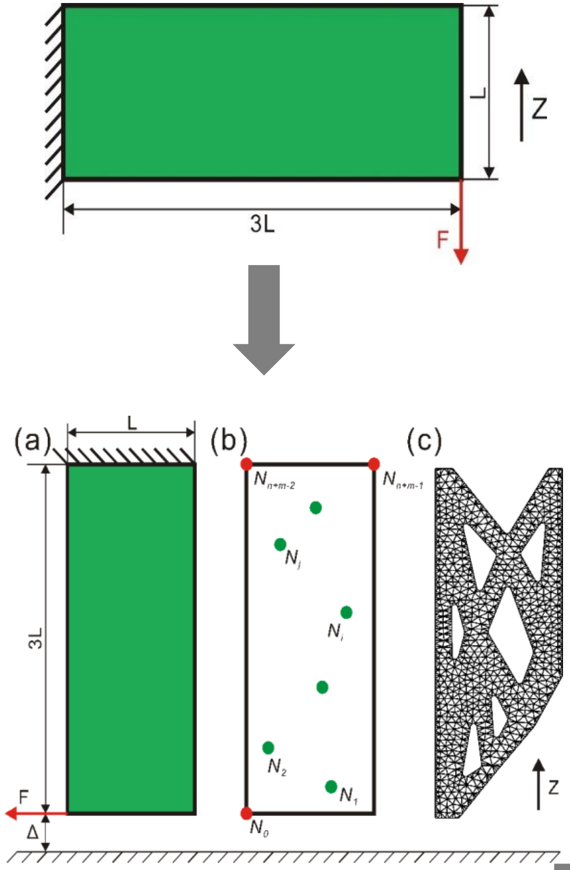
❖ Top-down constructive generative DFAM: CSG-based generative TO

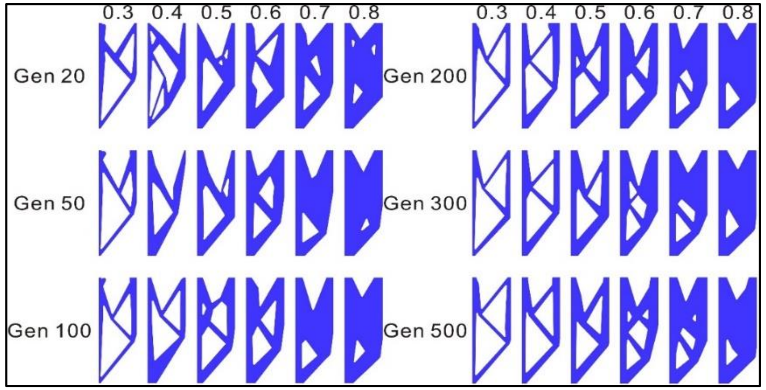


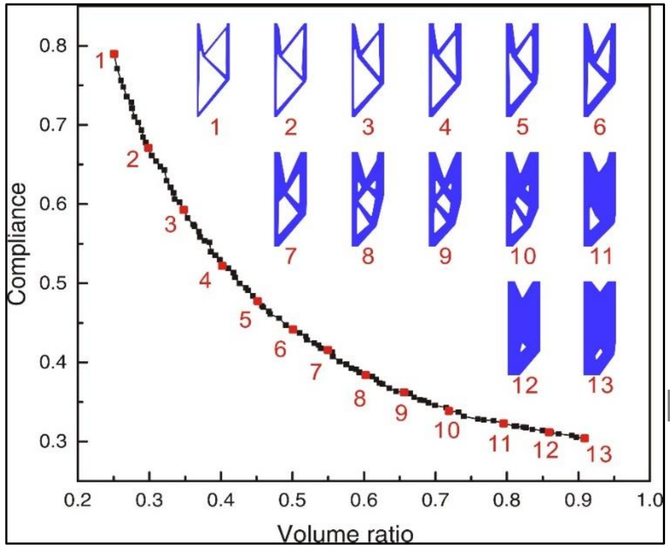


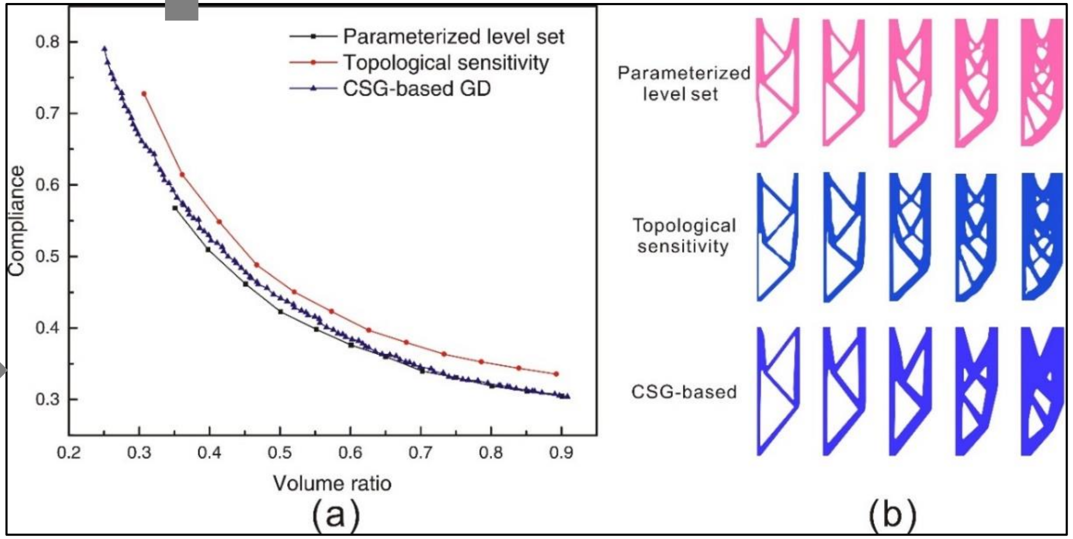
(Z Wang, Y Zhang, A Bernard, Additive Manufacturing, 2021)

❖ Top-down constructive generative DFAM: CSG-based generative TO









Highlights

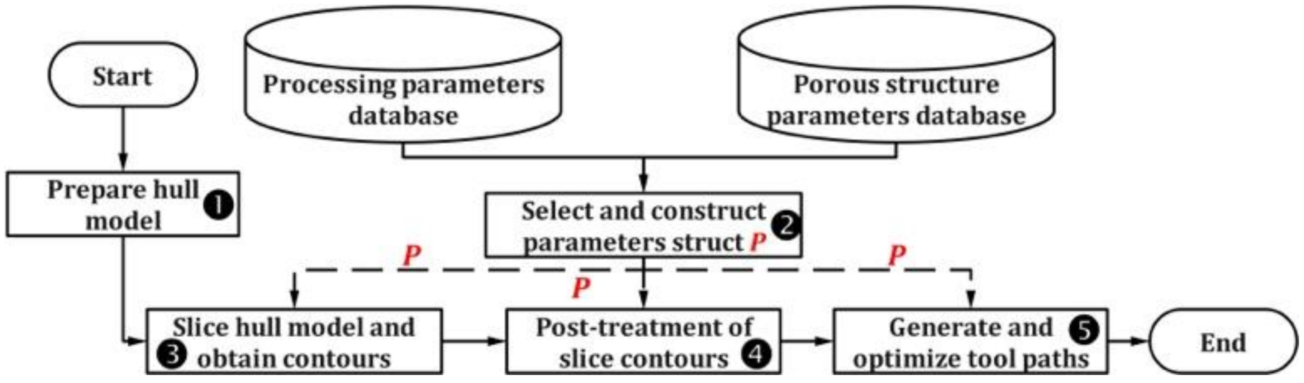
1. **Less variables & less computation**
2. **Smooth boundaries**
3. **All are qualified solutions (manufacturability checked in the geometry generation step)**
4. **Complex concave domains and 3D problems need further investigation**

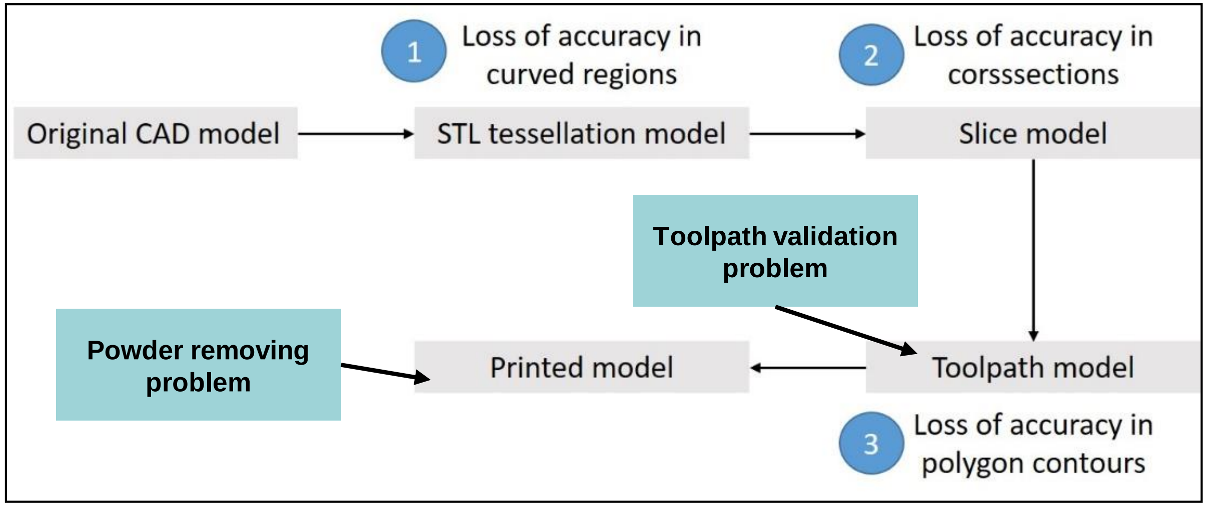
(Z Wang, Y Zhang, A Bernard, Additive Manufacturing, 2021)

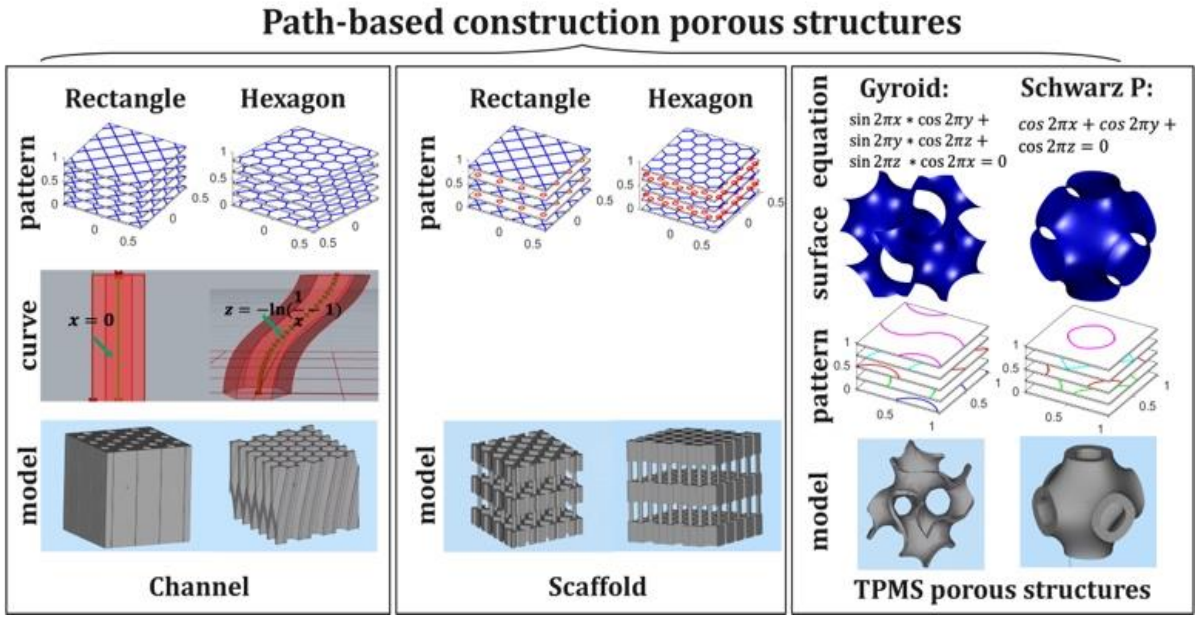
❖ Bottom-up constructive generative DFAM: toolpath-based construction

Current problems for porous structure design

1. **Manufacturability of porous structure is hard to check**
2. **Costly in CAD building and printing preparation**
3. **Accuracy loss in model transformation**
4. **Powder locked in pores after printing**

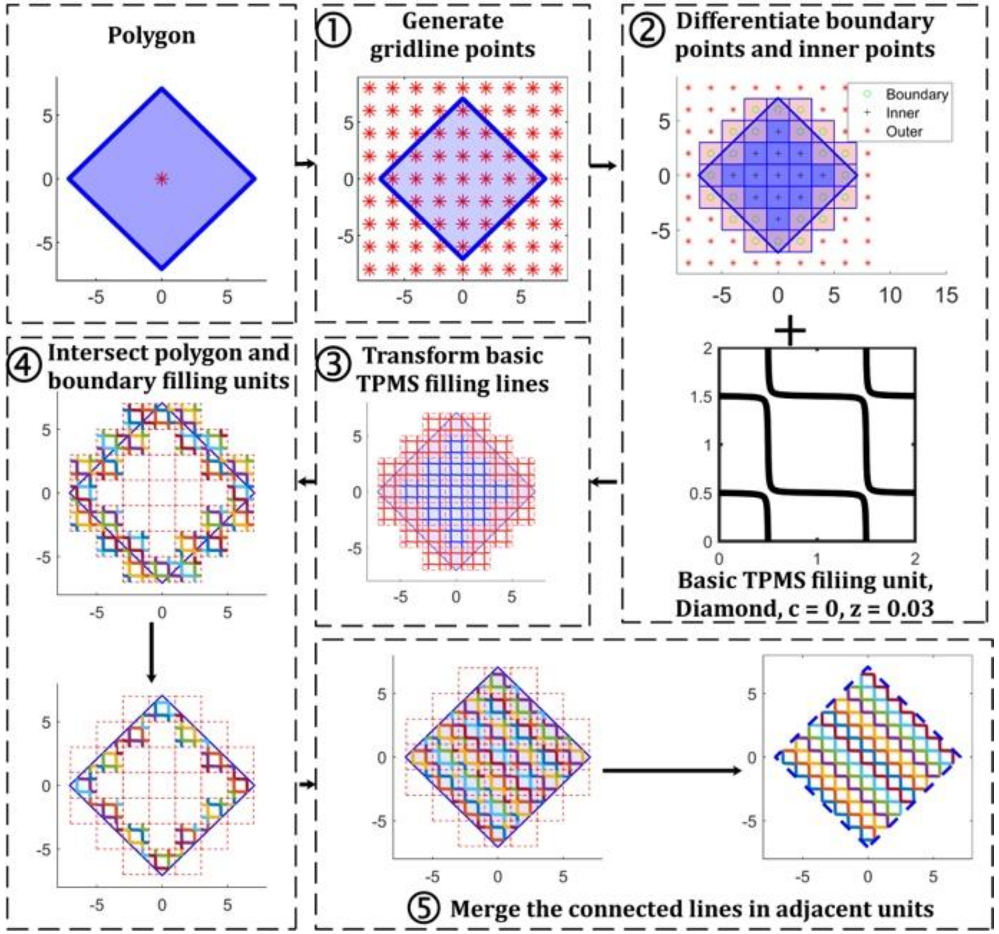




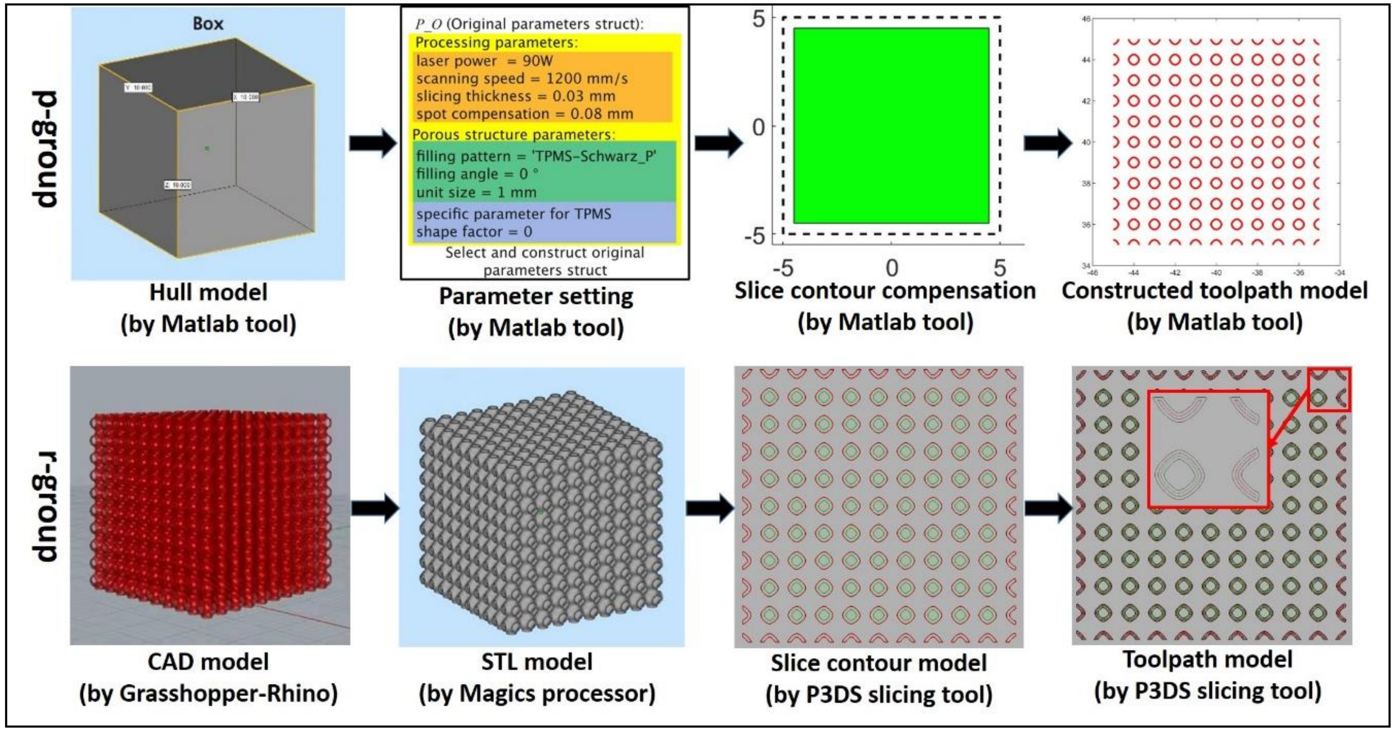


(Y Zhang, L Ding, S Tan, A Bernard, CRIP Annals, 2021)

❖ Bottom-up constructive generative DFAM: toolpath-based construction



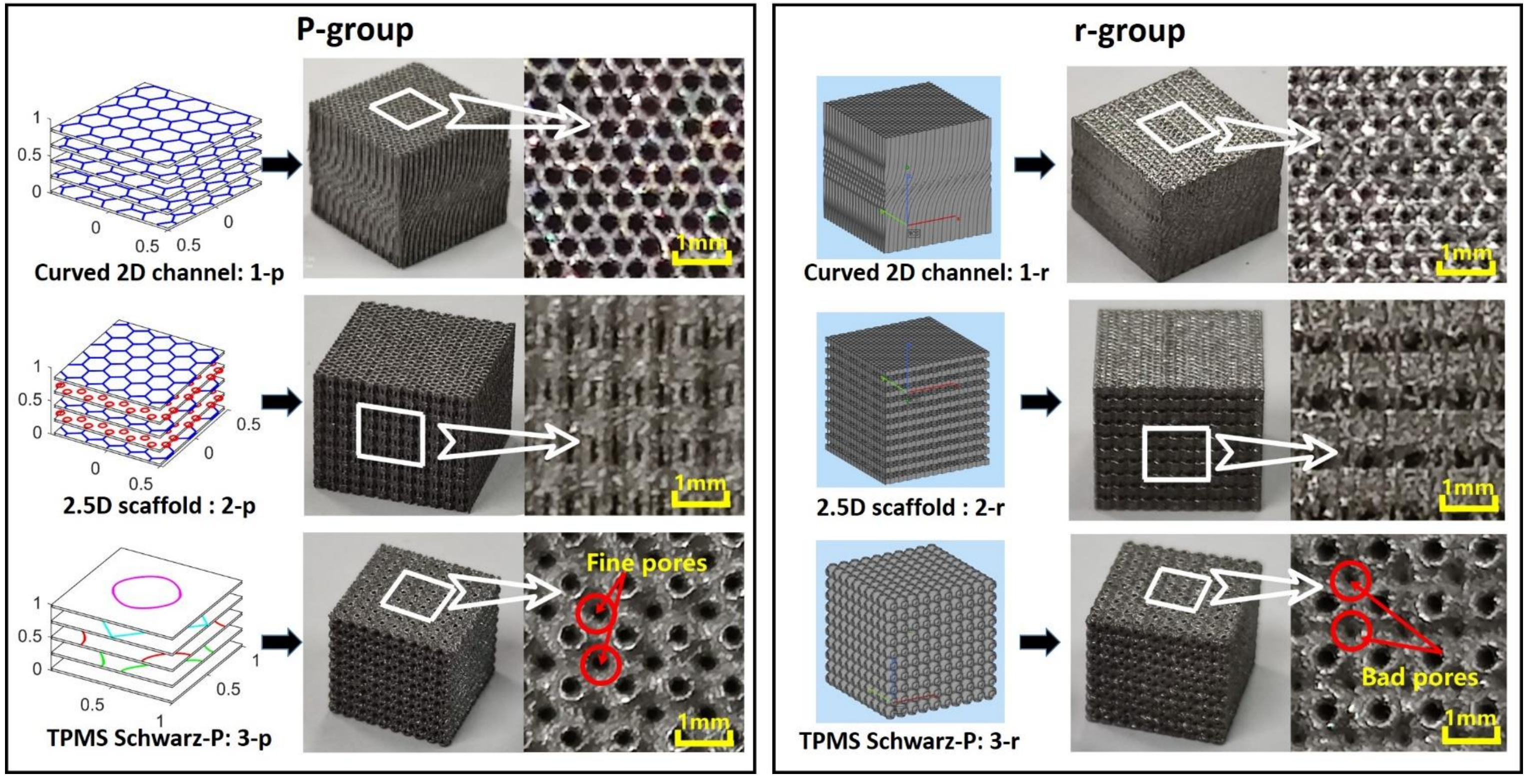
Example: Layer construction for a diamond TPMS lattice structure



Workflow comparison between the proposed method & conventional method

(Y Zhang, L Ding, S Tan, A Bernard, CRIP Annals, 2021)

❖ Bottom-up constructive generative DFAM: toolpath-based construction



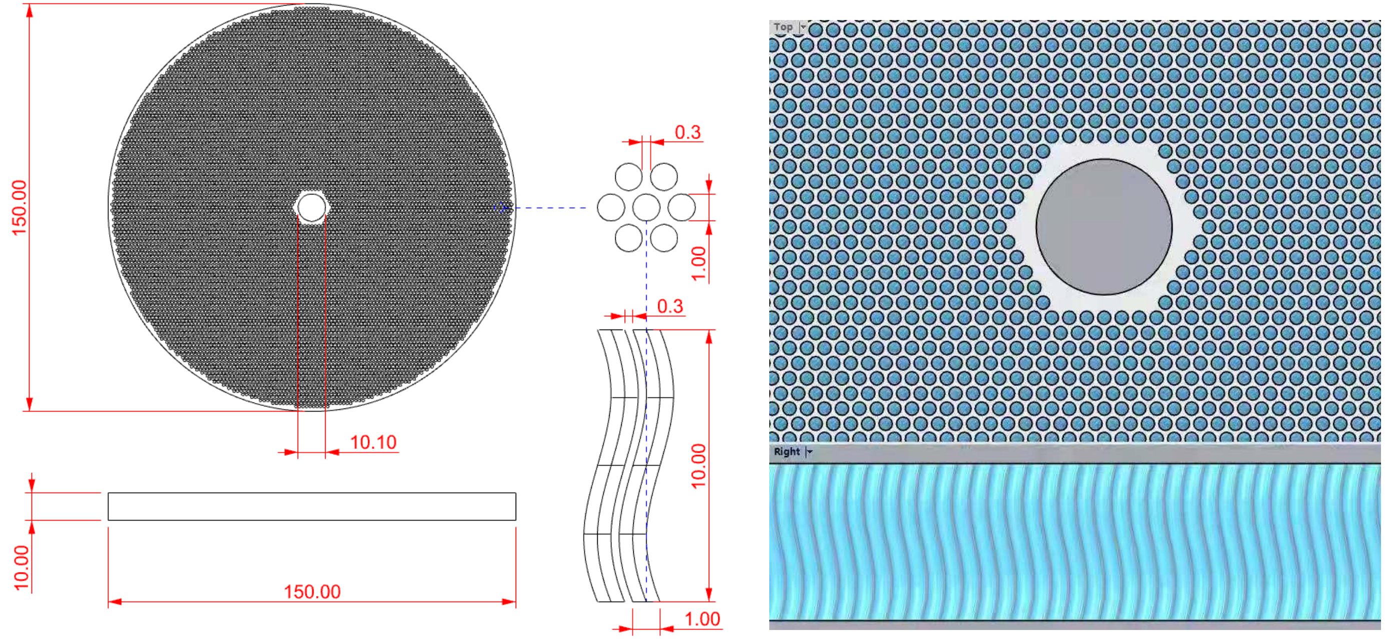
Printing result comparison (p-proposed method; r-regular method)

Processing time comparison (except design time/s)

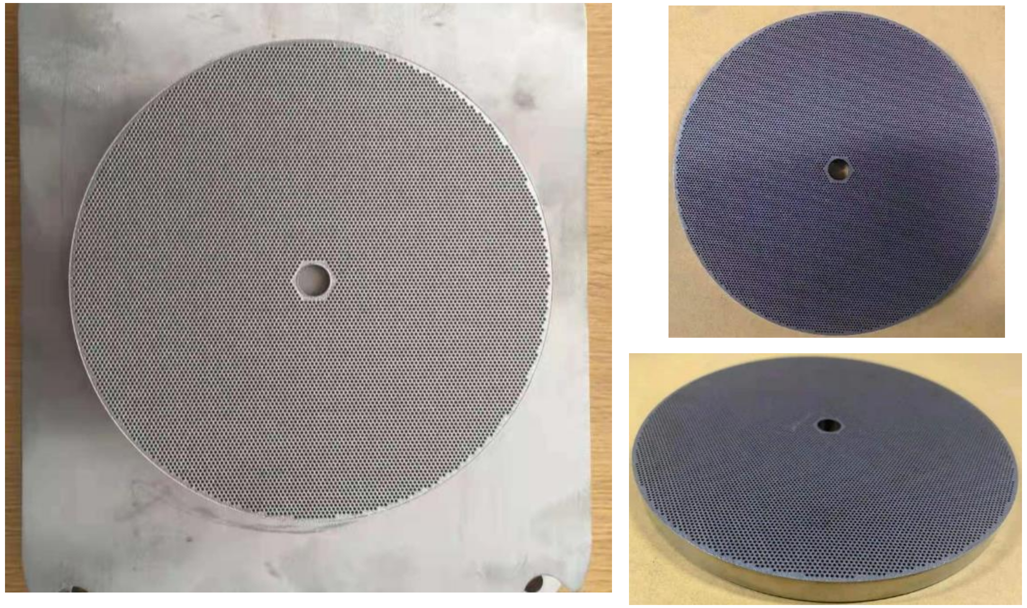
No.	1-p	1-r	2-p	2-r	3-p	3-r
Model updating time (s)	null	592	null	547	null	305
STL Conversion time (s)	null	166	null	437	null	243
Path generation time (s)	385	154	302	184	101	530
Total	385	912	302	1168	101	1078

(Y Zhang, L Ding, S Tan, A Bernard, CRIP Annals, 2021)

❖ Bottom-up constructive generative DFAM: toolpath-based construction



An industrial case from an oil/gas company (CAD model generated by Rhino GH)



Result of using the proposed method

Difficulties with commercial/existing methods

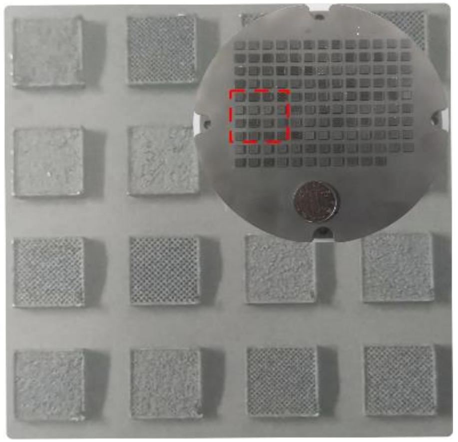
a. Modeling is time consuming
b. Slicing is costly and always has failures (e.g. Magics)
c. Toolpath is not validated, which causes printing failures, e.g. remelting caused shape accuracy loss & hole blocking

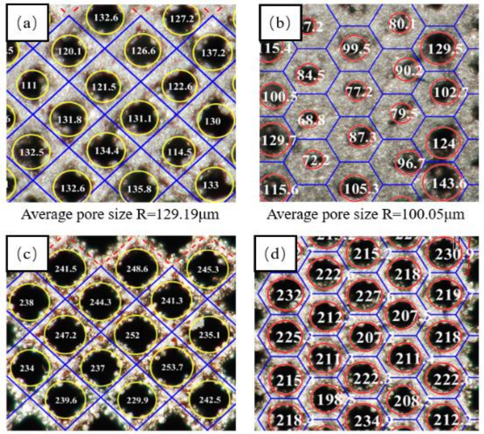
Advantages of the proposed method

a. No CAD modeling time
b. Slicing is rapid since only slice a cylinder hull
c. Toolpath is validated circle scanning pattern
d. Shape accuracy is perfect

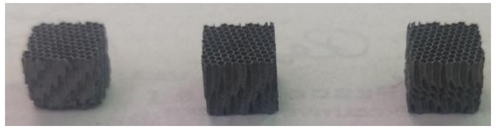
(Y Zhang, L Ding, S Tan, A Bernard, CRIP Annals, 2021)

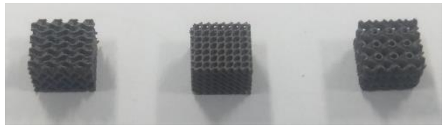
❖ Bottom-up constructive generative DFAM: toolpath-based construction

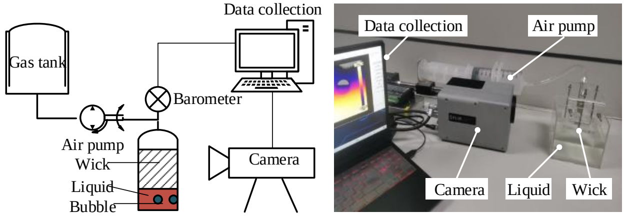


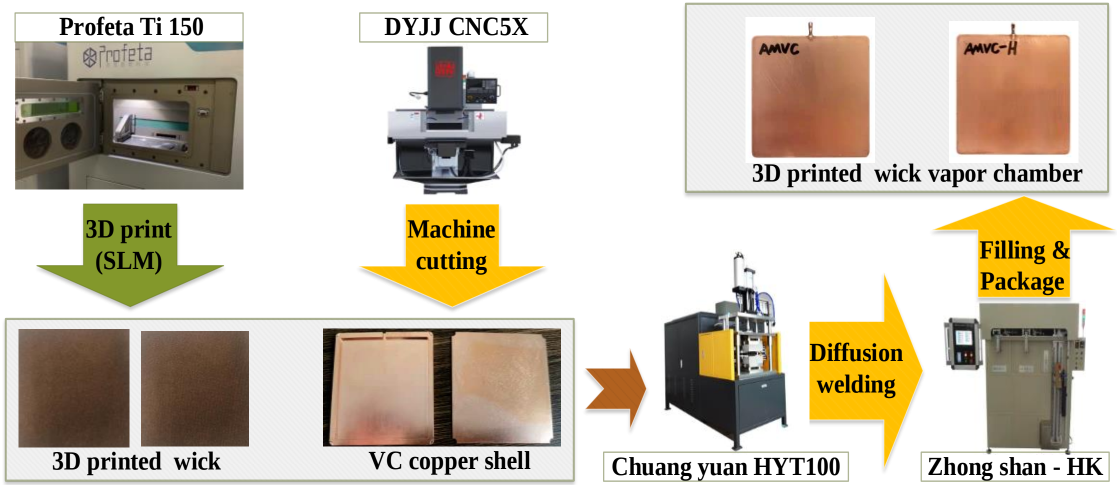


Average pore size R=129.19μm
Average pore size R=100.05μm
Average pore size R=241.99μm
Average pore size R=216.65μm









Highlights

1. Total pre-processing time has been greatly reduced
2. Ensured manufacturability & better printing quality
3. No powder locked in pores
4. KBE & parametric control for higher efficiency
5. Achieve stable size of around 150 microns (quite important for medical application)
   State-of-the-art performance (stable size around 150 microns-extra of 96 microns)

Next step

1. Non-uniformed construction (different cells)
2. Integration of numerical simulation
3. AI & Meta-model for efficient optimization computation
4. Using multi-axis HAM toolpath to define HAM components
   (cold spraying toolpath profile define volume, while CNC toolpath profile to subtract volume)

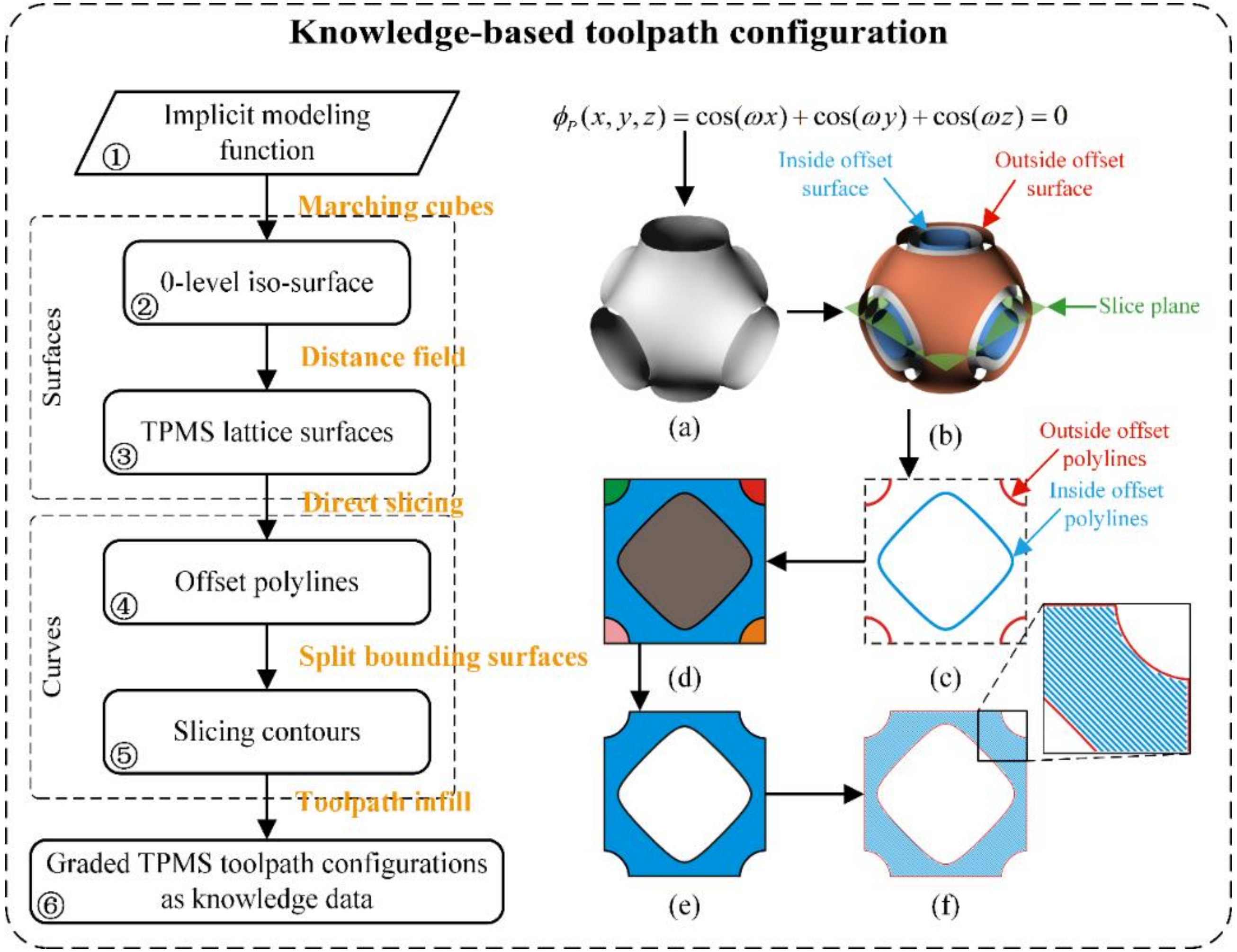
(Y Zhang, L Ding, S Tan, A Bernard, CRIP Annals, 2021)

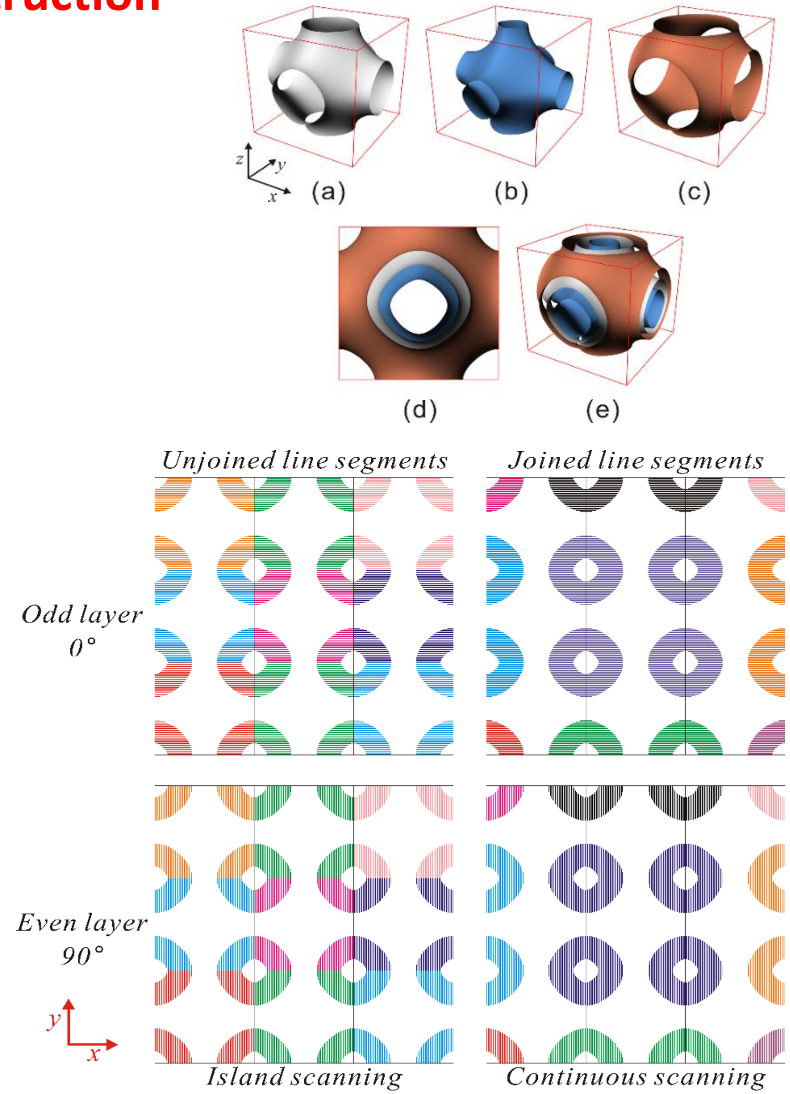
❖ Bottom-up constructive generative DFAM: toolpath-based construction

Different industrial case studies realized by using the developed DfAM methods

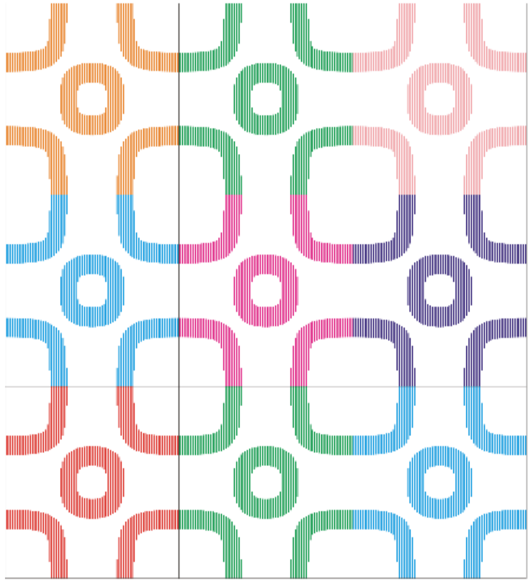
(Y Zhang, L Ding, S Tan, A Bernard, CRIP Annals, 2021)

❖ **Bottom-up constructive generative DFAM: toolpath-based construction**

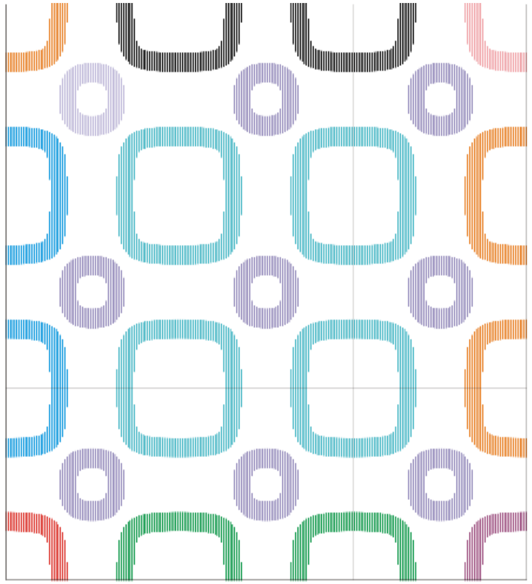




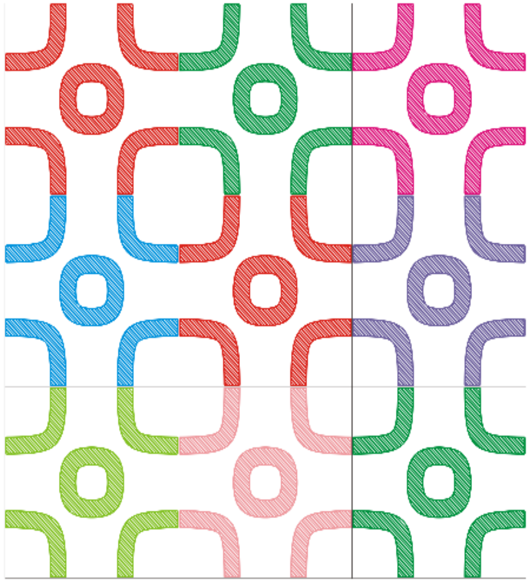
❖ **Bottom-up constructive generative DFAM: toolpath-based construction**



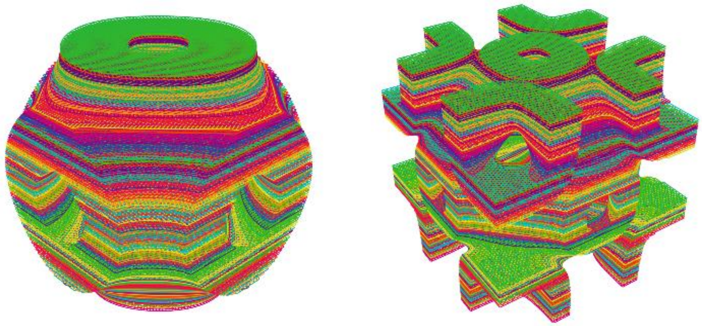
Island scan model



Parallel-vector scan model

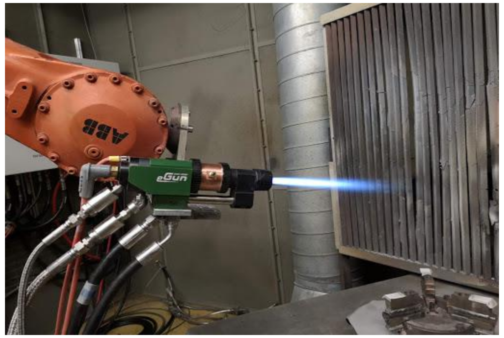


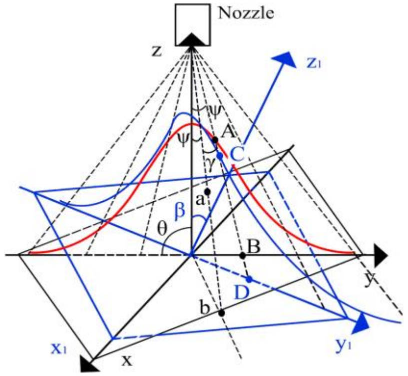
Island model with combined scans

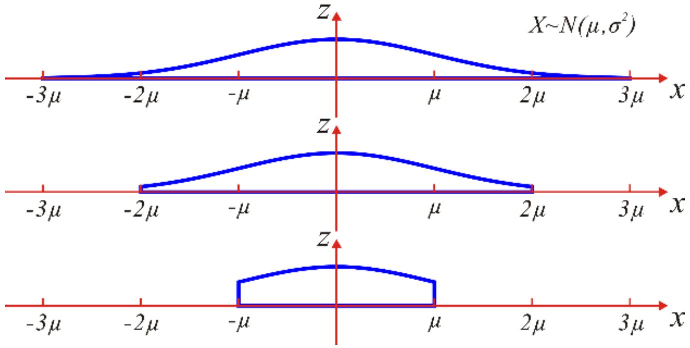


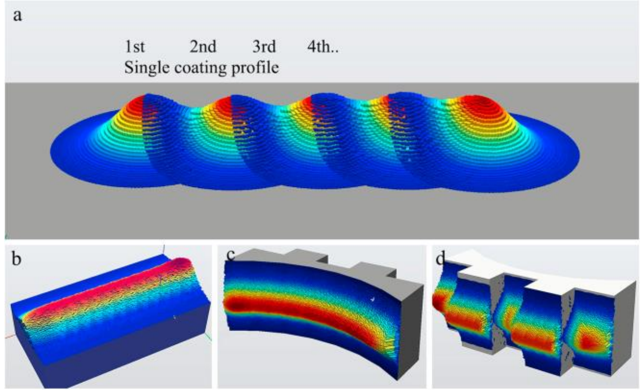
Toolpath constructed gradient parameteric lattice cells

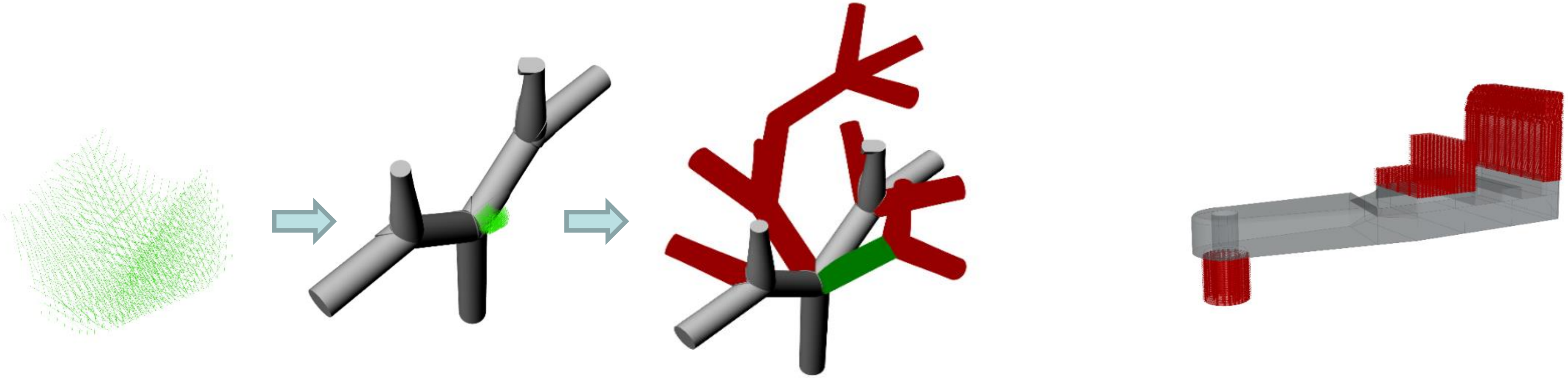
❖ **Bottom-up constructive generative DFAM: toolpath-based construction**



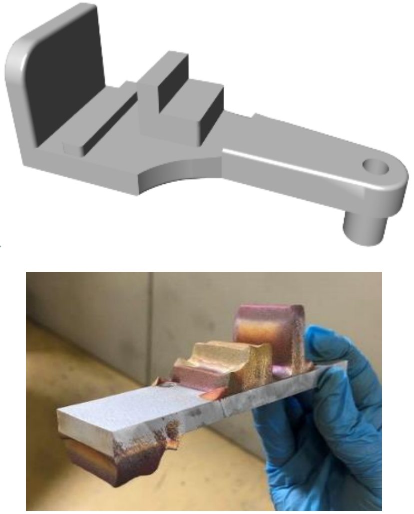








Deposition profile defined wolume for constructive DFAM (in development)



Outline

1. Lab & Research Introduction
2. Design for AM
3. Constructive Generative Design for AM
   - Top-down method
   - Bottom-up method
4. **Conclusion & Perspectives**

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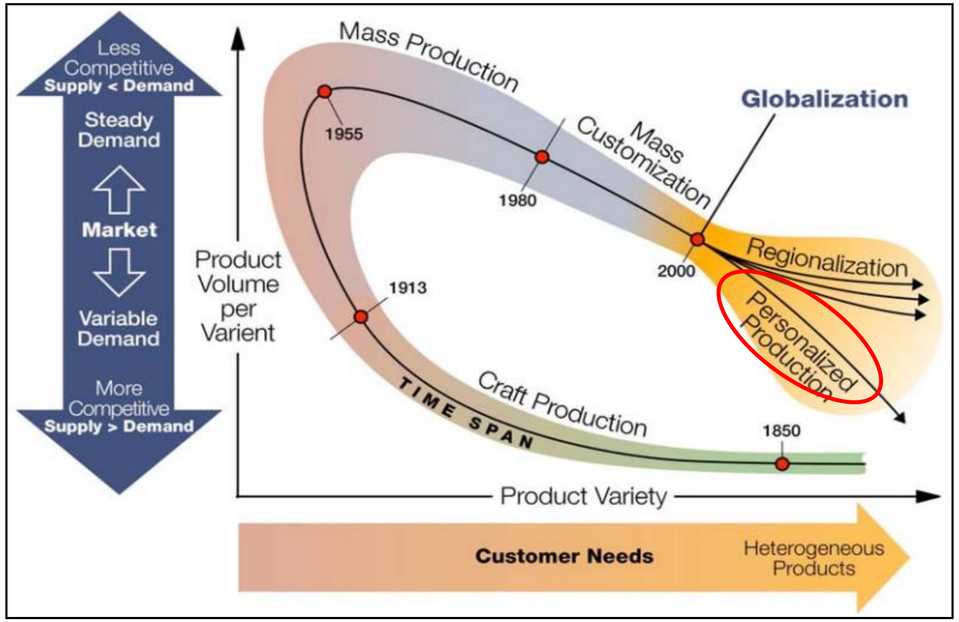
❖ Conclusion & Perspectives

1. **DFAM is a key for the industrialization of AM**
2. **Hybrid design method may play a critical role to cope with the HAM development trend**
3. **AI & other ICT digital tools are useful to support collaborative design for AM via cloud**
4. **KBE techs are the foundation to remove the threshold of design to enable the wide public to use AM for innovation**
5. **Public use of AM would be a solution for low cost personalized product innovation**
6. **Current DFAM methods focus more on structure level, but hybrid & system-level is in urgent need**



(Koren, 2010)

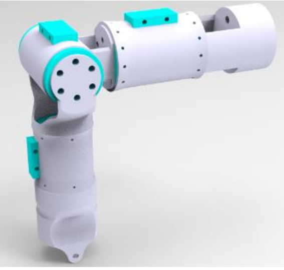
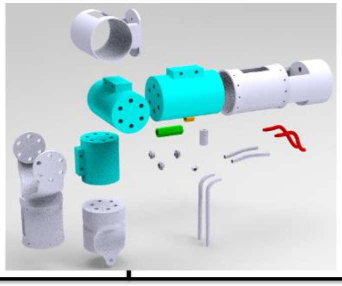
People can easily push the 'start' button for printing, but not every one who has no domain skills can design, which is a barrier for the wide use of printers.

❖ Conclusion & Perspectives

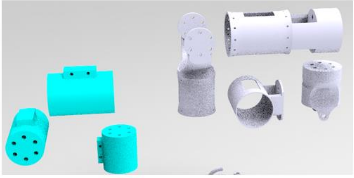
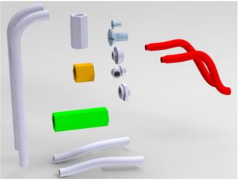
Design requirements → Generate concept solution → Build Initial CAD of product → Conduct system decomposition & classification

Conduct system decomposition & classification ⇅ Optimize sub-model & structure

Optimize sub-model & structure ⇄ Assembly interface check → Manufacturing analysis → Final solution

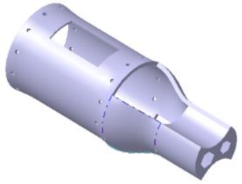
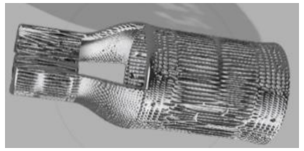



AM | Non AM

AM: Lightweight, Integration, Embedded

Non AM: Standard, Non-standard

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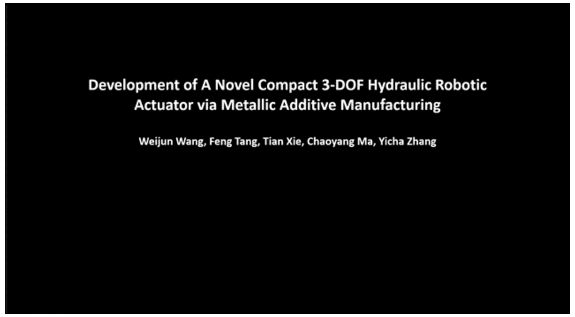

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Thanks a lot for your attention!

HAM, the choice of nature?