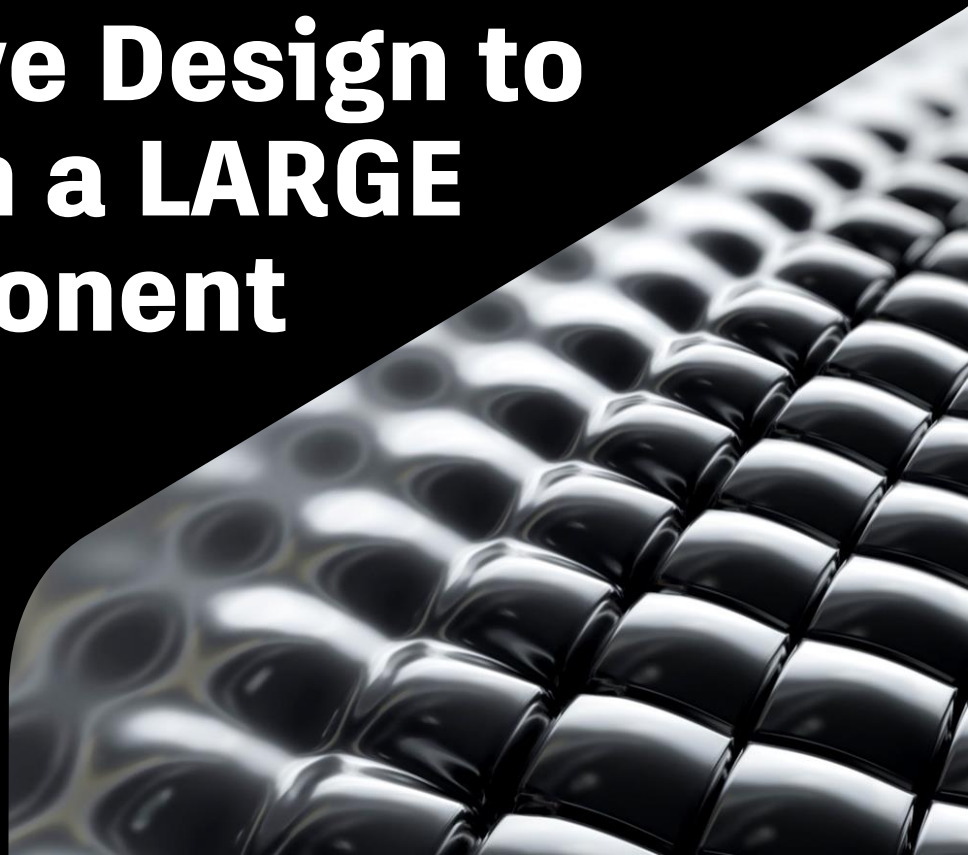
AUTODESK UNIVERSITY

Taking Generative Design to the Next Level on a LARGE Jet Engine Component



Nick Markovic
Research Manager | Autodesk Research

Philipp Manger
Sr. Implementation Consultant | Autodesk Consulting

Safe Harbor Statement

We may make forward-looking statements regarding planned or future development efforts for our existing or new products and services and statements regarding our strategic priorities. These statements are not intended to be a promise or guarantee of business results, future availability of products, services or features but merely reflect our current plans and are based on factors currently known to us. These planned and future development efforts may change without notice. Purchasing and investment decisions should not be made based upon reliance on these statements.

A discussion of factors that may affect future results is contained in our most recent Form 10-K and Form 10-Q filings available at www.sec.gov, including descriptions of the risk factors that may impact us and the forward-looking statements made in these presentations. Autodesk assumes no obligation to update these forward-looking statements to reflect events that occur or circumstances that exist or change after the date on which they were made. If this presentation is reviewed after the date the statements are made, these statements may no longer contain current or accurate information.

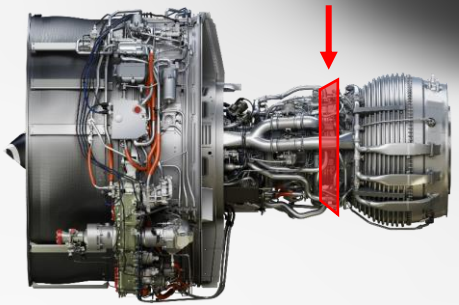
This presentation also contains information, opinions and data supplied by third parties and Autodesk assumes no responsibility for the accuracy or completeness of such information, opinions or data, and shall not be liable for any decisions made based upon reliance on any such information, opinions or data.

Autodesk's partners frequently compete against each other in the marketplace, and it is critically important that all participants in this meeting observe all requirements of antitrust laws and other laws regarding unfair competition. Autodesk's long insistence upon full compliance with all legal requirements in the antitrust field has not been based solely on the desire to stay within the bounds of the law, but also on the conviction that the preservation of a free and vigorous competitive economy is essential to the welfare of our business and that of our partners, the markets they serve, and the countries in which they operate. It is against the policy of Autodesk to sponsor, encourage or tolerate any discussion or communication among any of its partners concerning past, present or future prices, pricing policies, bids, discounts, promotions, terms or conditions of sale, choice of customers, territorial markets, quotas, inventory, allocation of markets, products or services, boycotts and refusals to deal, or any proprietary or confidential information. Communication of this type should not occur, whether written, oral, formal, informal, or "off the record." All discussion at this meeting should be strictly limited to presentation topics.

Agenda

- Project motivation
- Eco-design engine demonstrator
- Multi-physics Generative Design
- Design for Additive Manufacturing
- Summary

Project ‘Monaco’: Manufacturing of a Large-Scale AM Component



Ref. GE.com

Clean Sky

AUTODESK

TUHH
Technische Universität Hamburg

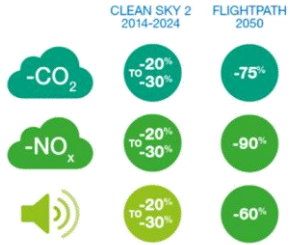
TECHNISCHE UNIVERSITÄT DRESDEN

AUTODESK UNIVERSITY

Where Innovation Takes Off

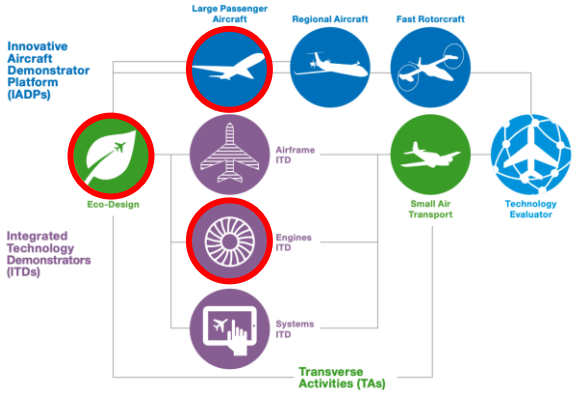
Objectives

Clean Sky 2 Goals



Ref. cleansky.eu

Clean Sky 2 Structure



Ref. cleansky.eu

The Consortium

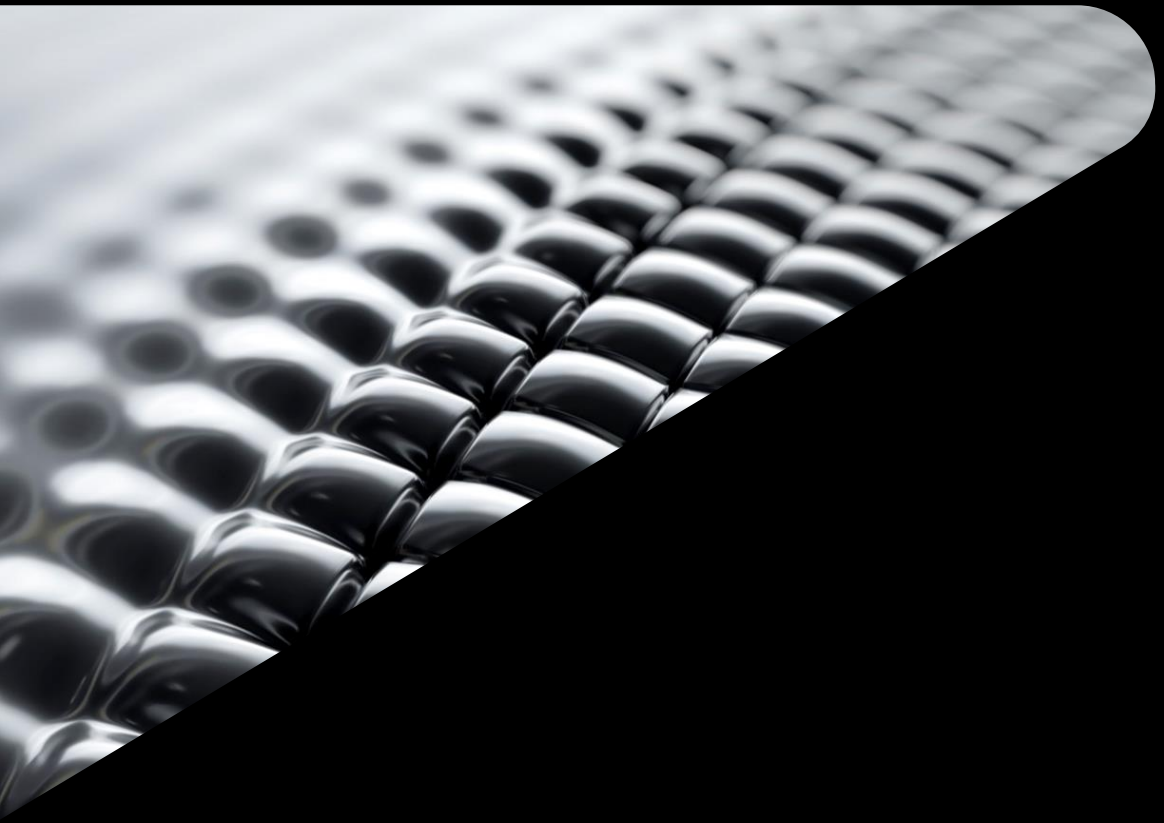
TUHH
Technische Universität Hamburg

AUTODESK

Clean Sky

TECHNISCHE UNIVERSITÄT DRESDEN

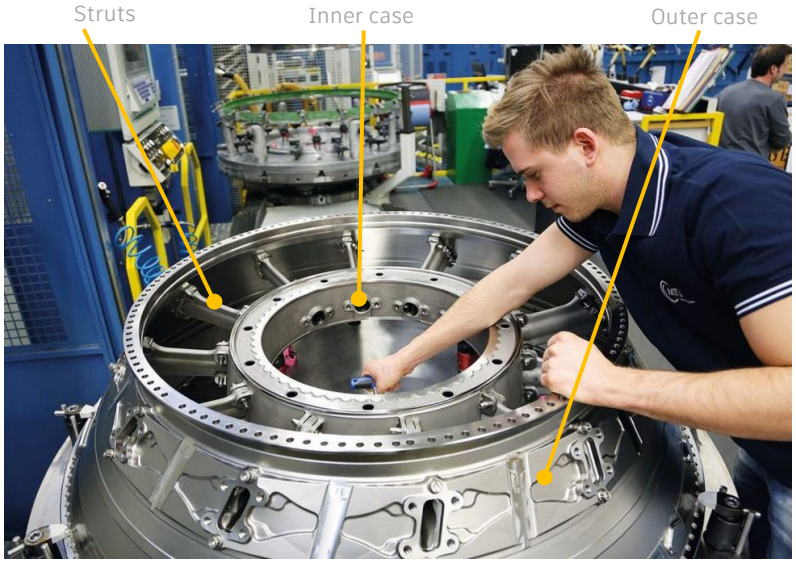
AUTODESK UNIVERSITY



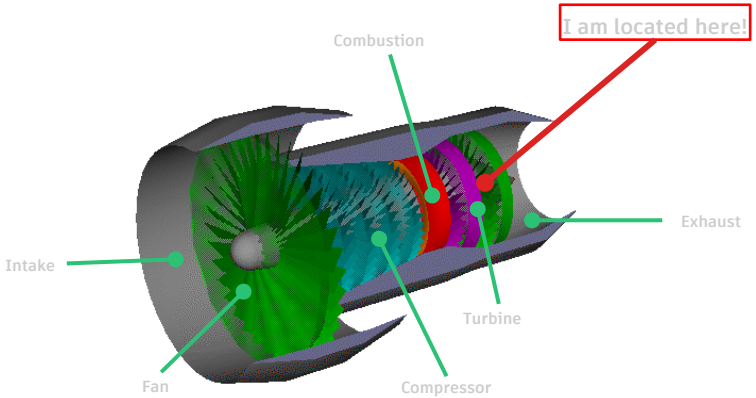
Goals and Challenges

What Am I?

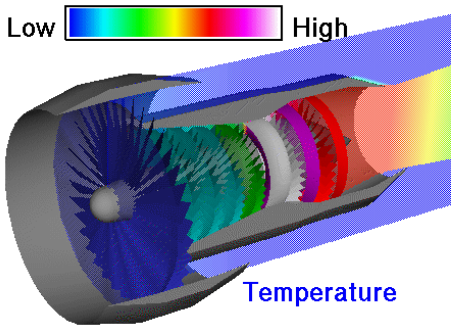
Turbine Center Frame Assembly



The turbine center frame of a GEnx engine is a demonstration component of the project partner MTU Aero Engines for hybrid additive manufacturing by laser material deposition. Photo via MTU Aero Engines.



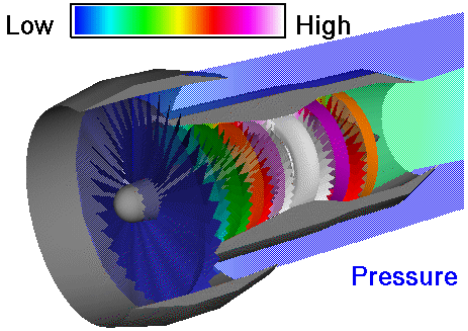
Ref: grc.nasa.gov



Ref: grc.nasa.gov

Max operating Temperature =

<400℃



Ref: grc.nasa.gov

Max operating radial loading =

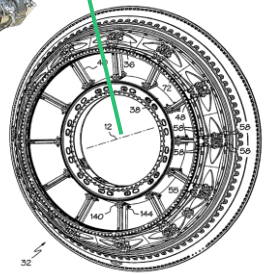
>600kN

Making a Leaner, Cleaner and Greener Aircraft

Engine schematic

TCF location

Ref. cfmaeroengines.com



Ref. patent 1149986

1m size

Program workflow

Design and Make the TCF

Requirements

Multiphysics Generative Design

numerical validations

Build prep & simulation

Physical DoE's

Build

AUTODESK

TECHNISCHE UNIVERSITÄT DRESDEN

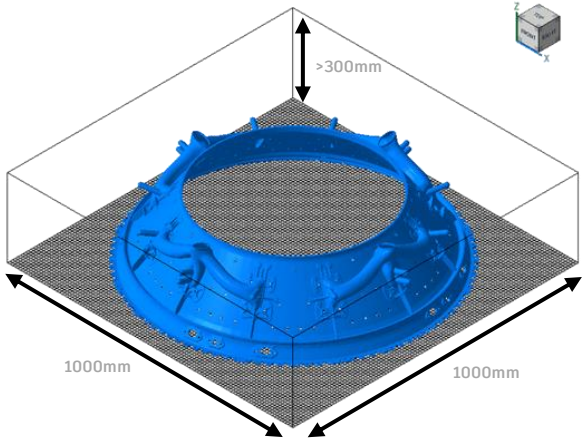
TUHH Technische Universität Hamburg

Digital threads

Digital threads

Large scale L-BPF machine

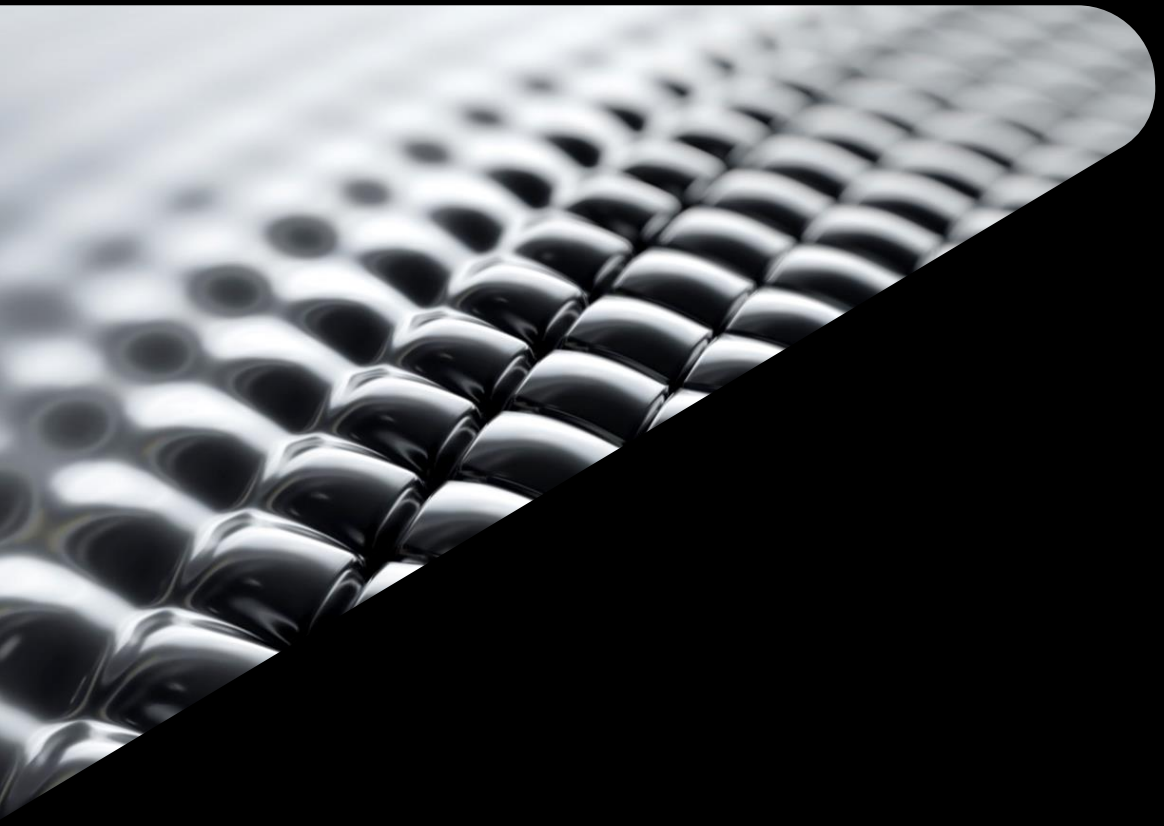
One of the biggest metal printer of its kind!



AUTODESK

DfAM for iN718

Objectives: Reduce mass, increase performance, add functionality, reduce cost and for **large scale AM**



Generative Design

Design Evolution

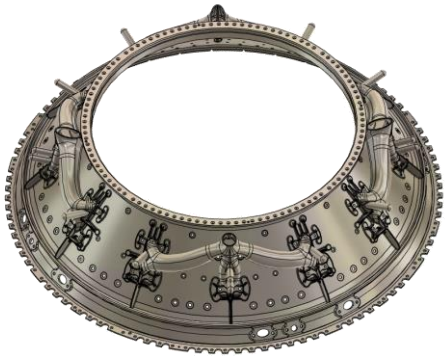
Design 1

Skin Optimization Philosophy

- 100+ to 1 part consolidation
- Mass reduction: 28.9%
- Pressure drop: 58%

Design 2

Manual design Philosophy



- 100+ to 1 part consolidation
- Mass reduction: 29.4%
- Pressure drop: 69%

Design 3

GD Inspired 'ribs' Philosophy

- 100+ to 1 part consolidation
- Mass reduction: 21%
- Pressure drop: 71%
- Meets stiffness requirements

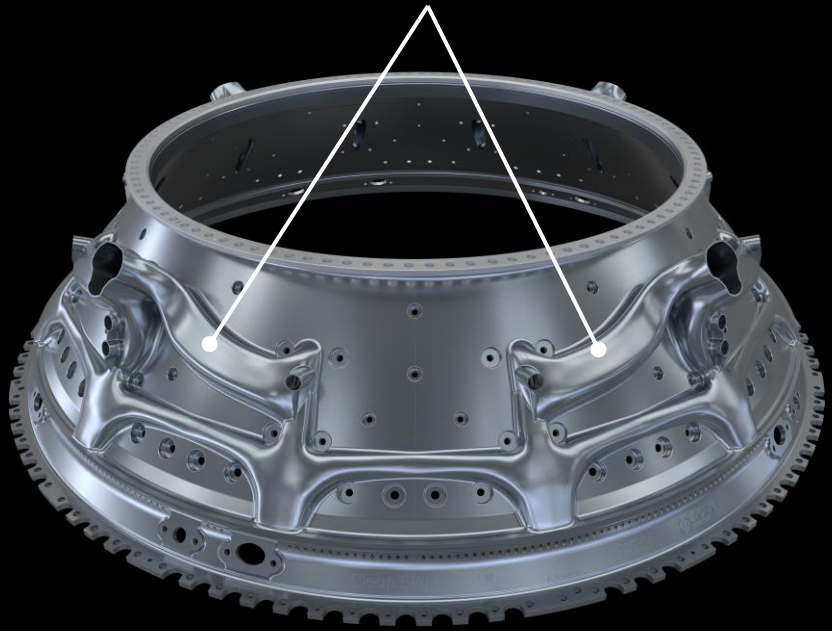
Design 4.1 & 4.2

GD Inspired 'lattice' Philosophy

Generative Design Inspiration

Latticing and structural refinement regions were inspired from the Generative Design outcome highlighted in orange

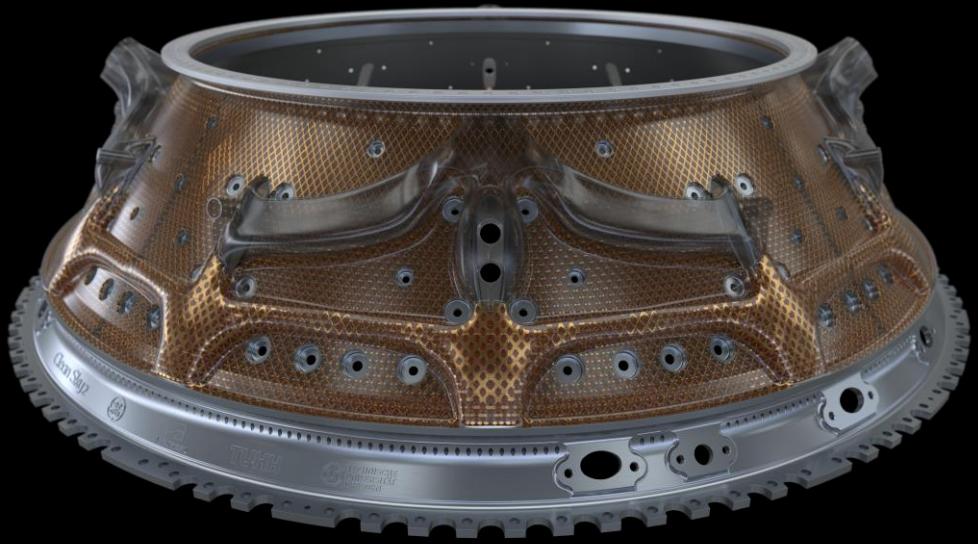
Manifold has been integrated to the main case to increase structural integrity.

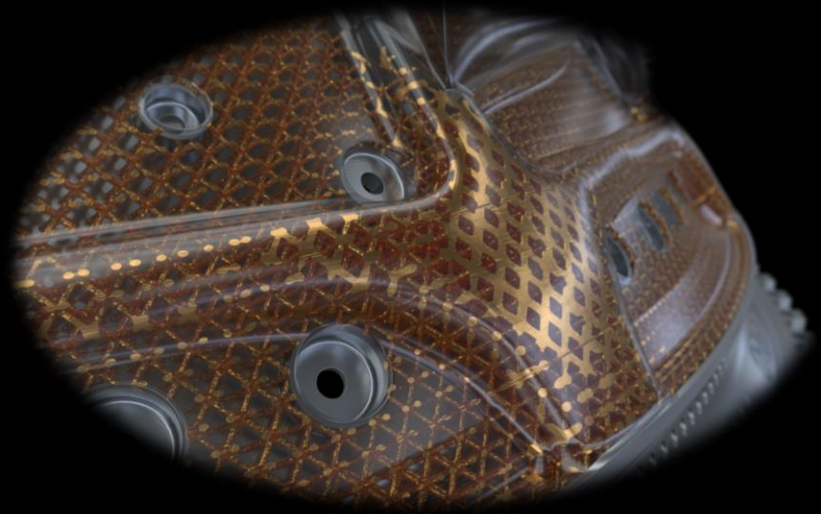


100+ parts have been consolidated to one part!

Lattice Generation

Double Conformal Latticing was used to increase stiffness to weight ratio

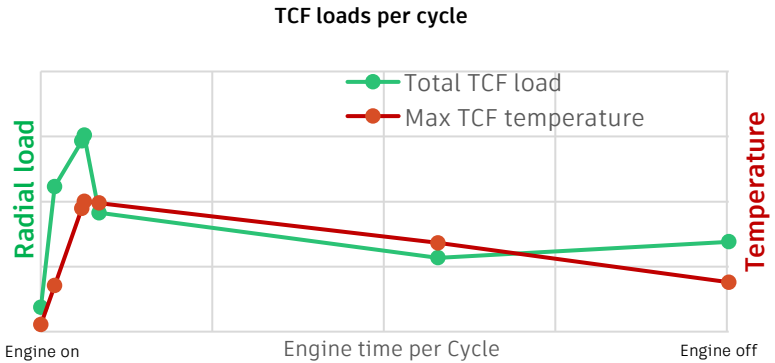


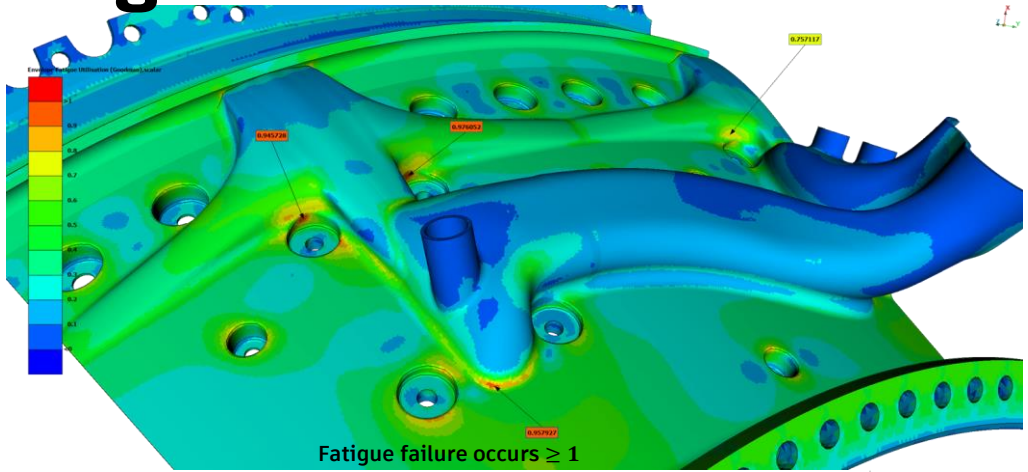


Variable beam density – structural reinforcement

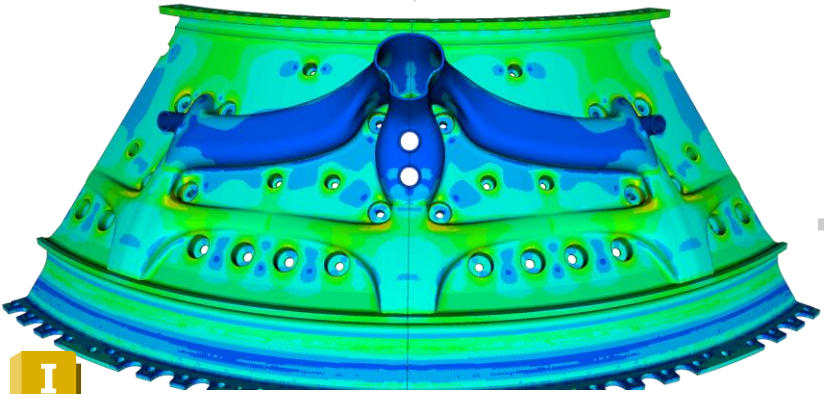
- Mass reduction is **35%**
- Meets stiffness (max displacement ≤ **37microns**)

Thermal-Mechanical Fatigue Assessment





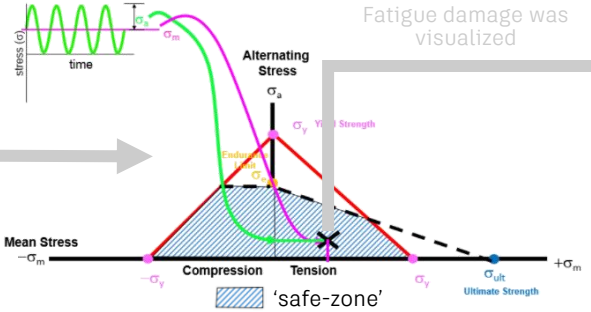
Aero-thermal Boundary Conditions



Transient stress simulation (speed up x1671)

IN718 SN data

Calculated stress cycle for each node @ 90k cycles

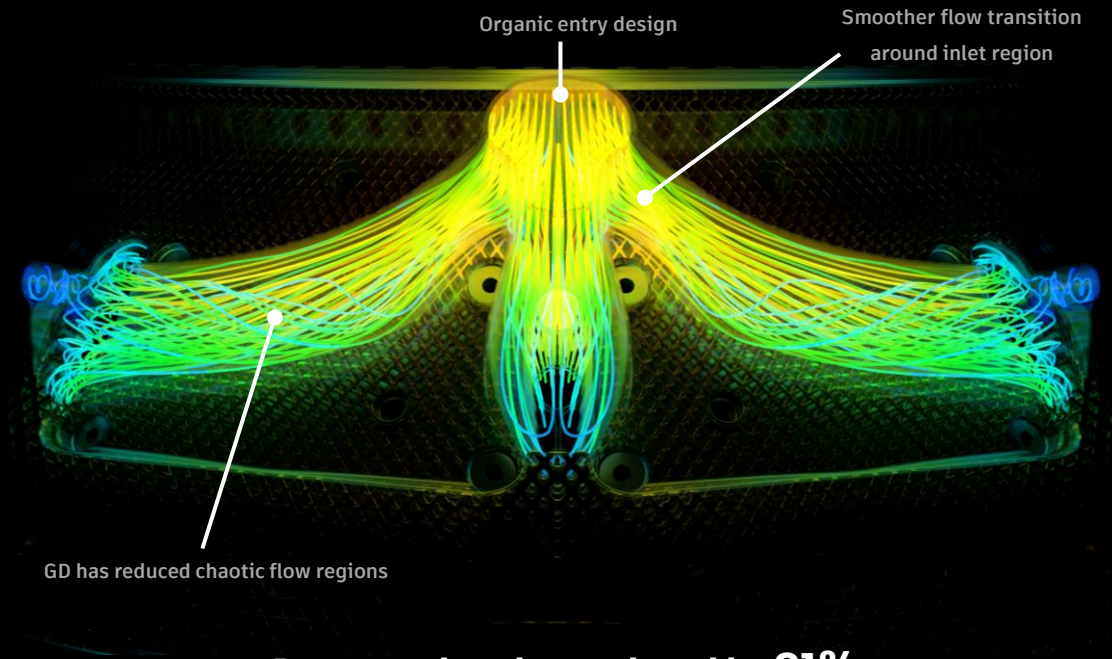


Fatigue damage was visualized

Using the Haigh Diagram to calculate fatigue damage

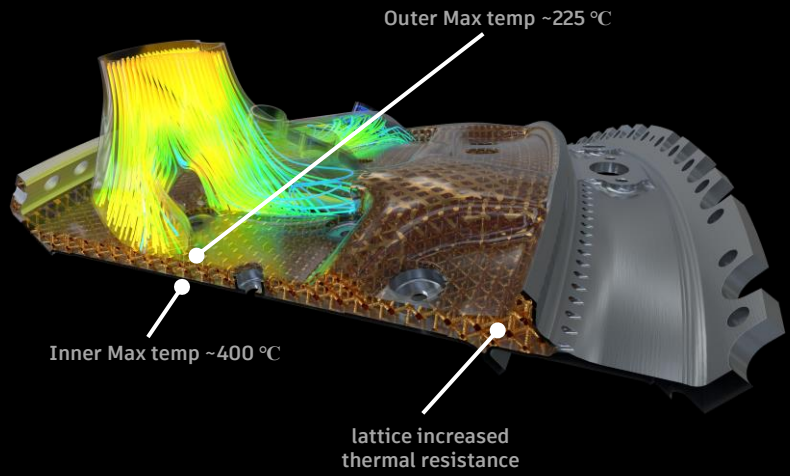
Generative Fluids + Thermal Energy Savings

Generative fluids



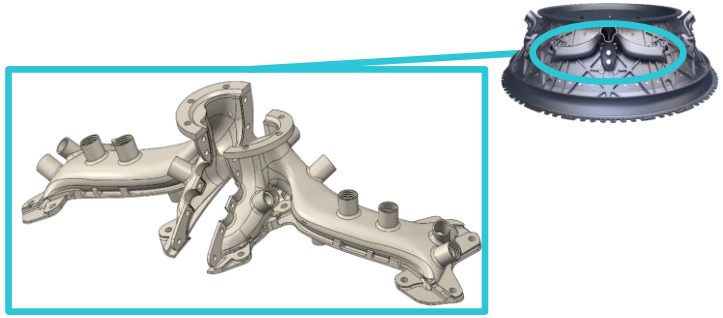
- **Pressure drop has reduced by 91%**
- **Flow outlets remained balanced**

Lattice insulation

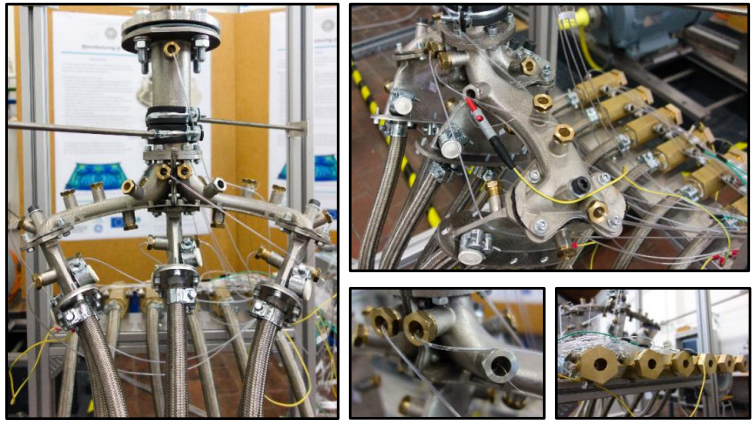


- **Lattice design has saved 16GJ of heat energy**

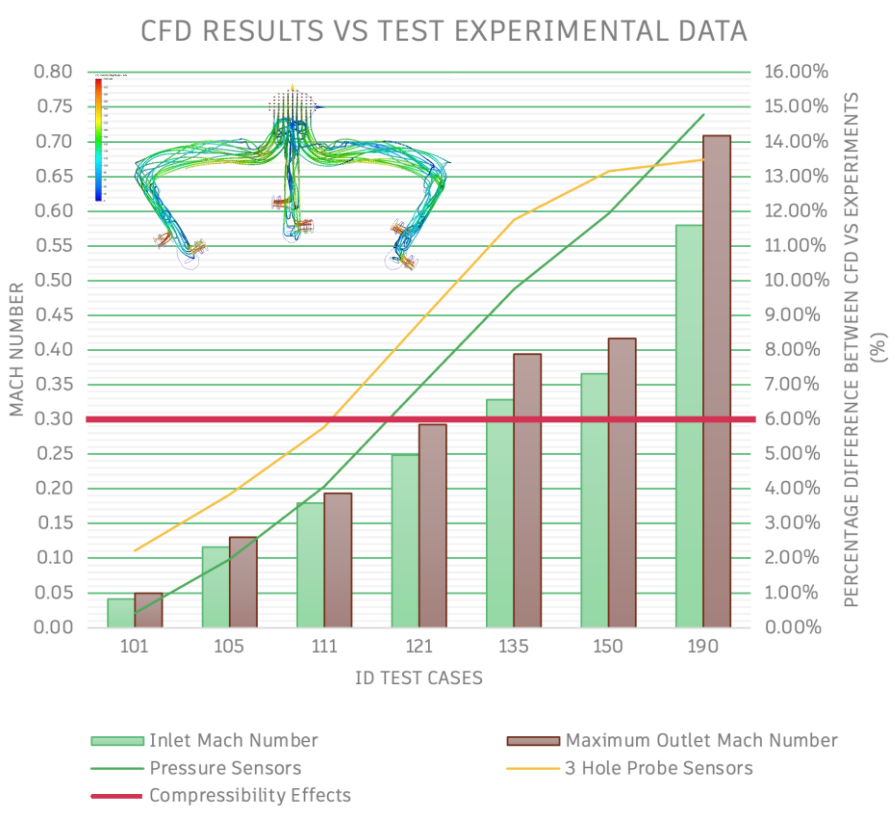
Aerothermal Testing



Manifold was manufactured out of two parts



Assembled and instrumented test rig



CFD Simulation Vs. Test Mach No. Results

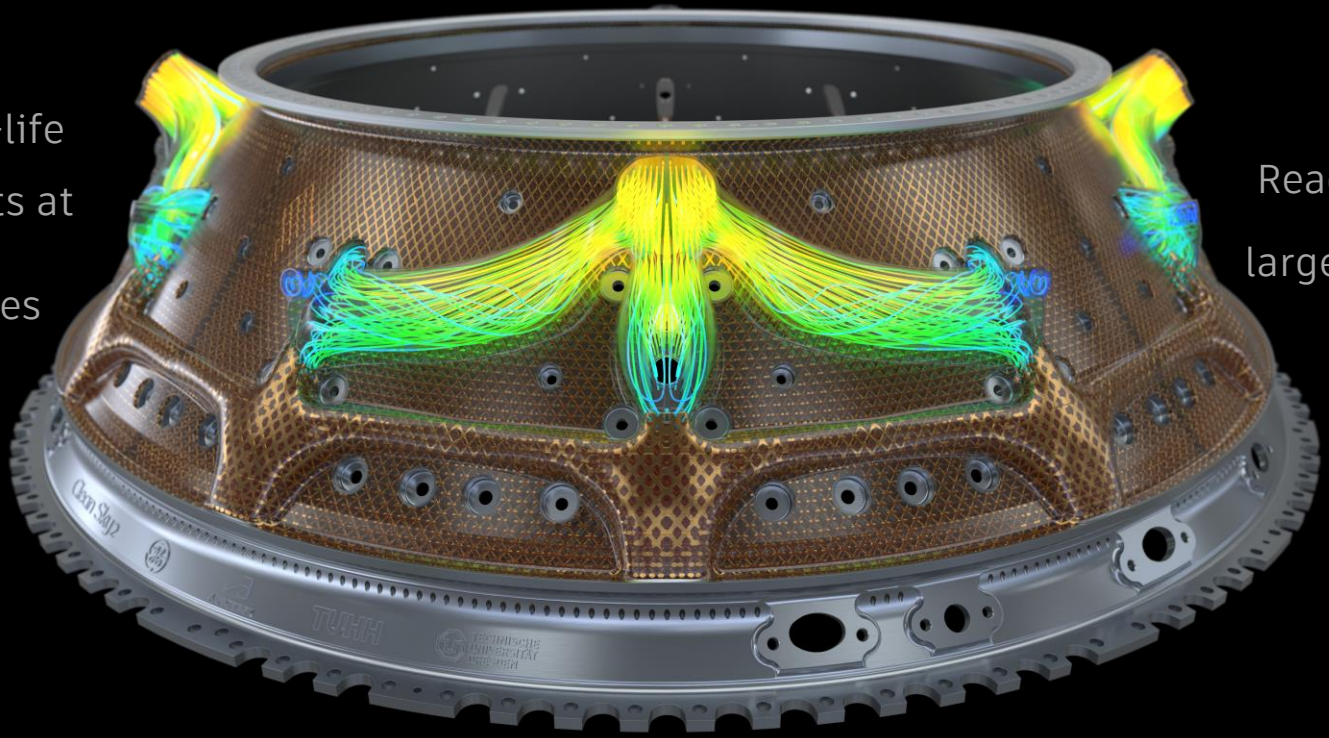
Design 4.2 Summary

100+ parts consolidated into **1**

~16GJ of heat has been saved

Meets safe-life requirements at

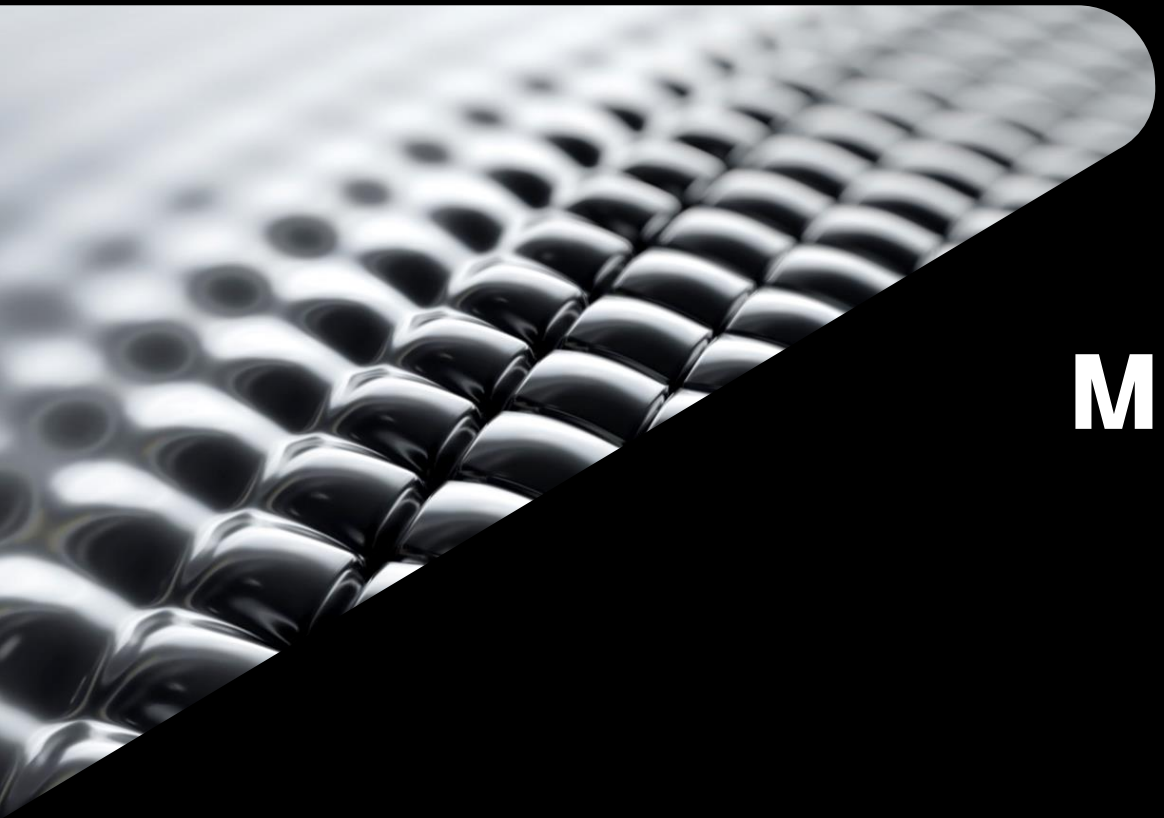
90k cycles



Ready for **~ 1m** large scale printing

System pressure drop : **~91%**

Overall mass reduction: **~35%**

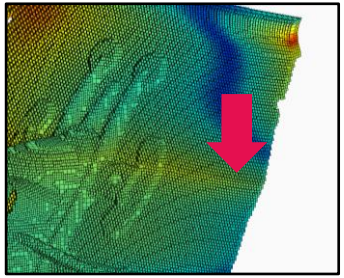


Manufacturing Optimization

Manufacturing Design Evolution

Design 2

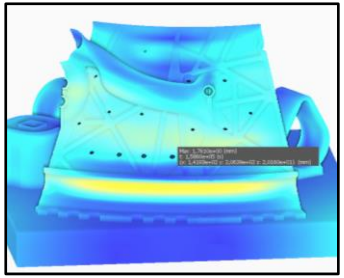
Manual Design Philosophy



- Manufacture first 1/8 section of TCF
- First comparison between printed + scanned part and build process simulation

Design 3

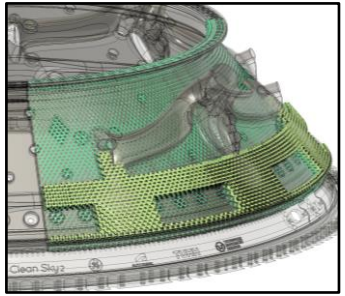
GD Inspired 'Ribs' Philosophy

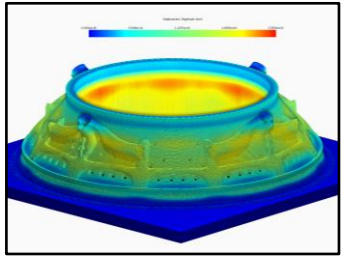


- Improved manufacturability with less distortion through the added stiffness rips
- Build process simulation and validation

Design 4.1

GD Inspired 'Lattice' Philosophy

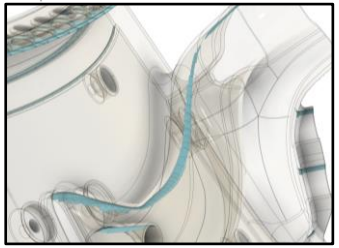


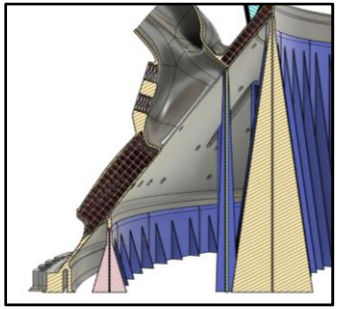


- Meets the stiffness and weight requirement
- Conformal lattice following the cone shape
- Full scale print simulation for large scale laser powder bed fusion process

Design 4.2

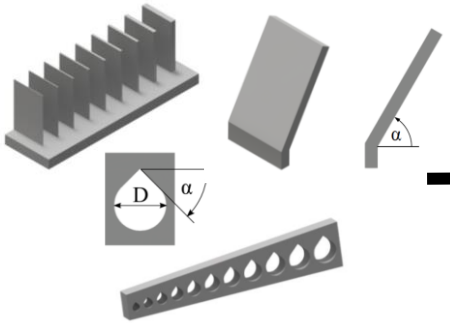
GD Inspired 'lattice' + **DFAM Guidelines**



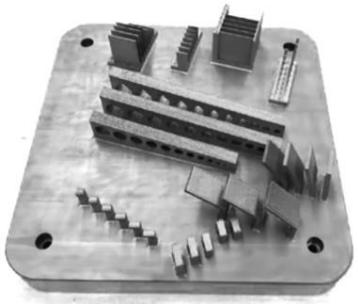


- Applied DFAM guidelines for IN718 on large scale powder-bed fusion machine

Design 2 to Design 4 - DfAM learnings



design features



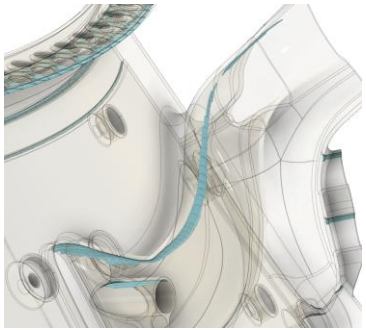
printing & geometrical evaluation

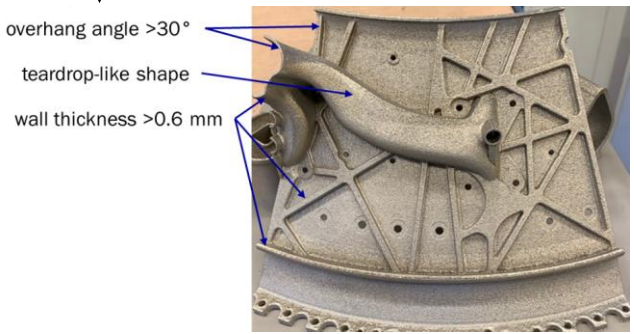
Journal of Laser Applications ARTICLE scitation.org/journal/jla

TABLE IV. Design guidelines and recommendations for L-PBF of IN718.

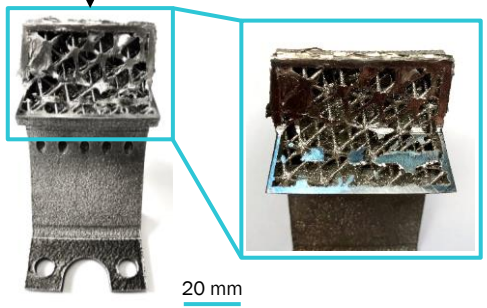
Geometry feature		Recommendation	
Name	Illustration	Value	Comment
Unsupported small walls		Wall thickness ≥0.3 mm	• 15 mm height with no deviation from the design if thickness ≥0.3 mm • Manufactured thickness max. 12% smaller for a thickness of 0.3 mm
Unsupported large walls		Wall thickness≥0.6 mm	• 30 mm height with no deviation from design

design guidelines (published in J. Laser Appl. 34, 012015 (2022))





application to TCF case & validation on design 3 and design 4.x

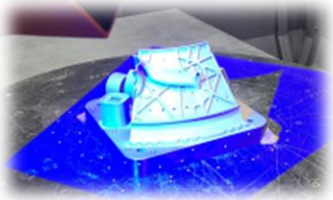


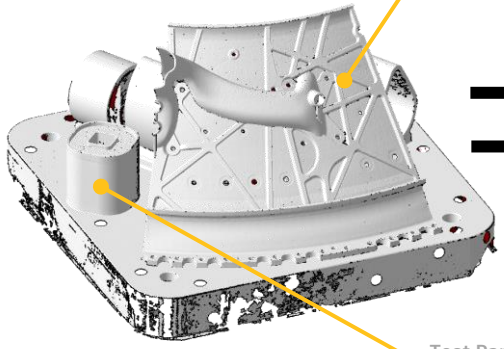
validation of lattice printing and powder removal process for design 4.x

Design 3 - Build process simulation validation

3D Scans at ATC Birmingham

GOM cell was used

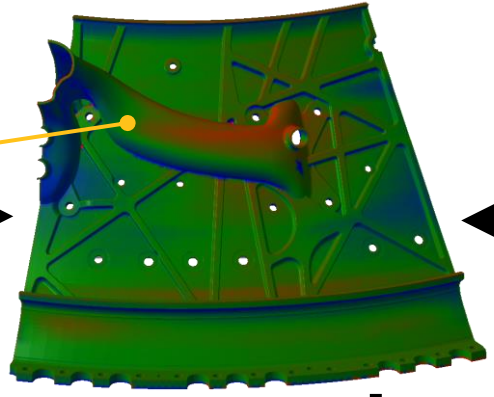


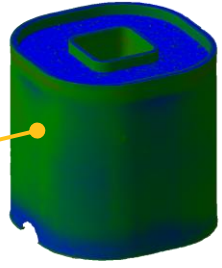


1/8 of the design 3 was printed

Test Part for additional validation

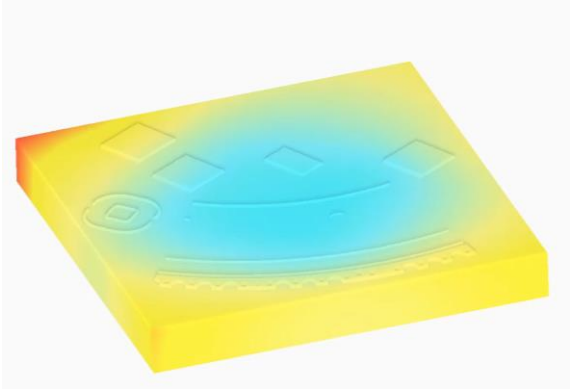
Comparison between Scan data and simulation results

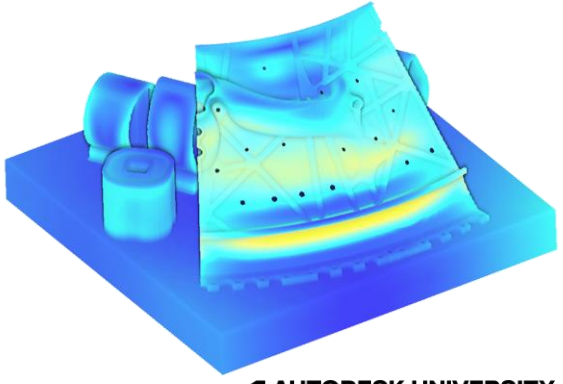




Comparison results are used for refining the build simulation

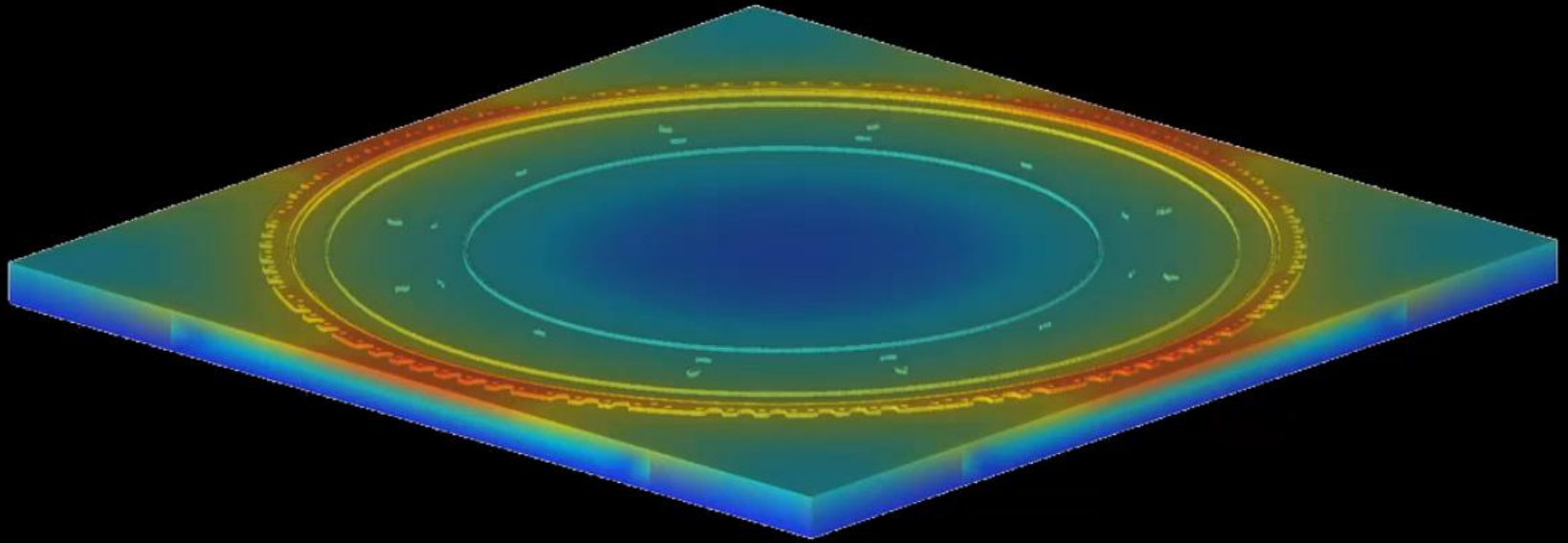
Netfabb build process simulation





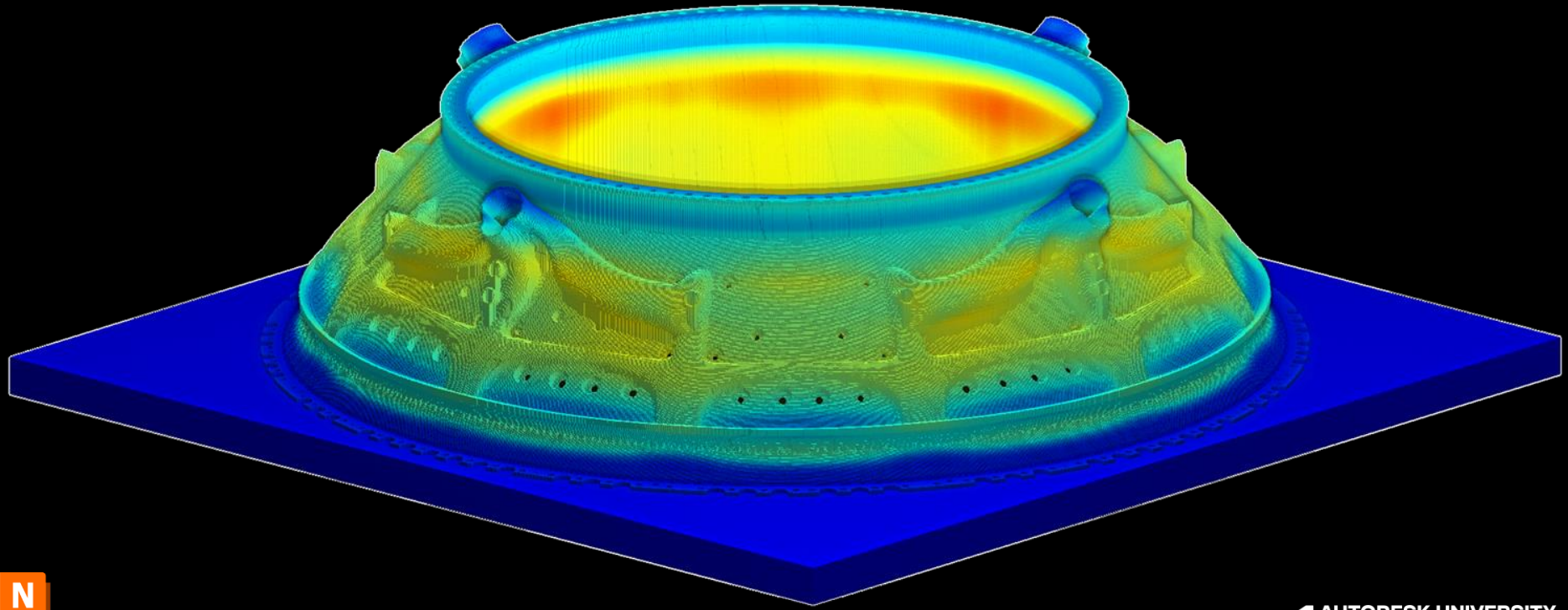
Design 4.1- Build process simulation

Full TCF simulation was done to identify potential problem areas



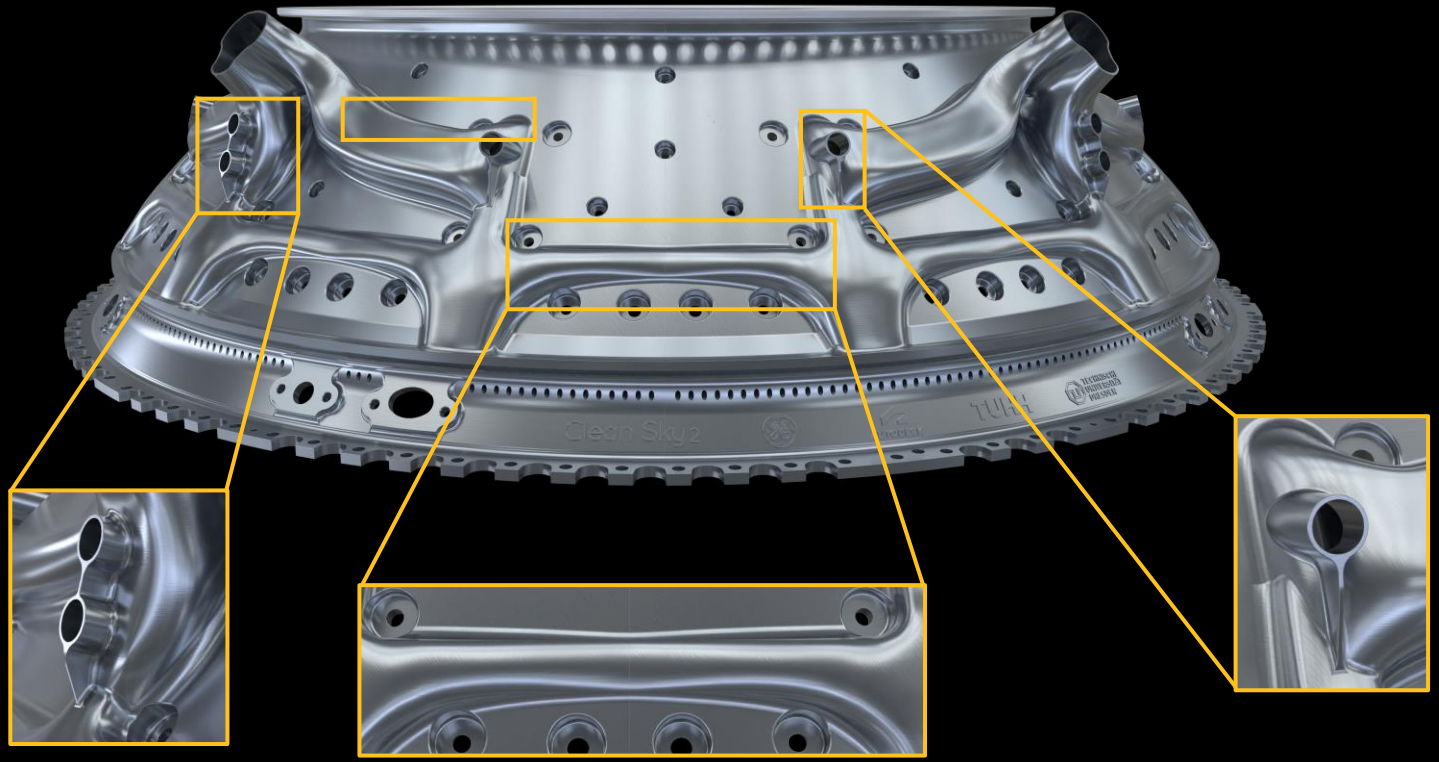
Design 4.1- Build process simulation

Full TCF simulation was done to identify potential problem areas



Design 4.2 – Final DfAM applications

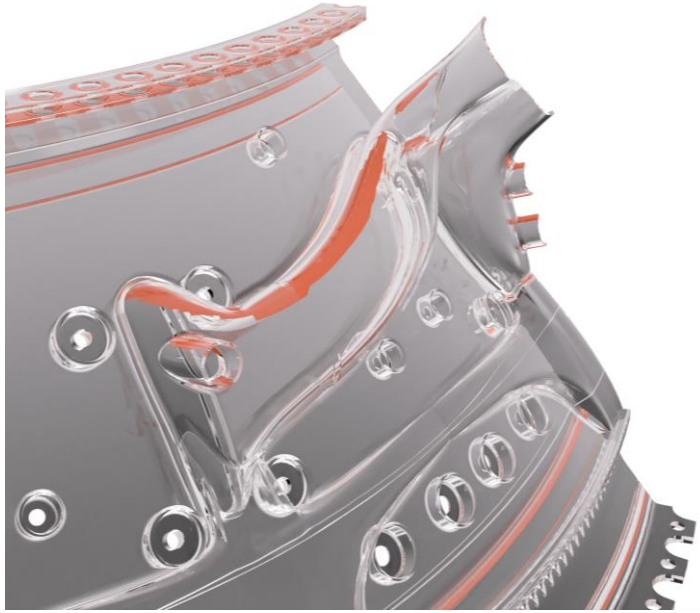
Further DFAM applied at R4.2 to reduce necessary support and improve problem areas



Design 4.2 - Manifold modifications

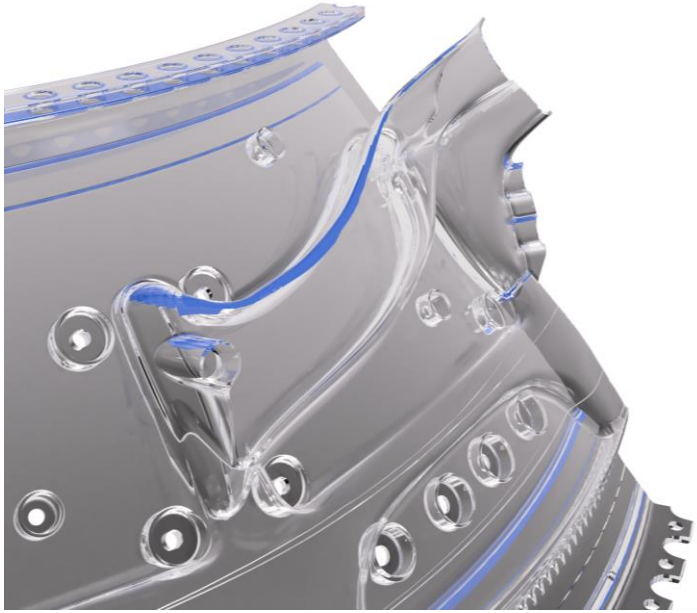
Reduced radii at top to avoid internal support requirements

Design 4.1



Total Predicted support structure volume: 965 cm^3

Design 4.2



Total Predicted support structure volume 755 cm^3 (-22%)

Design 4.x – Conformal lattice workflow

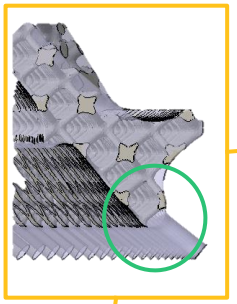
Conformal X-lattice around the whole hardware with variable beam thicknesses

Design 4.x outside + inside cavity bodies

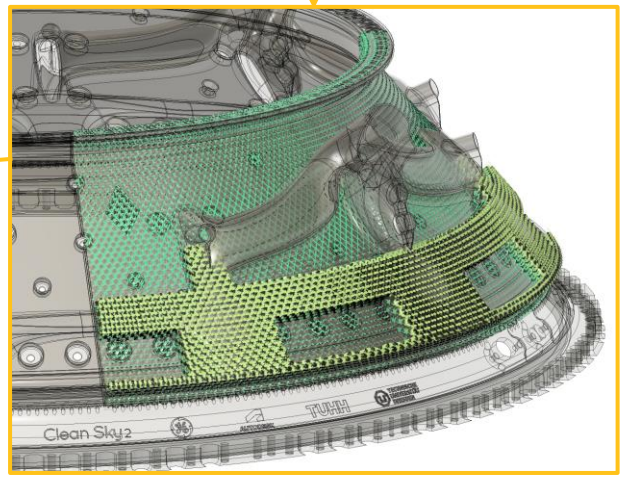
Conformal Lattice positioned and created using AVK

Cutting lattice to final shape (0.2mm overlap)

Lattice ready to be printed using specific process parameters

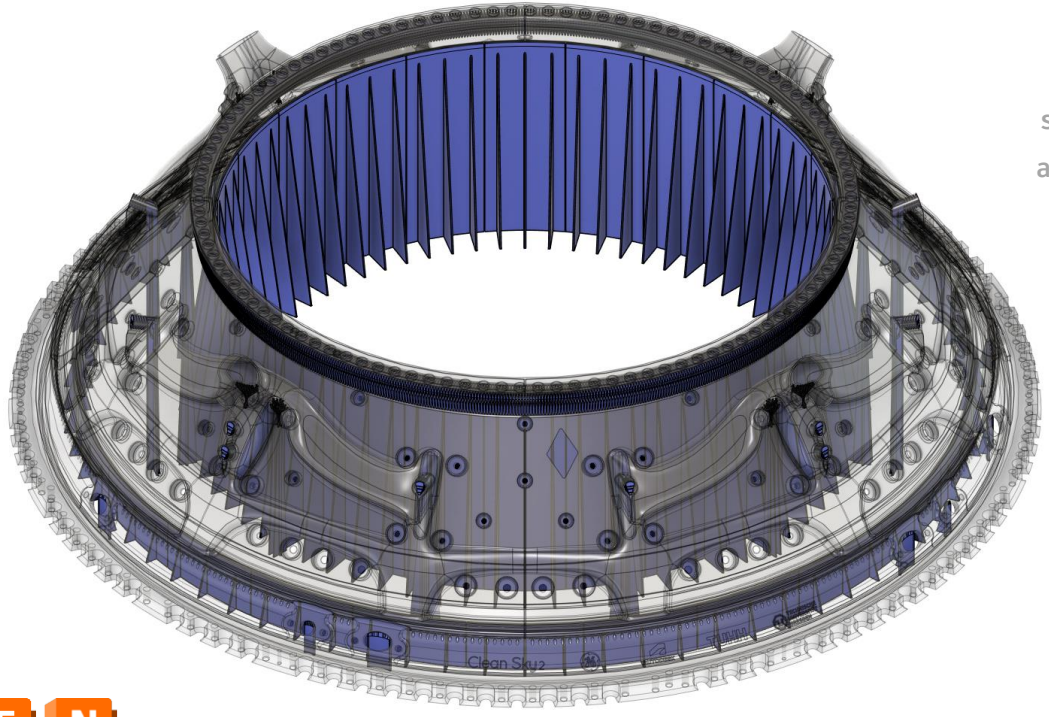


Powder drain holes are completely free of beams and no open beams at the bottom

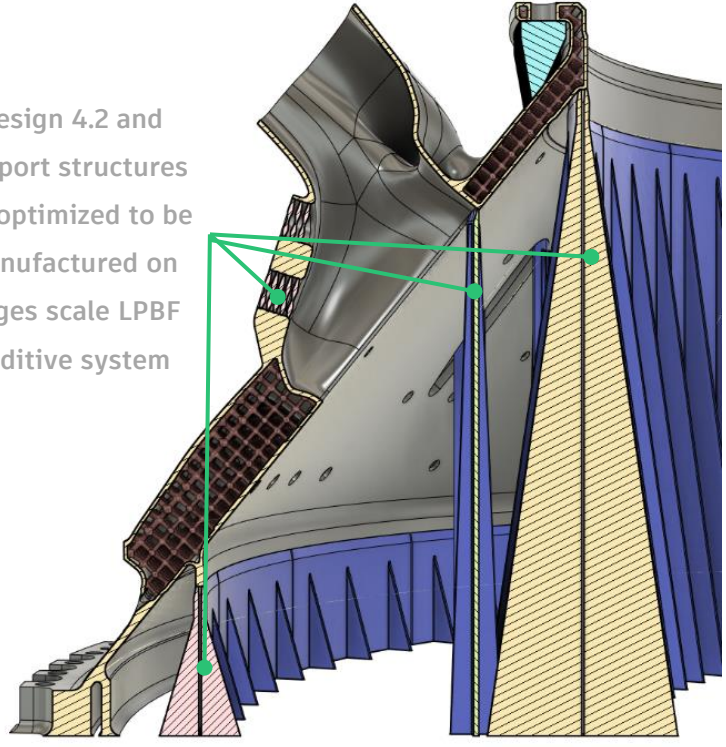


Design 4.2 – final build preparation

Break off support structures for large scale powder bed fusion process

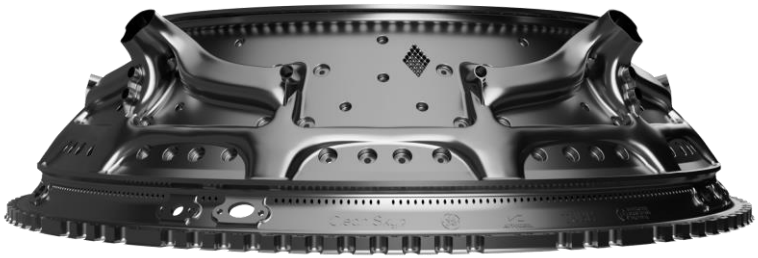


Design 4.2 and support structures are optimized to be manufactured on larges scale LPBF additive system

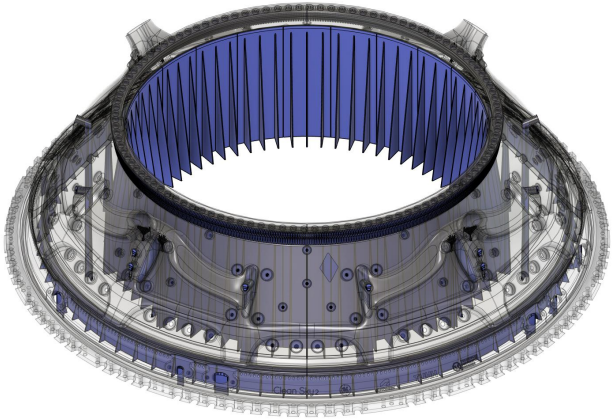


Printing Design 4.2 on Large scale AM system

DIGITAL hardware with DfAM modifications



Prepared for Additive Manufacturing



Build data

REAL hardware

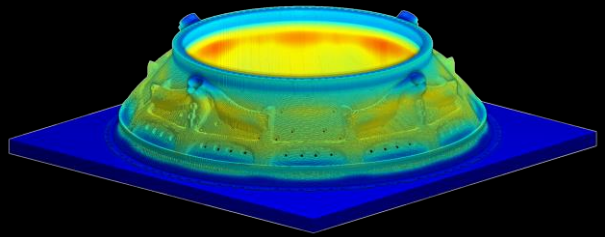
Project MOnACO Summary

Part design

- Structural and fluid optimization of the turbine hardware
- Reduce mass by 35% and meet aero-thermal requirements
- Parts consolidation 100+ to 1

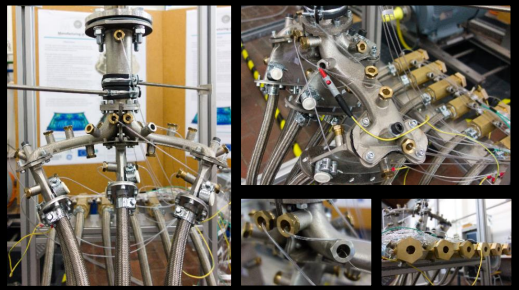
AM Process

- Simulation of build process & validation
- DMLM (PBF-LB/M) of up to 1m part diameter
- Created design guidelines for IN718



Testing

- Thermal and flow testing
- Mechanical properties
- Validation of Manufacturing
- TRL4/MRL4 at project end



This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 831872. The JU receives support from the European Union's Horizon 2020 research and innovation program and the Clean Sky 2 JU members other than the Union.

Credits:

Clean Sky

AUTODESK

TUHH
Technische Universität Hamburg

TECHNISCHE UNIVERSITÄT DRESDEN

Thank you to everyone involved into the project over the last three years!!!