Progettazione per la fabbricazione additiva

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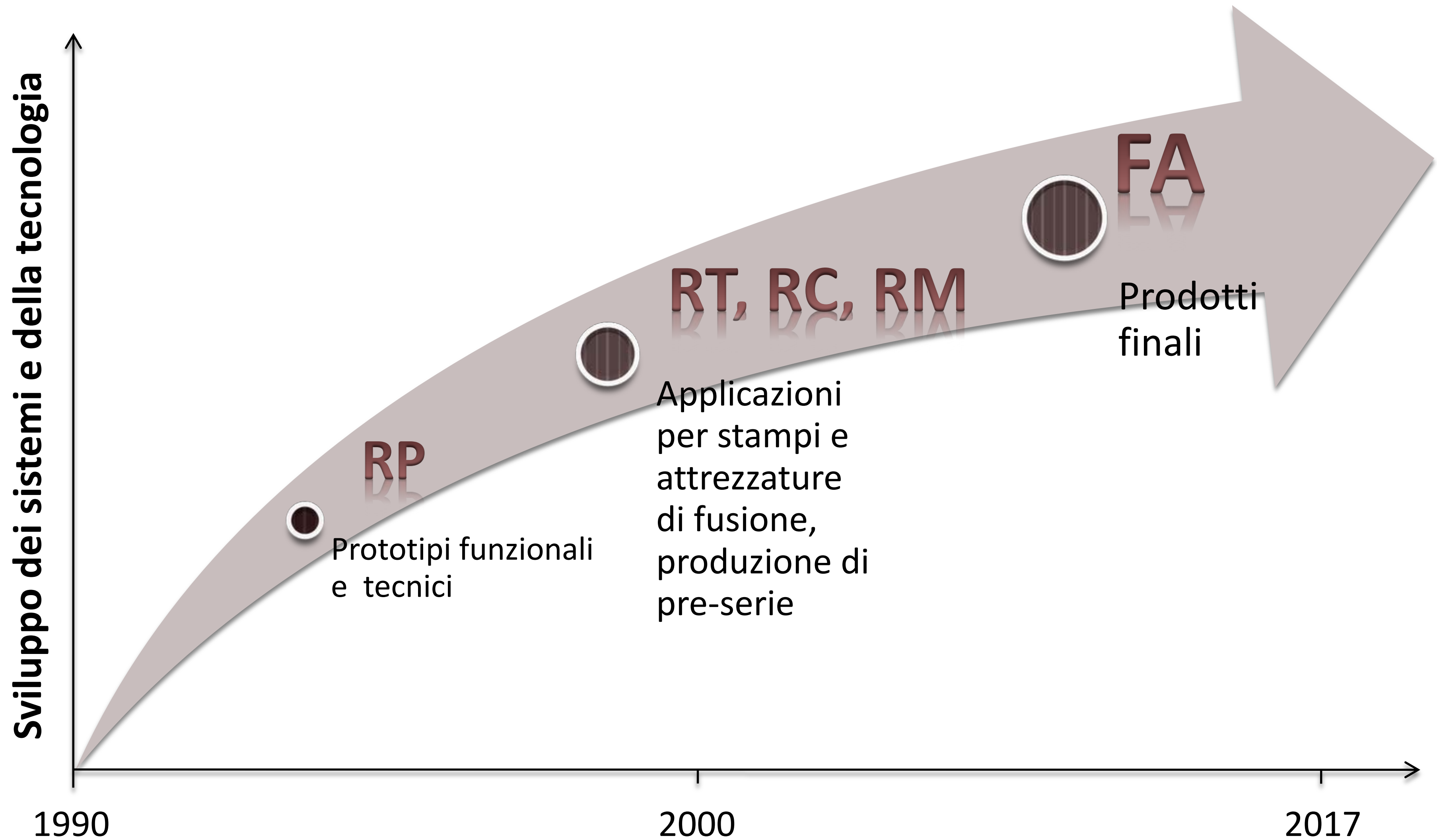
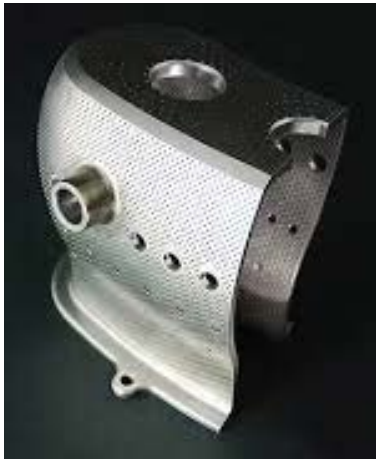
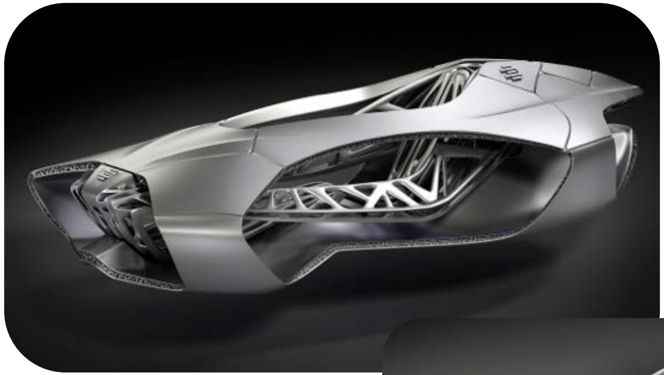
Dalla prototipazione rapida alla Fabbricazione Additiva



Aerospace

Automotive





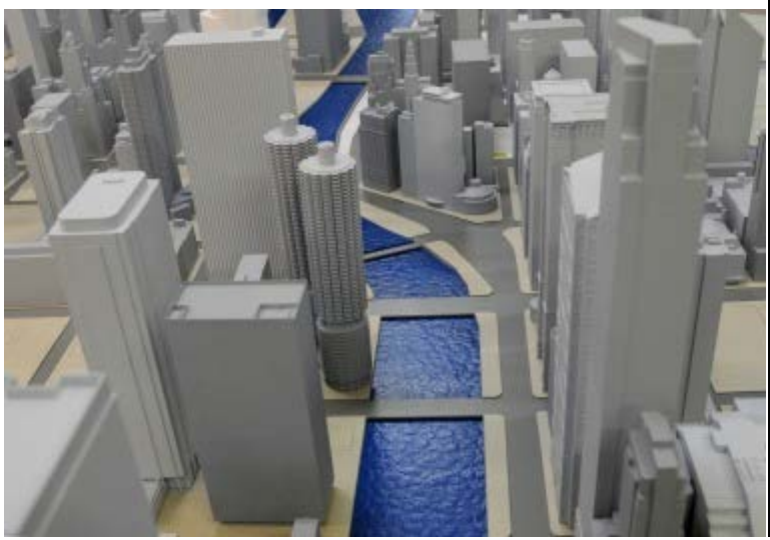
Medical and Dental

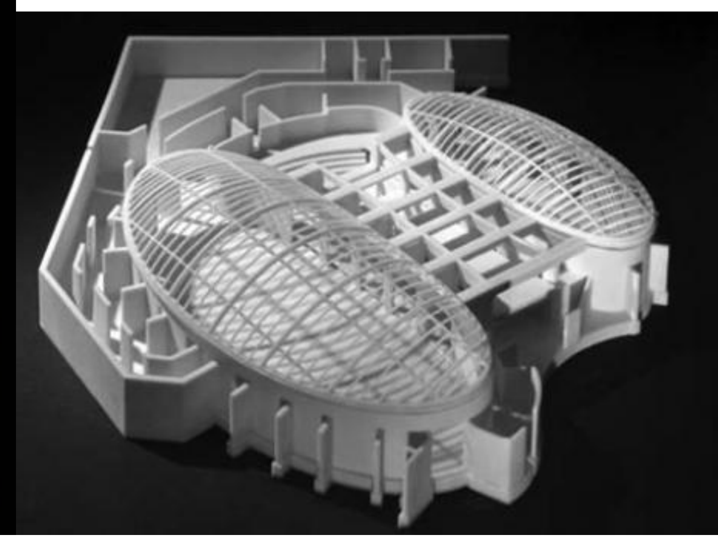
Image courtesy of ARCAM AB

Image courtesy of EOS GmbH

Jewelry

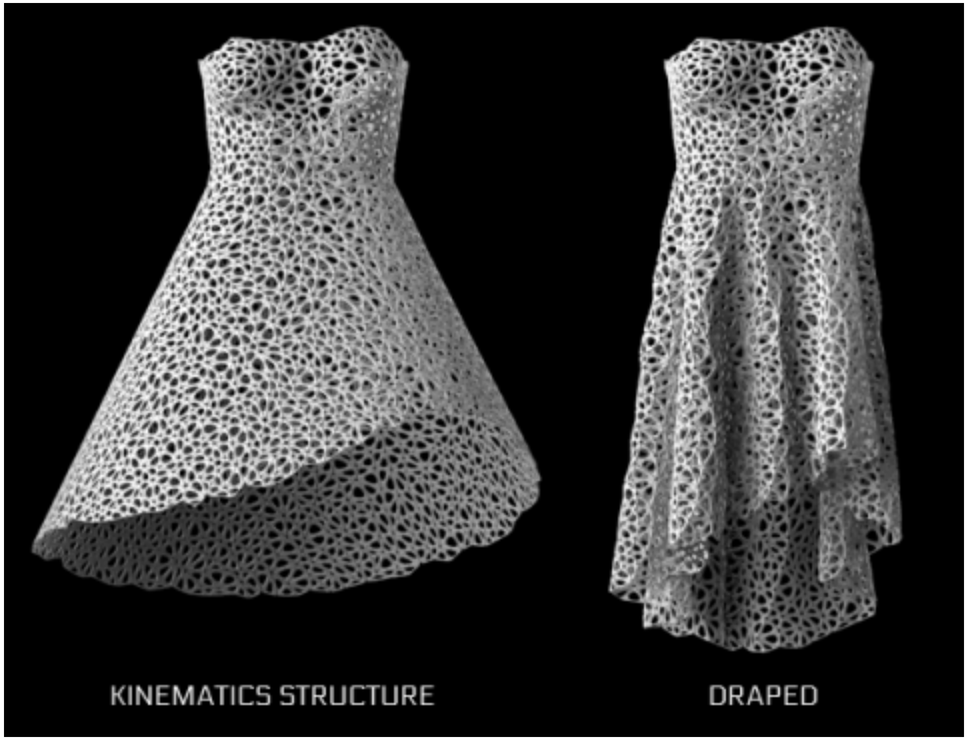
Architectural



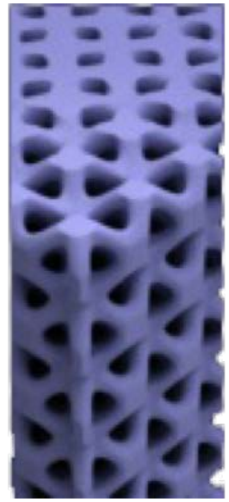


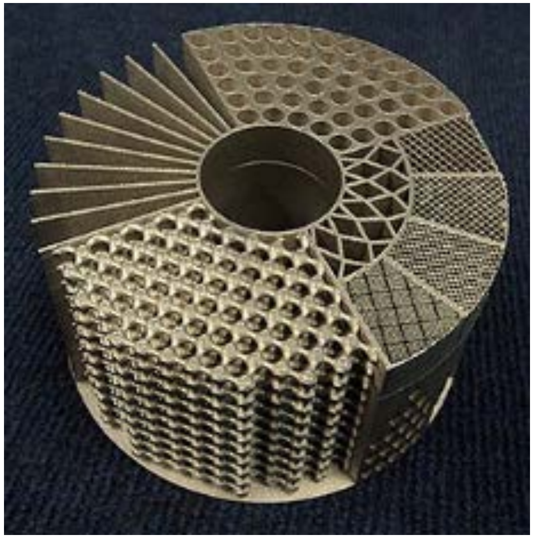
Design and Fornitures

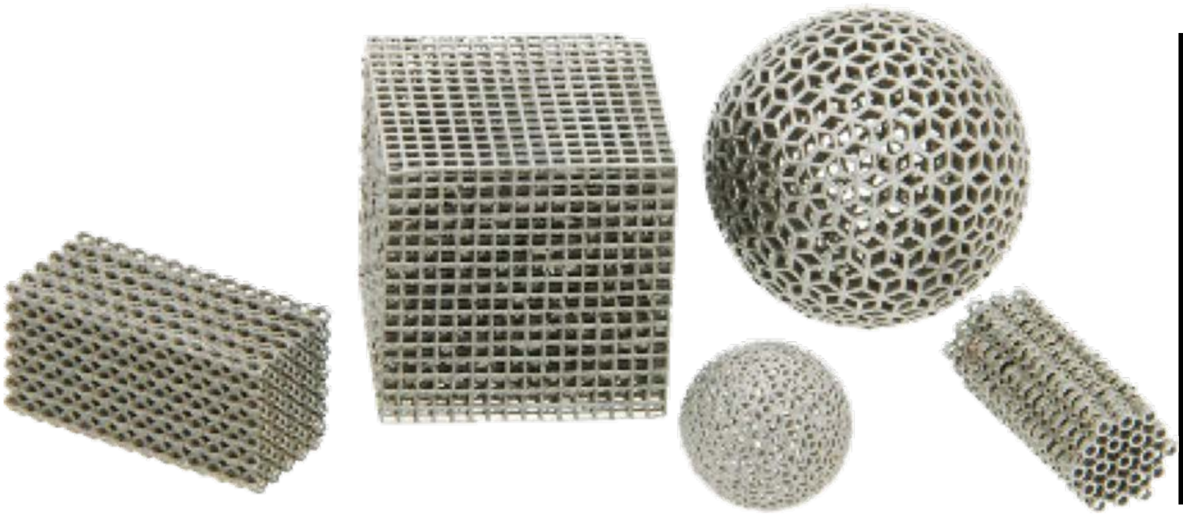
Fashion

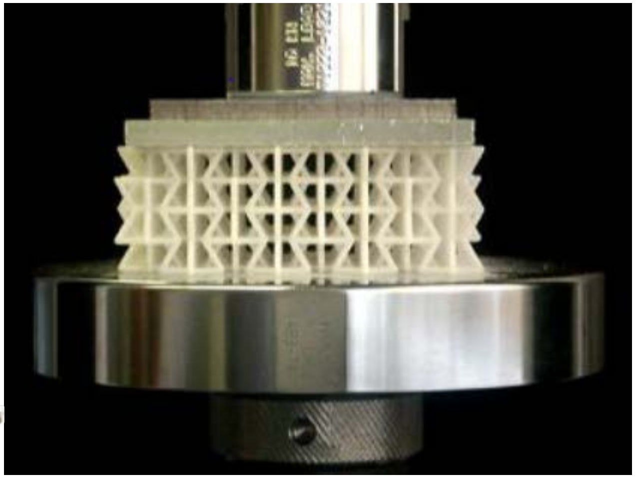


Lattice Structures and Filters

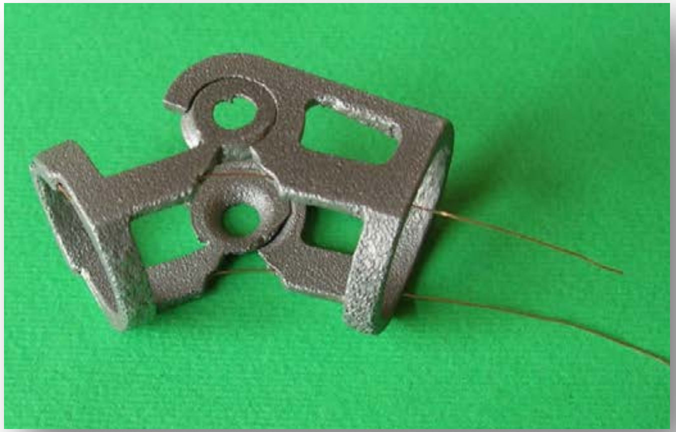






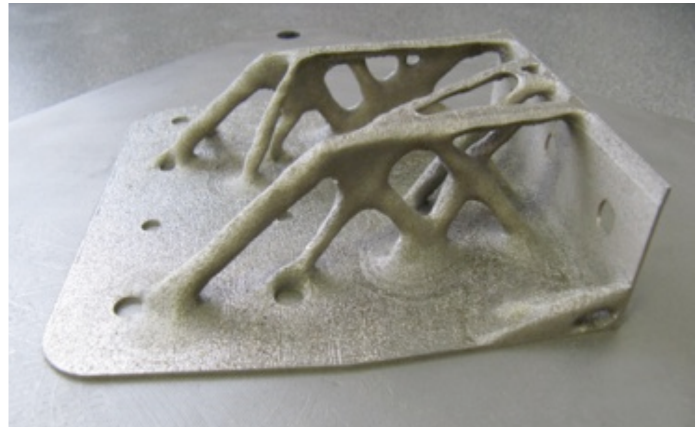


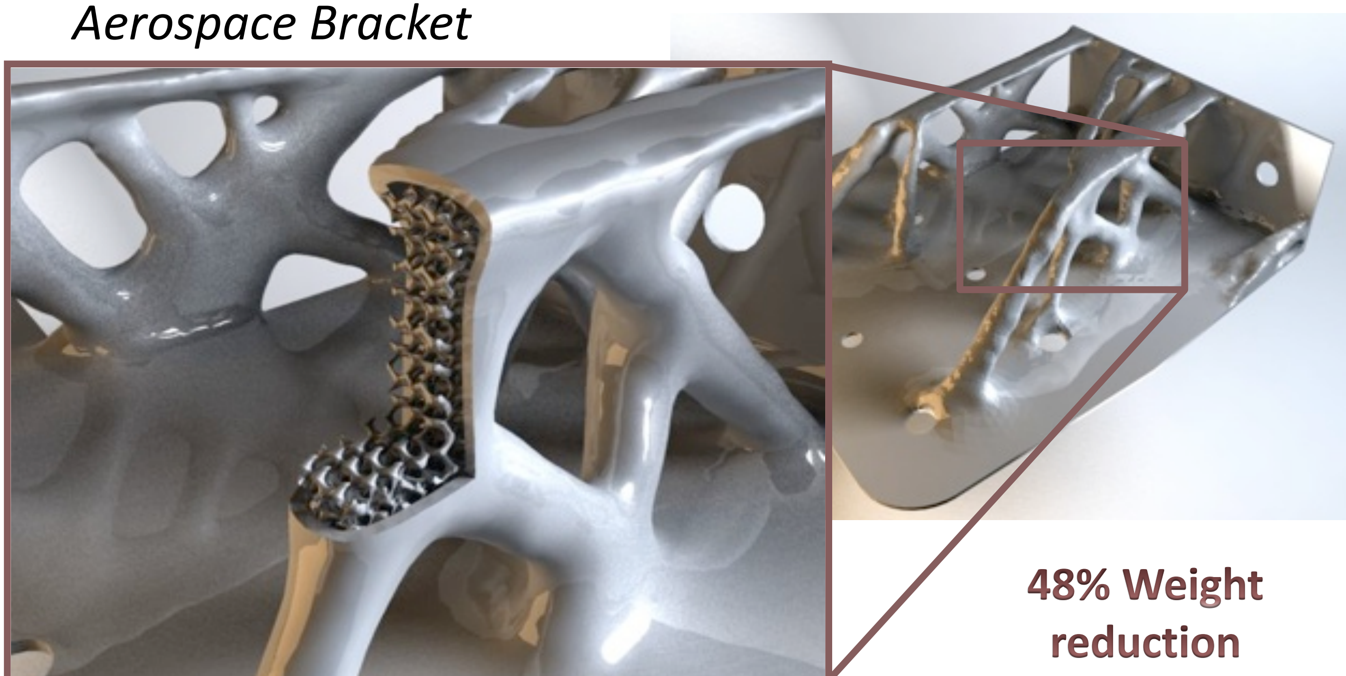
Living Hinges and Assemblies



Design from Biological Structures

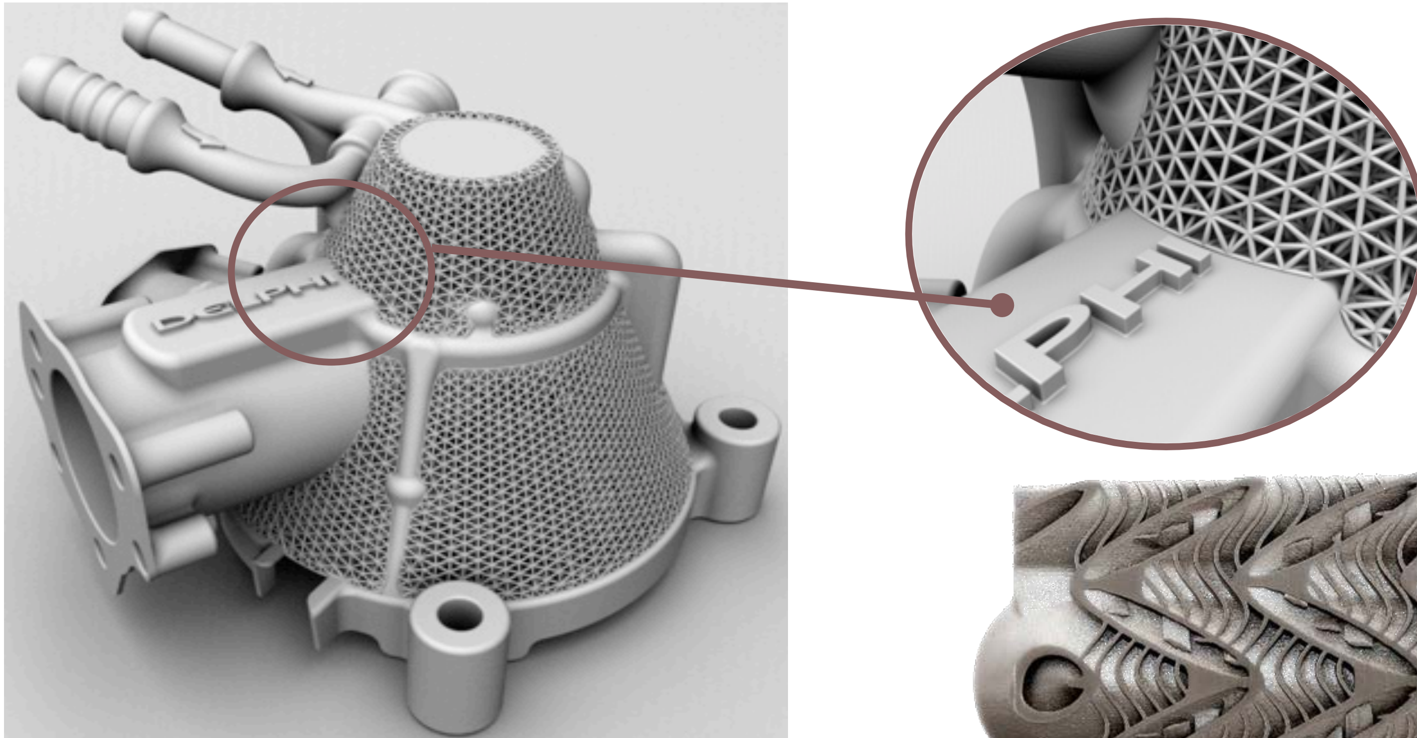
Aerospace Bracket



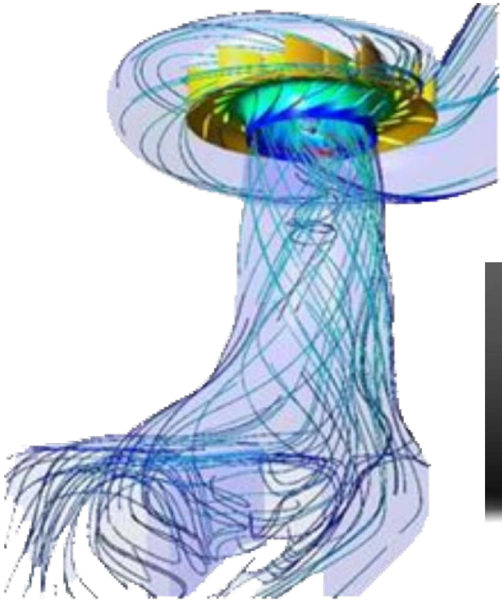


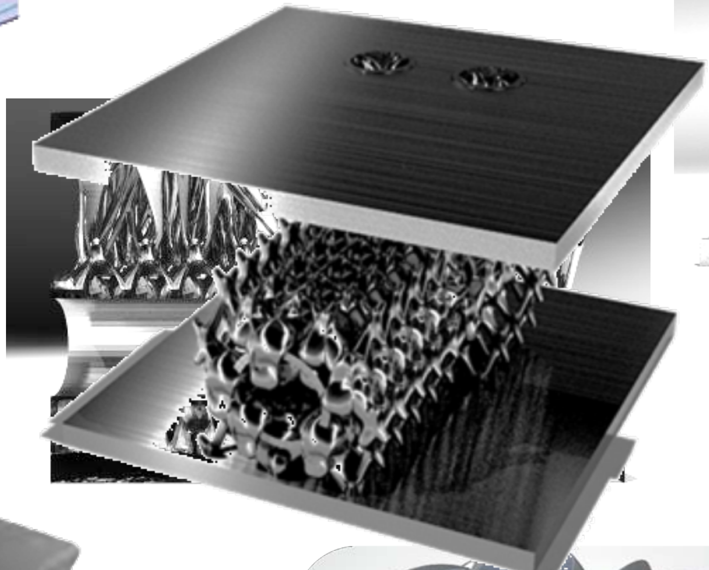
48% Weight reduction

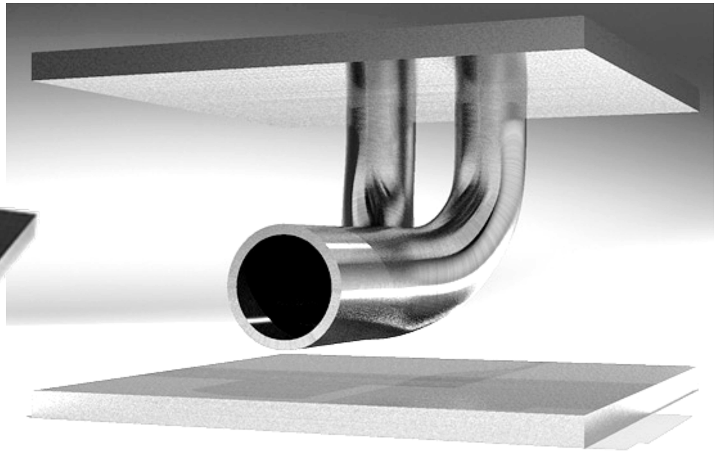
Optimisation of Heat Exchangers and Dissipation Surfaces



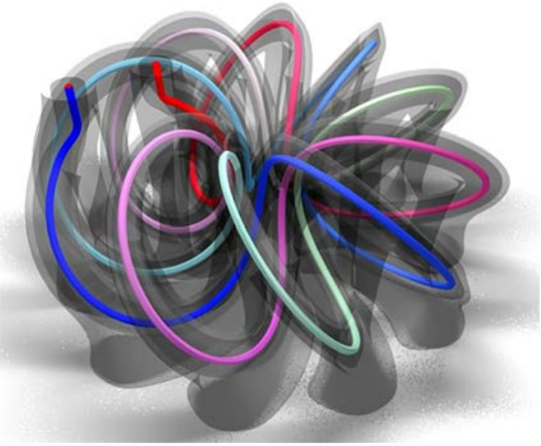
New Opportunites for Fluid Dynamics







Images courtesy of Within Lab



I vantaggi della Fabbricazione Additiva

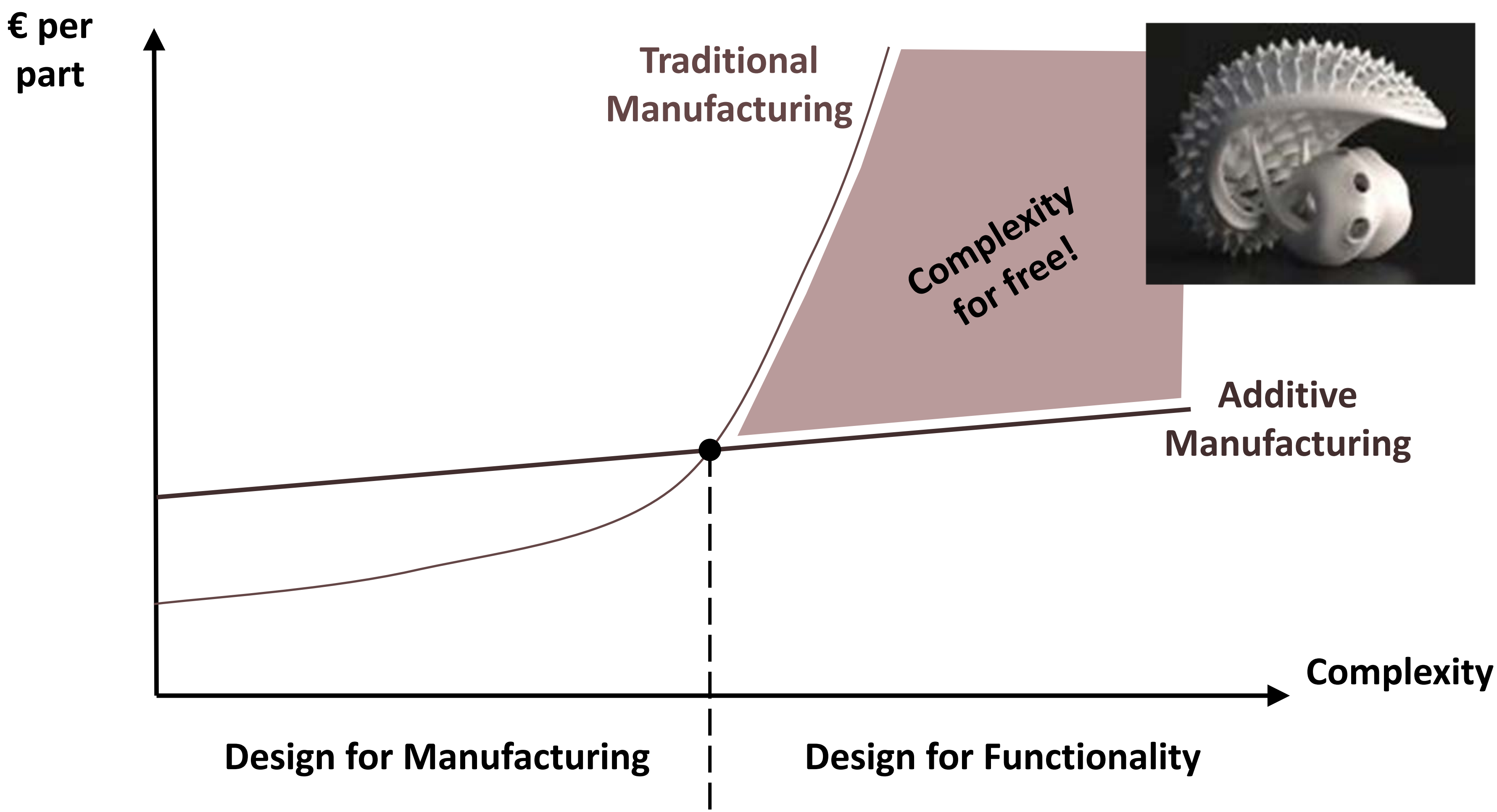
I vantaggi sono capitalizzabili se e solo se il componente viene progettato per essere prodotto in AM

1. Migliorare le performance del componente

2. Ridurre il peso del componente

3. Ridurre il tempo e i costi di sviluppo prodotto

Costi in funzione della complessità geometrica



I vantaggi della Fabbricazione Additiva

PRODOTTO

- Libertà di progettazione
- Strutture leggere

  (*forme cave complesse*)
- Parti integrate
- Design ergonomico
- Personalizzazione

PROCESSO

- Una sola macchina, forma illimitate
- Assenza di attrezzature
- Assenza di dispositivi di bloccaggio
- Sottosquadri ammessi
- Un solo step produttivo
- Minimo intervento dell’operatore
- Tempi e costi legati solo alle dimensioni e non alla complessità geometrica

Gli svantaggi della Fabbricazione Additiva

PRODOTTO

- Necessità di strutture di support (metallo)
- Finitura superficiale scarsa
- Numero limitato di materiali commerciali
- Costo dei materiali

PROCESSI a LETTO di POLVERE

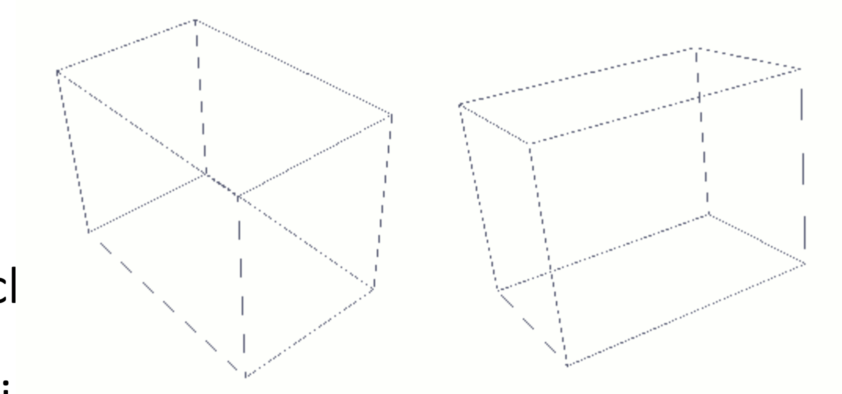
- Macchine nate per produrre prototipi
- Volumi di lavoro limitati
- Velocità di costruzione limitate
- Carenze sul controllo di processo on-line

Design for Additive Manufacturing (DFAM)

- I principi della progettazione per la fabbricazione additiva (Design For Additive Manufacturing – DFAM) e le modifiche rispetto ai processi di produzione tradizionali sono già stati delineati da diversi ricercatori (Hague *et al.*, 2003; Iuliano *et al.* 2004, Becker *et al.*, 2005).
- Lo scopo del DFAM è ***"la massimizzazione delle prestazioni de prodotto attraverso una sintesi delle forme, dimensioni, strutture gerarchiche e composizione del materiale soggetta al potenziale delle tecnologie additive*"**.
- Per perseguire tali obiettivi i progettisti devono considerare che:
  - la FA consente di avere sottosquadri, spessore di parete variabile e canali profondi e di geometria complessa;
  - attraverso la FA è possibile produrre componenti con complessità geometrica illimitata, che ammette forme contorte e svergolate, fori ciechi e filettature/viti con un elevato rapporto resistenza/peso;
  - La FA consente la riduzione del numero di parti: è possibile produrre direttamente un assemblato come unico componente integrando giunti e cerniere.

Design For Additive Manufacturing

Il DFAM può essere finalizzato:



- Minimizzare il peso;
- Massimizzare le prestazioni meccanicl
- Ottimizzare il comportamento dinamico,
- Ottimizzare le prestazioni termiche;
- Ridurre il numero di component;
- Integrazioni di funzioni in un unico elemento

DRIVERS FOR ADDITIVE MANUFACTURING

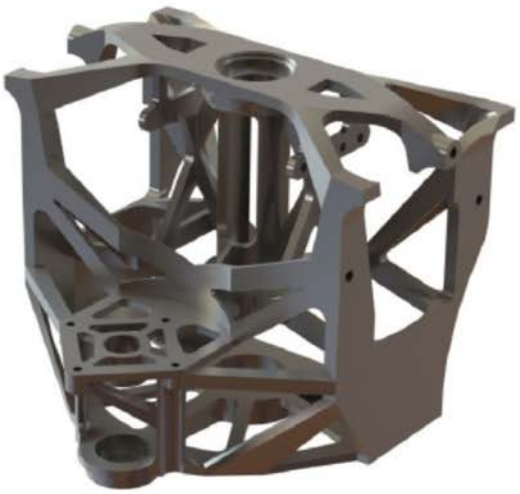
- material efficiency
- flow optimisation
- function integration
- mass customization
- tuning mechanical properties
- custom made porosities

material efficiency

"What If" we can use material, only there where needed…

Original (7) parts

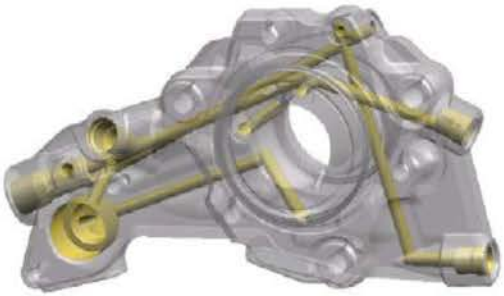
Design volume



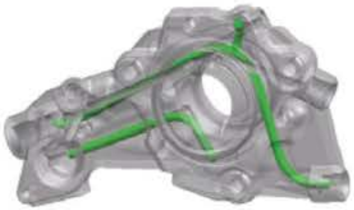
Optimised structure

DIESEL PUMP FACE PLATE *ATKINS PROJECT*

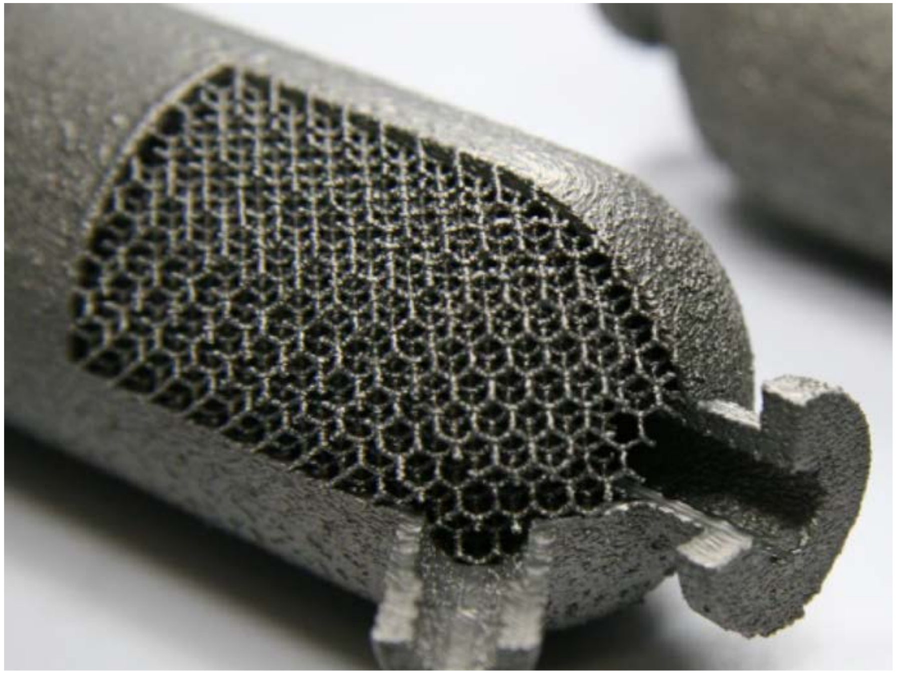
CONVENTIONAL

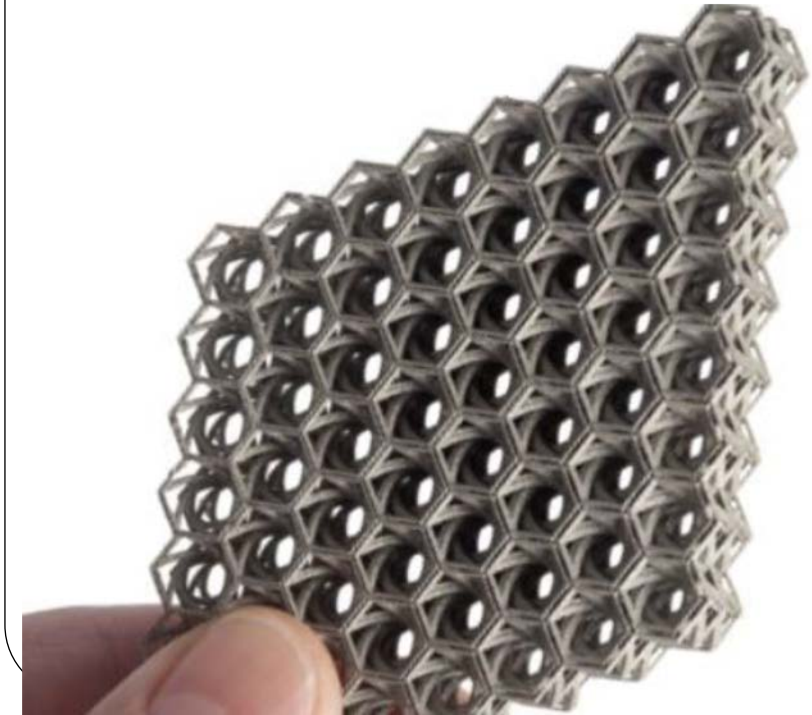


OPTIMISED



40% weight saving
Reduced fluid friction flowlosses
A more efficient car

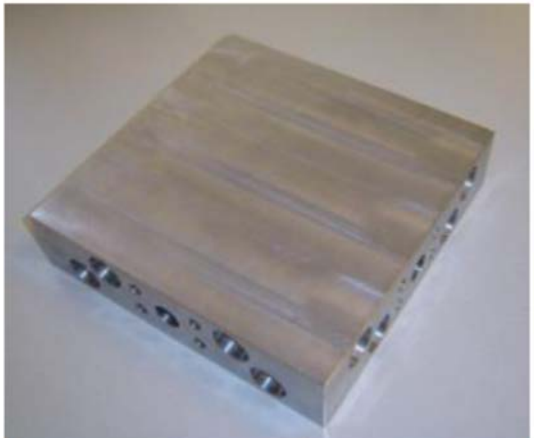


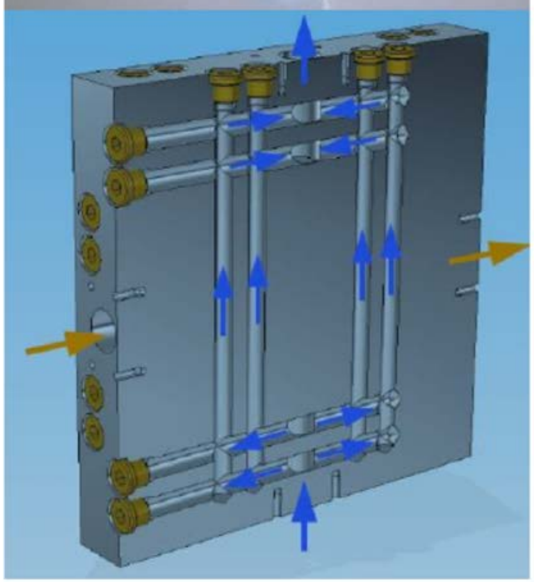


flow optimisation

"What If" *we can create complex channels inside our products*

HEAT EXCHANGER *HYDROVISION*

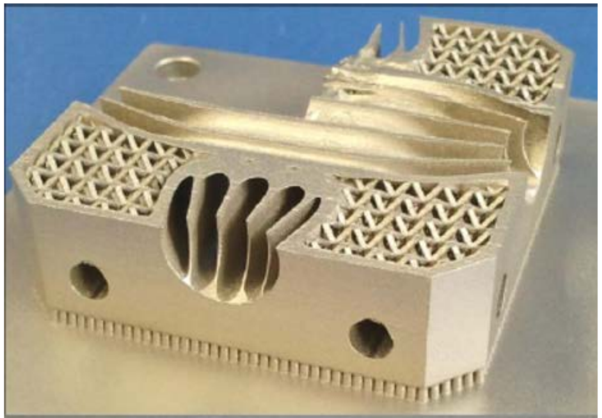


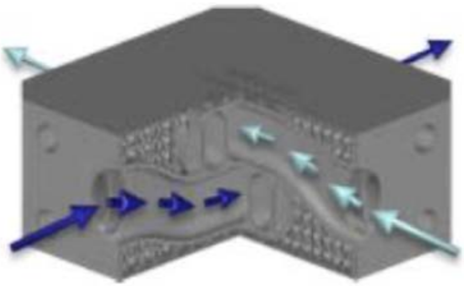


2.900 cm³ vs 244 cm³

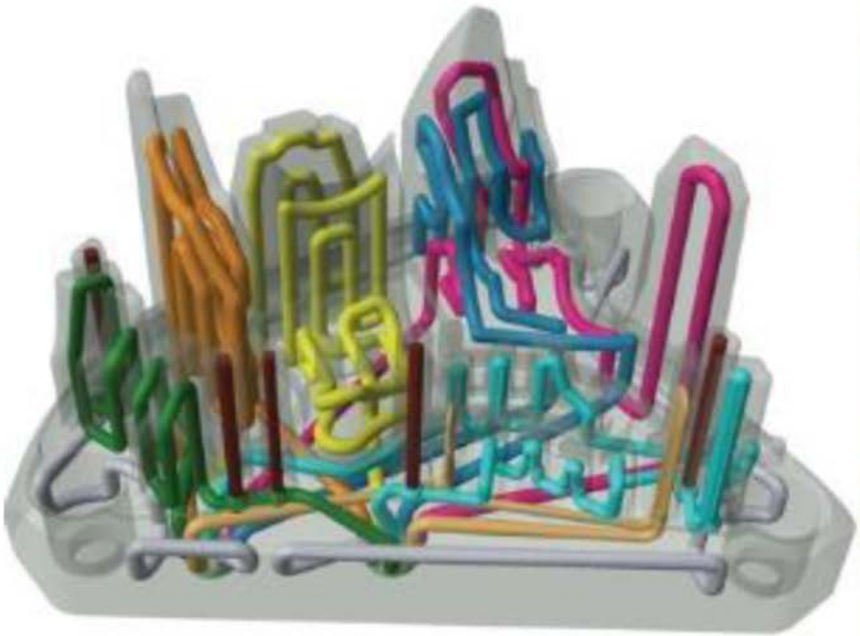
19.2 kg vs 1,2 kg

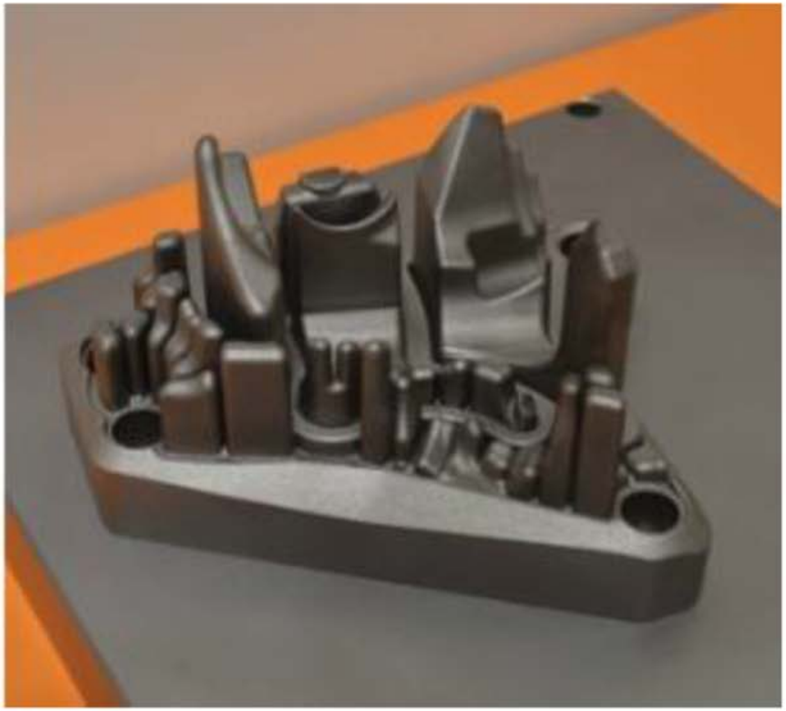
210 mm vs 85 mm

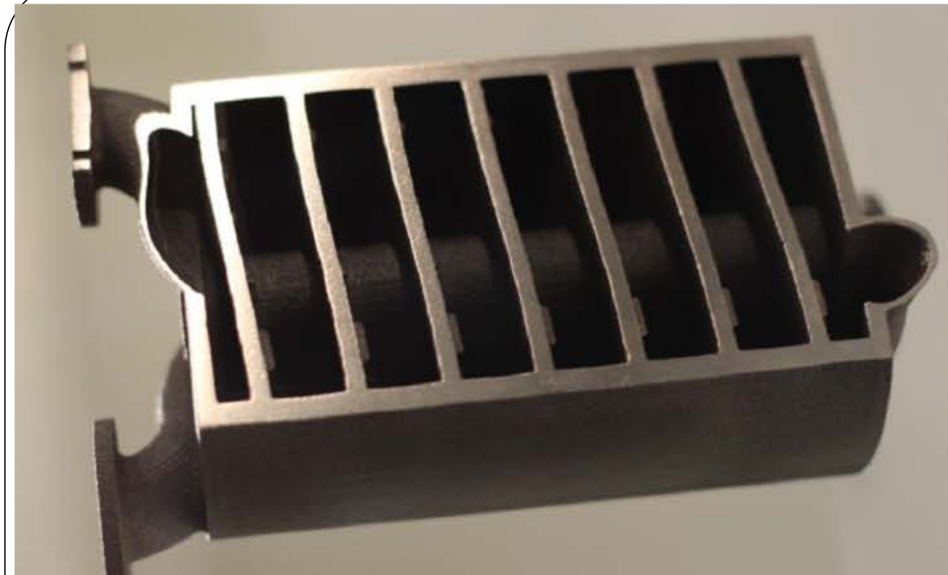




CONFORMAL COOLING RENISHAW









function integration

"What If" *we can maximize the functional integration in our part?*

FUEL NOZZLE GE – LEAP ENGINE

25% lighter

18 parts to 1 part

5 times more durable due to improved cooling system


FESTO

FLYING CAM

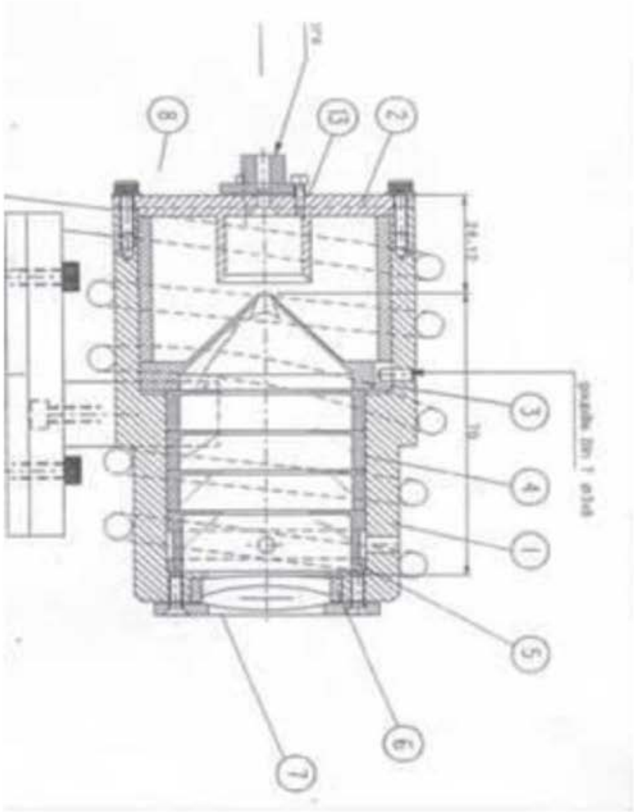
530g vs 392g (-26%)

7 components vs 2 components

3 materials vs 1 material (1 technology)

Much smaller carbon foot print

COLLIMATOR Sirris-CSL



13 parts vs 2 parts

Internal cooling channels

Tollerances ok

mass customization

"What If" we can start a serieproduction where each part is slightly different

HEARING AIDS MATERIALISE

Invisible

100% custom made

> 10.000.000 pcs

tuning of mechanical properties

"What If" *we can tune the material properties in a part*

CARDRIDGE ORTOFON

Cartridge with needle for pick-up

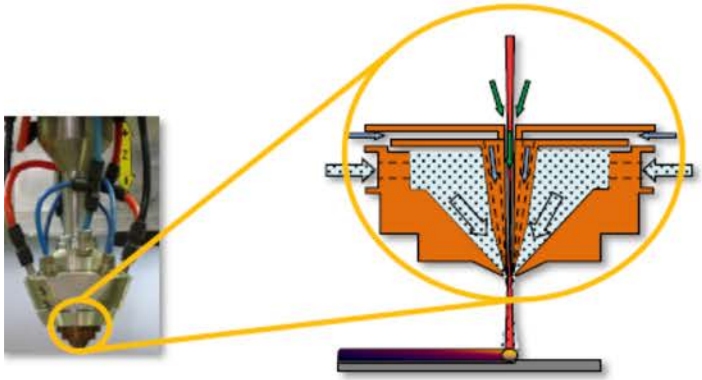
Higher internal damping

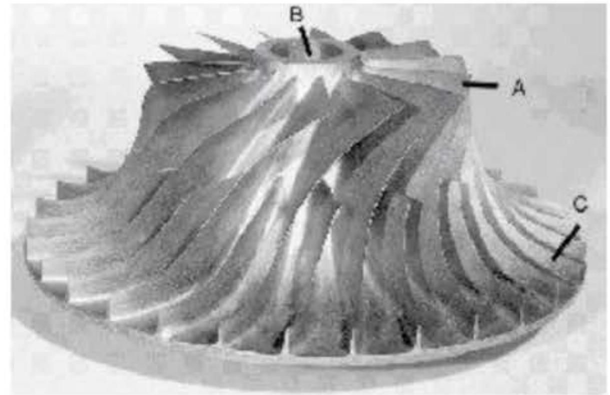
Better sound quality

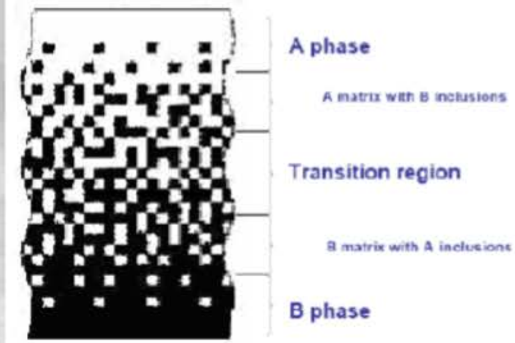
Danisch Technology Institute

VAPOR CARBON NIKE

LASER DEPOSITION







Different alloys for specific functions

Impact & corosion resistance

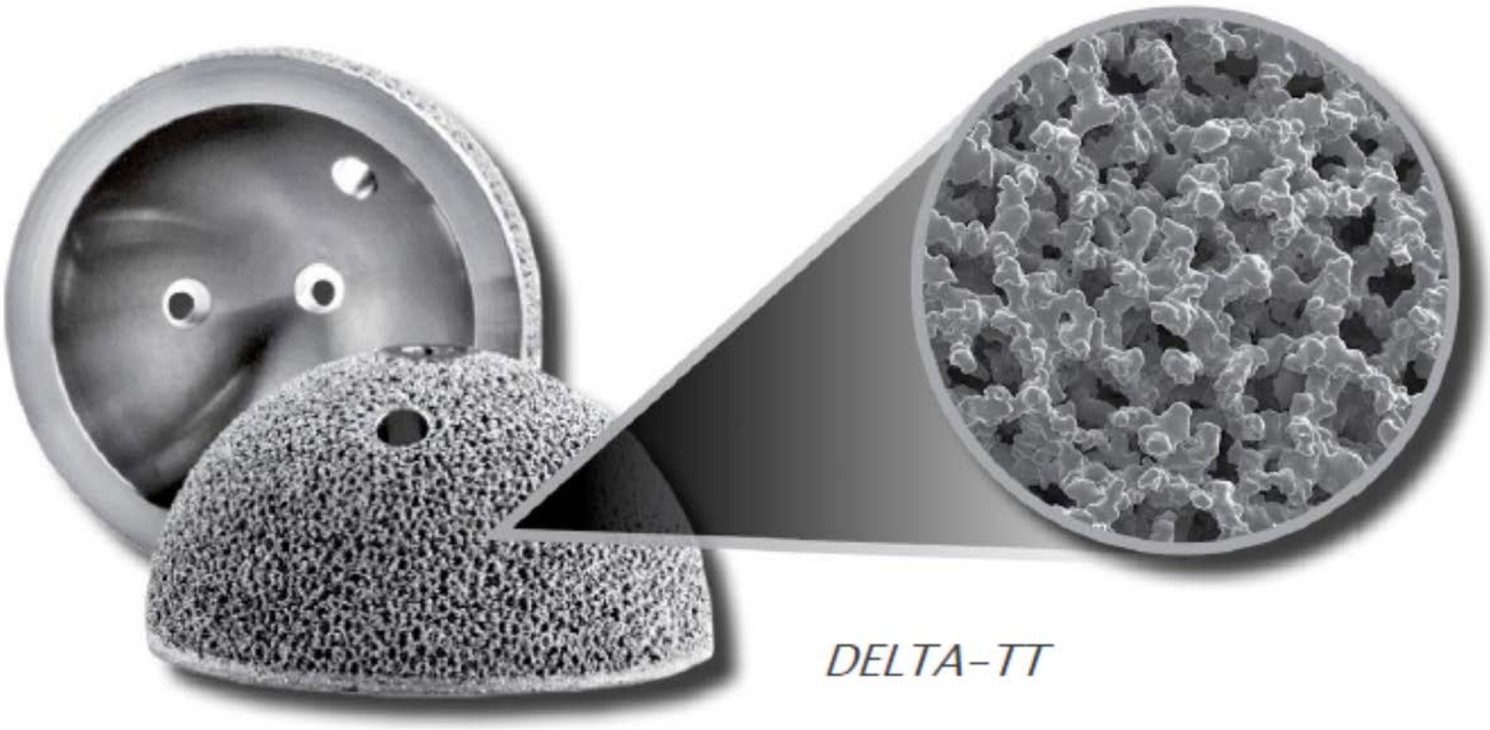
Fatigue

Creep

Ductility

custom made porosities

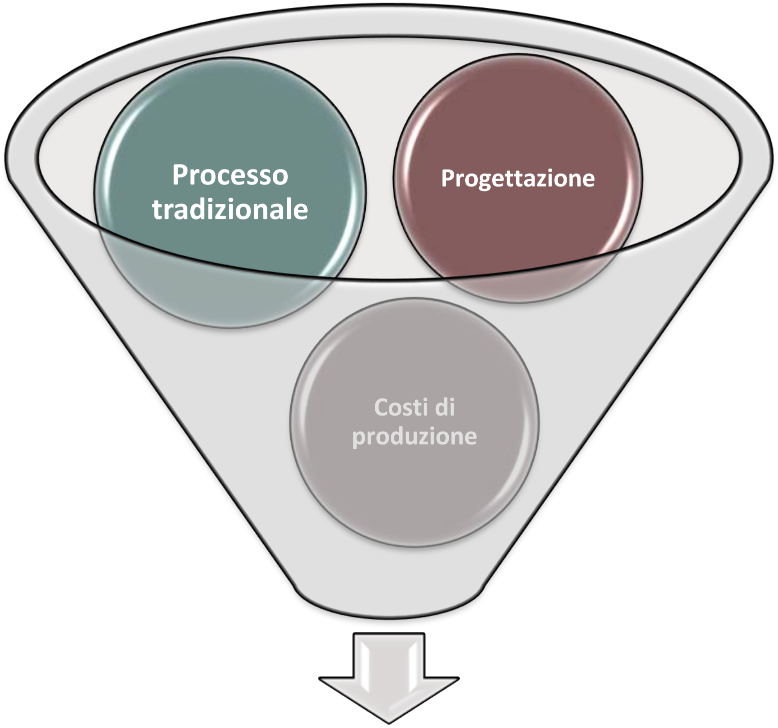
"What If" we can add porous structures to our part



DELTA-TT

Progettazione Tradizionale verso il DFAM

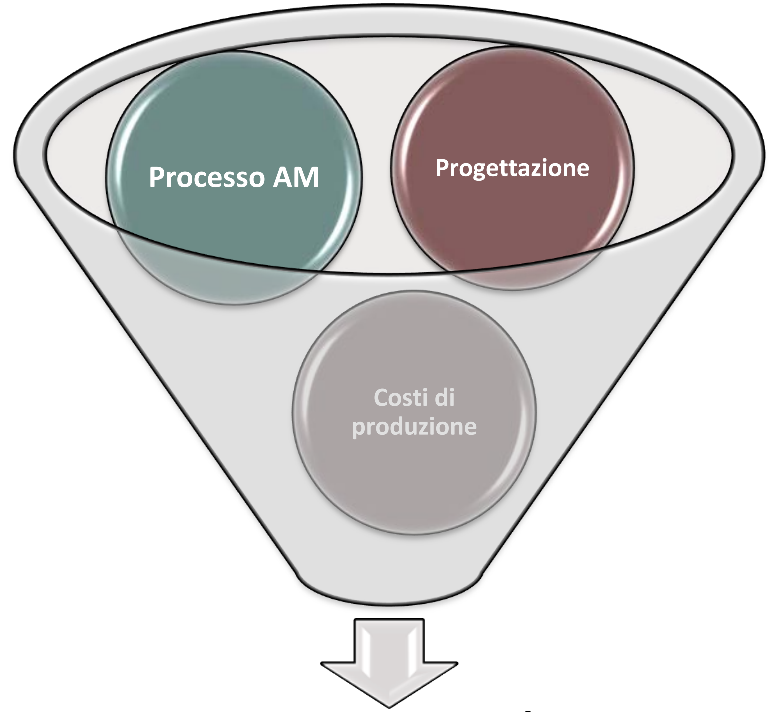
Progettazione Tradizionale



1 geometria

(compromesso)

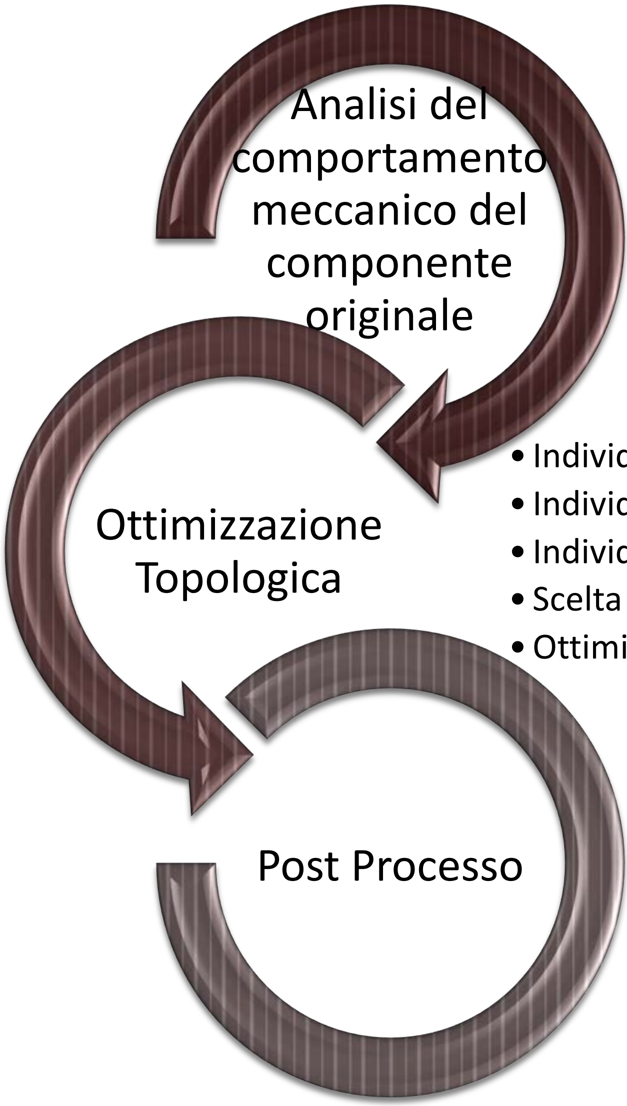
Progettazione per AM



Geometria personalizzata

- **Geometria A**
- **Geometria B**
- **....**

Metodologia – DFAM

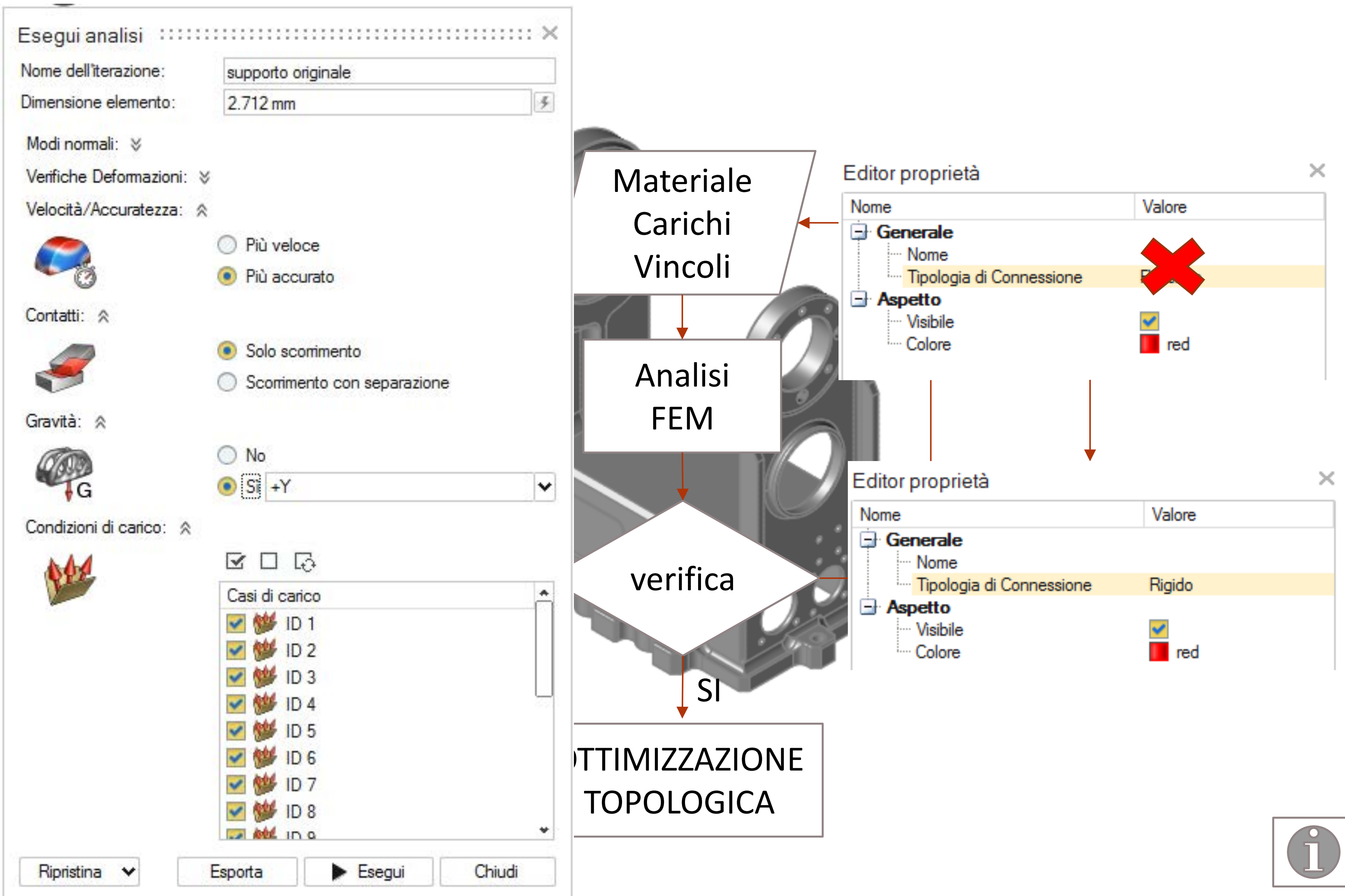


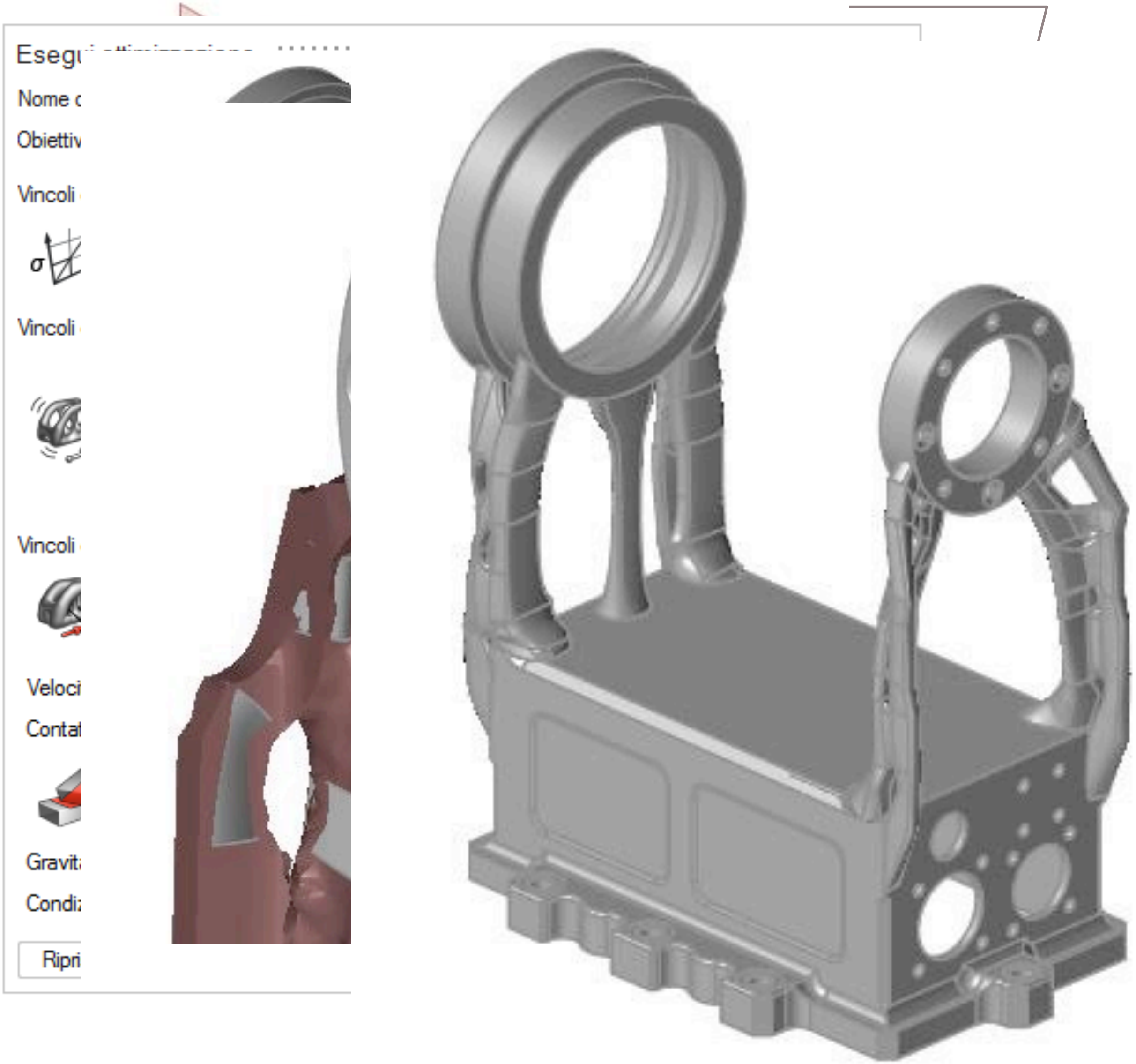
- Costruzione del modello FE
- Analisi Statica
- Analisi Quasi-Statica
- Analisi Dinamica

- Individuazione degli obiettivi di progettazione
- Individuazione dei vincoli progettuali
- Individuazione dello spazio di progettazione
- Scelta del materiale e del processo di AM
- Ottimizzazione topologica del componente

- Elaborazione CAD della geometria ottimizzata
- Verifica del comportamento meccanico del componente riprogettato

Metodologia

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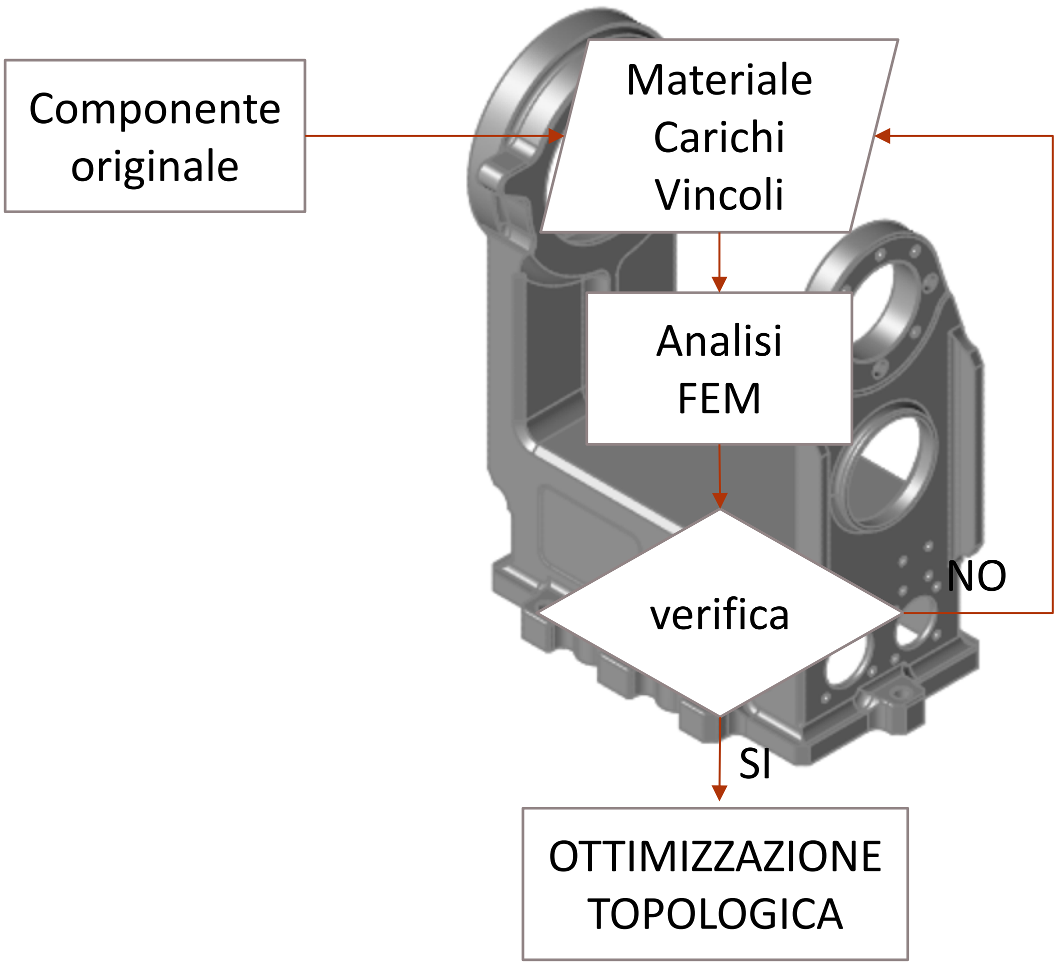
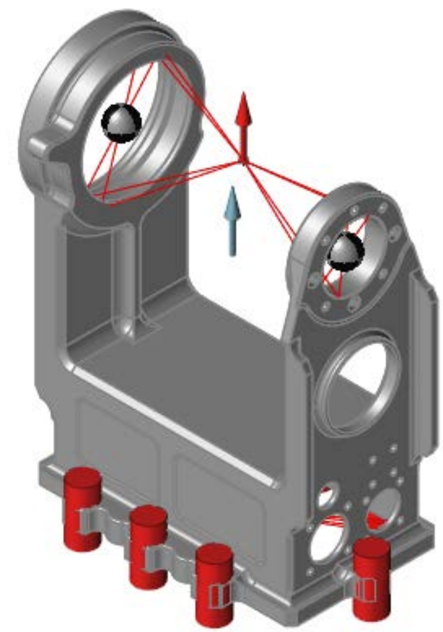
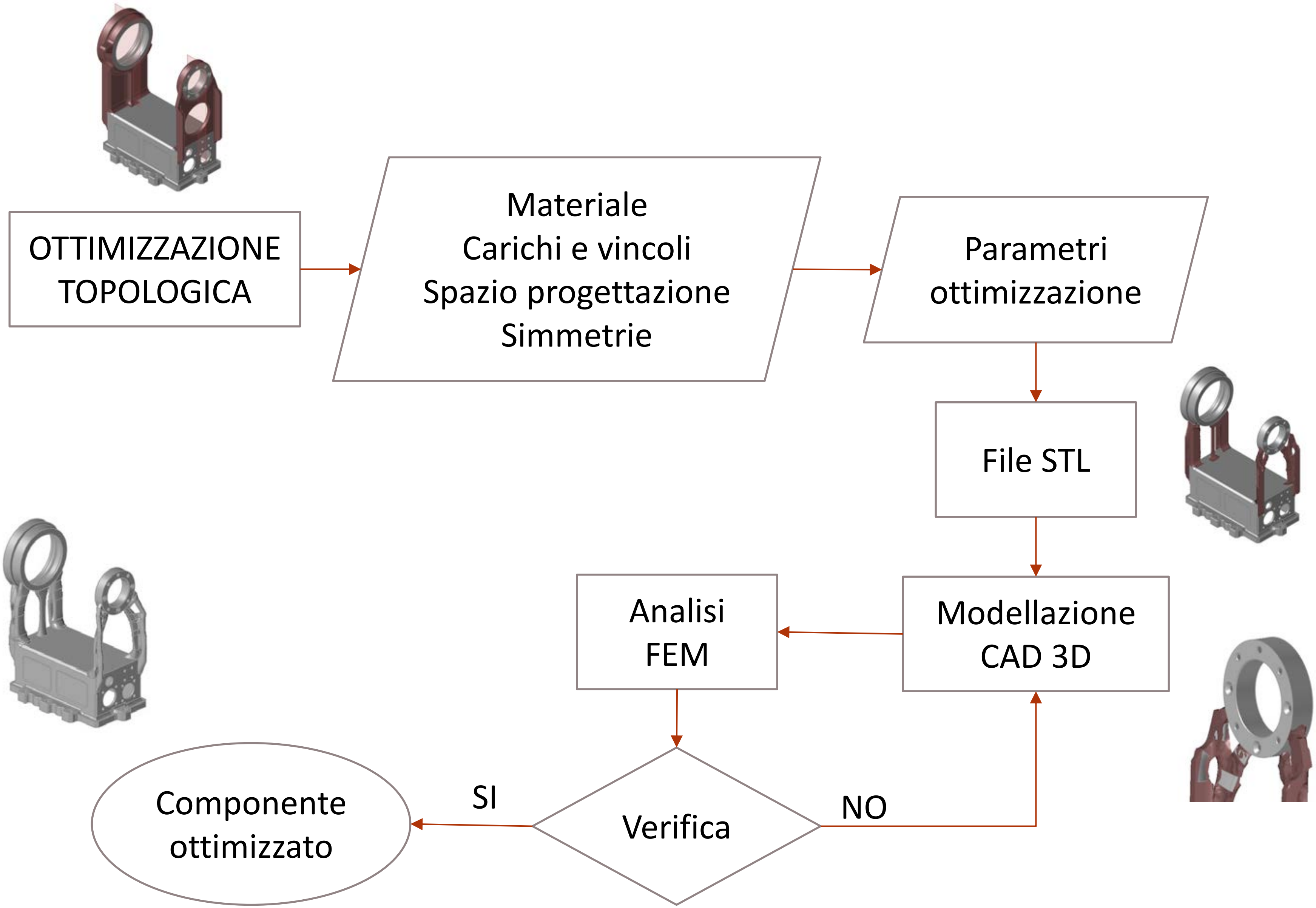
Metodologia





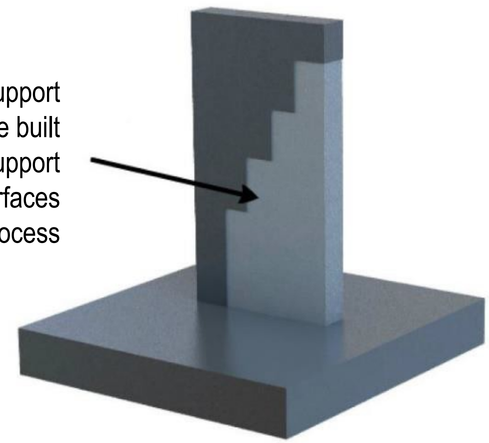

OTTIMIZZAZIONE TOPOLOGICA
Materiale
Carichi e vincoli
Spazio progettazione
Simmetrie
Parametri ottimizzazione
File STL
Modellazione CAD 3D
Analisi FEM
Verifica
SI
NO
Componente ottimizzato

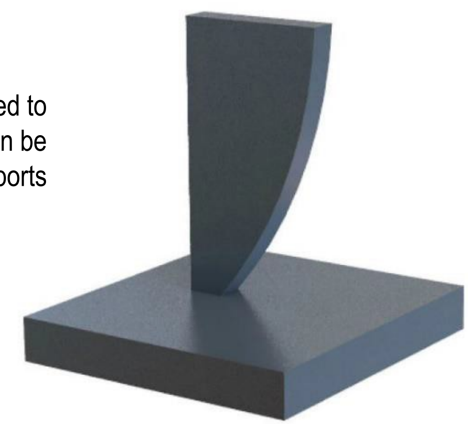
Supports – What Do They Do?

Supports are a *necessary evil* in the DMLS process. Good design practice will minimize them, as they use a lot of energy - both in their construction and removal - but they also fulfil a number of vital functions within the process:

- they support the newly melted surface, particularly on downward facing surfaces and shallow angles;
- they can prevent the new geometry from deforming;
- they dissipate heat away from the newly formed geometry;
- they provide temporary support for geometry that will be strong when complete, but that is weak during the build process.

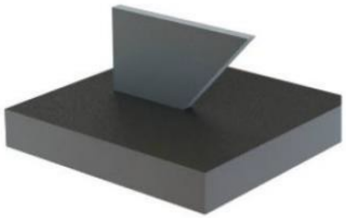
The ideal situation is to design a part that requires no supports at all. The reality is that it is rarely possible to design parts that require no supports at all, but minimizing them will save time, energy, and money.

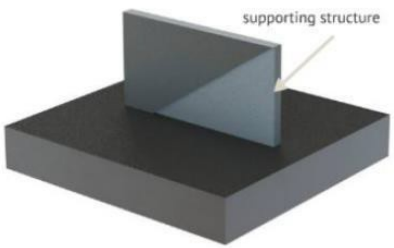




Design Basics – Angled Surfaces

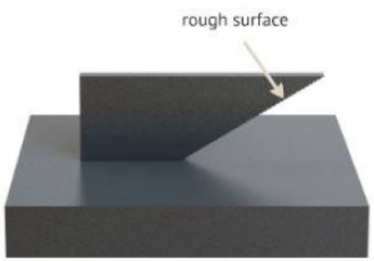
The powder in the build chamber does not provide any support to the part as it builds, so any angled surfaces will ideally be self-supporting

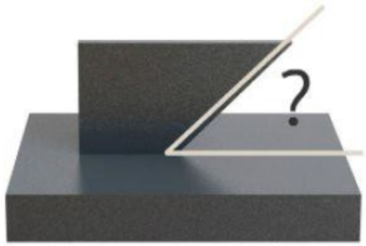




If the angle is too acute, the surface will need a supporting structure built in as part of the model. This supporting structure will then need to be removed by machining or wire cutting, increasing energy use

If the angle is near the point where it needs supports, the downward facing surface will become rough and may require considerable post-finishing



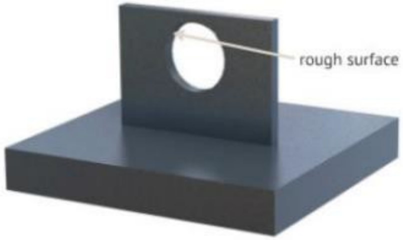


The minimum angles that will be self supporting are approximately:

- Stainless steel: 30 deg
- Inconel: 45 deg
- Titanium: 20-30 deg
- Aluminium: 45 deg
- Cobalt Chrome: 30 deg

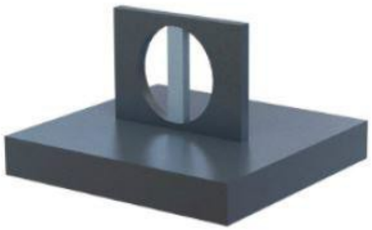
Design Basics – Horizontal Holes

Small holes can be accommodated easily. Holes of less than 6 mm diameter are ideal



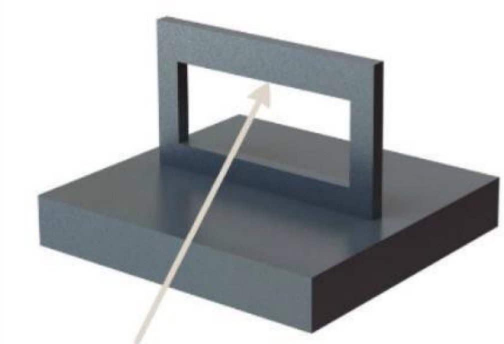
Larger circular holes will result in a roughened surface at the top which may need post- machining

Large holes will require support structures to be added in the center to prevent the part collapsing or becoming distorted during the build process. These supports will need to be removed by wire cutting or machining

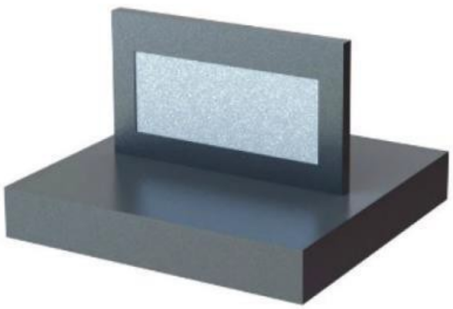


If the hole has an angled or arched upper area it will probably not require any supports. This is one of the features of DMLS that can have a significant impact on the design process

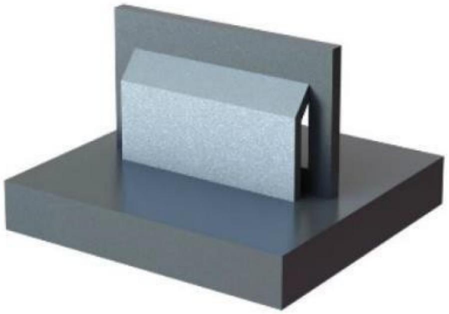
Design Basics – Downward Facing Surfaces



Any downward facing surface will require support. Support structures will need to be removed by wire cutting or machining, which will increase the energy and waste involved in the process

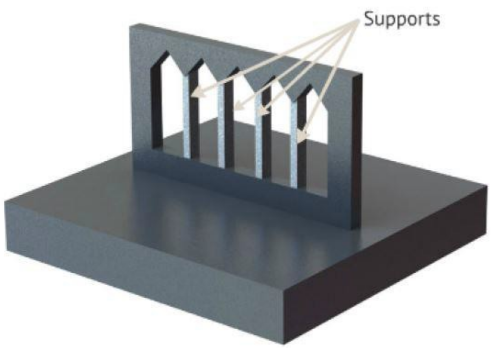


The most simple support structure will fill the hole that creates the downward facing surface. This can be removed by wire cutting or machining



An offset support structure can be used that will be easier to remove. In this case, the base of the support will be cut when the part is removed from the base by wire cutting, leaving one edge to be cut in order to remove the rest of the support

Design Basics – Downward Facing Surfaces



An alternative to this approach will be to turn the part through 45 deg to make all the surfaces angled and remove the need for supports. Orientation is a major issue in finding the most efficient build method - please see item 3 in Other Issues for more details on the limits and possible pitfalls of using angled edges like the ones shown above…

If the top surface of the hole can be made of a series of angles (which are self supporting) the supports can be minimized to the base of each angled surface

If the hole is simply for weight reduction or cooling, for example, it can be modified as a series of semi- circular topped slots which will not require supports. However, the *pillars* between the holes need to be self-supporting

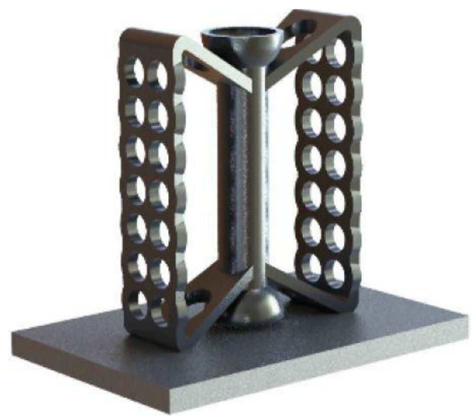
Case Study – Bicycle Pedal


A conventional rat trap bicycle pedal (left) has a large number of surfaces. If it is built in the horizontal plane, the large number of downward facing surfaces will require a significant amount of support (right). A large number of these can be offset, which will reduce the removal time, but building the part would require a considerable amount of energy


If the geometry is modified to reduce the number of downward facing surfaces, mainly by putting in a number of 45 degree angled surfaces, the amount of supports needed is reduced significantly (right)

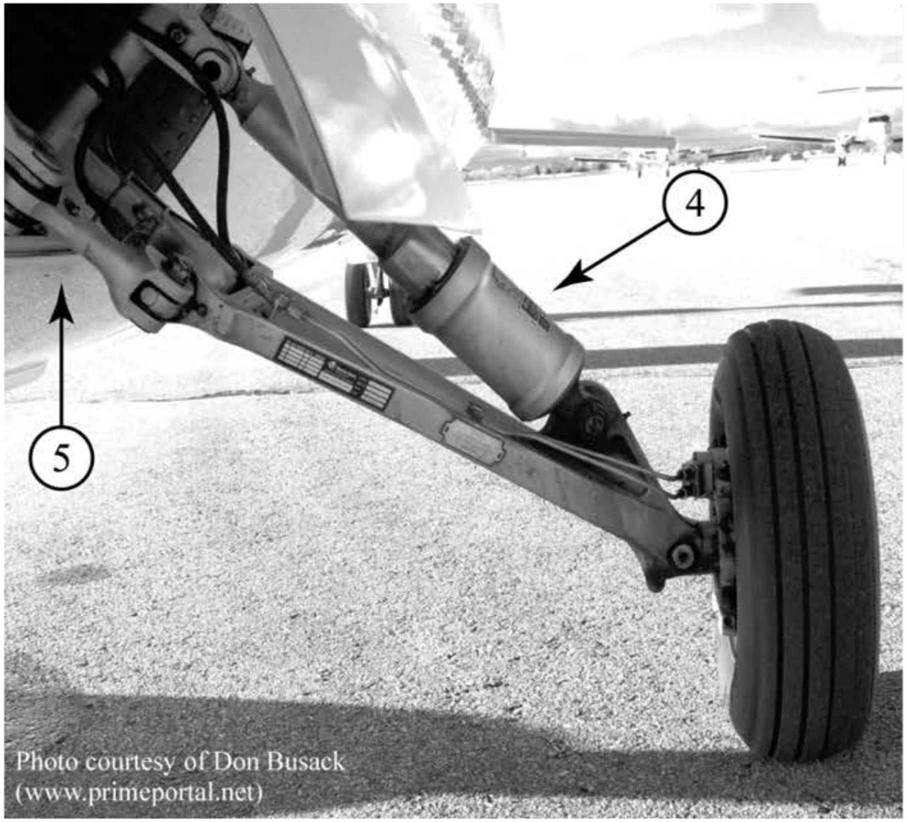
Case Study – Bicycle Pedal

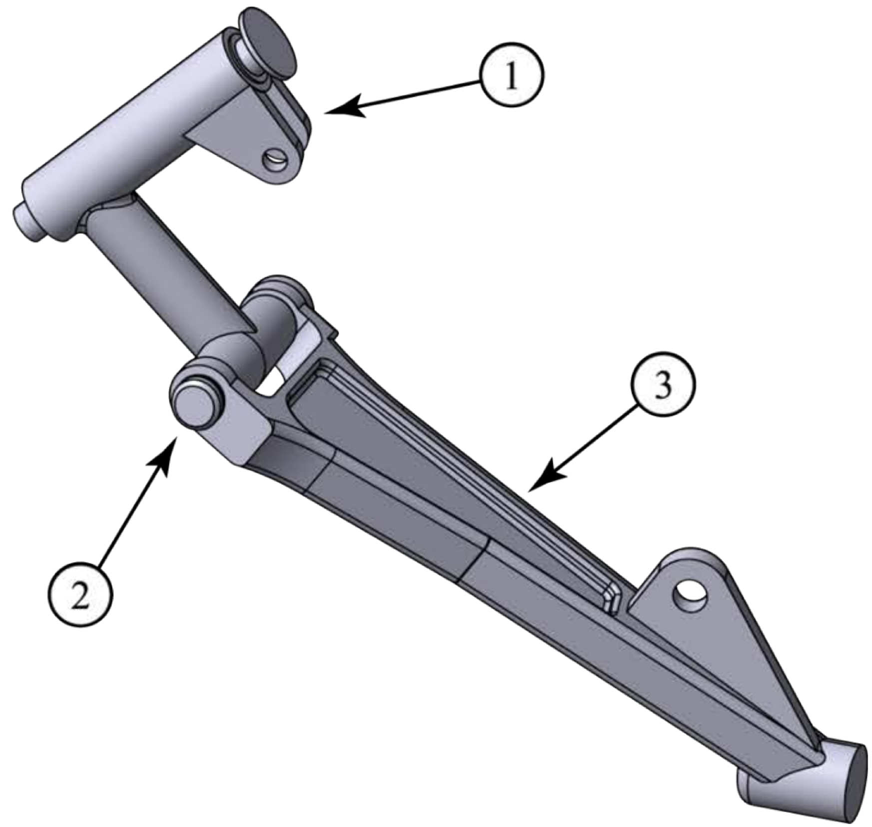
However, by changing the orientation of the part to vertical, the number of supports needed is dramatically reduced



This vertical orientation, combined with design changes to the pedal, would allow designs to be produced that require no supports at all

Caso di studio





Carrello principale di atterraggio del Piaggio P180

Il componente è costituito da supporto principale (1), cerniera (2), braccetto (3), ammortizzatore (4) e attuatore (5).

Modello in scala 1:5

Ingombri: 70 × 210 × 70 mm

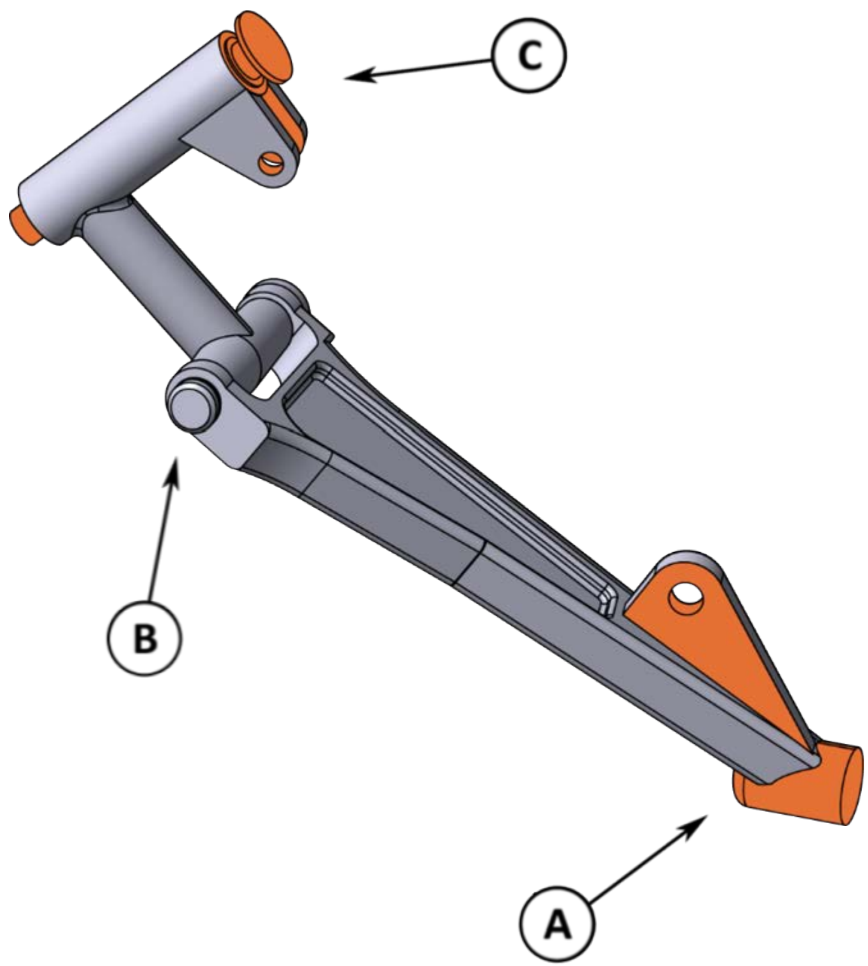
Materiale: AlSi10Mg

Caso di studio – DFAM

Un certo numero di limitazioni associate alle tecnologie di produzione tradizionali posso essere rimosse. Il carrello è stato riprogettato e adattato per la fabbricazione additiva secondo le linee guida del DFAM preservandone la funzionalità.

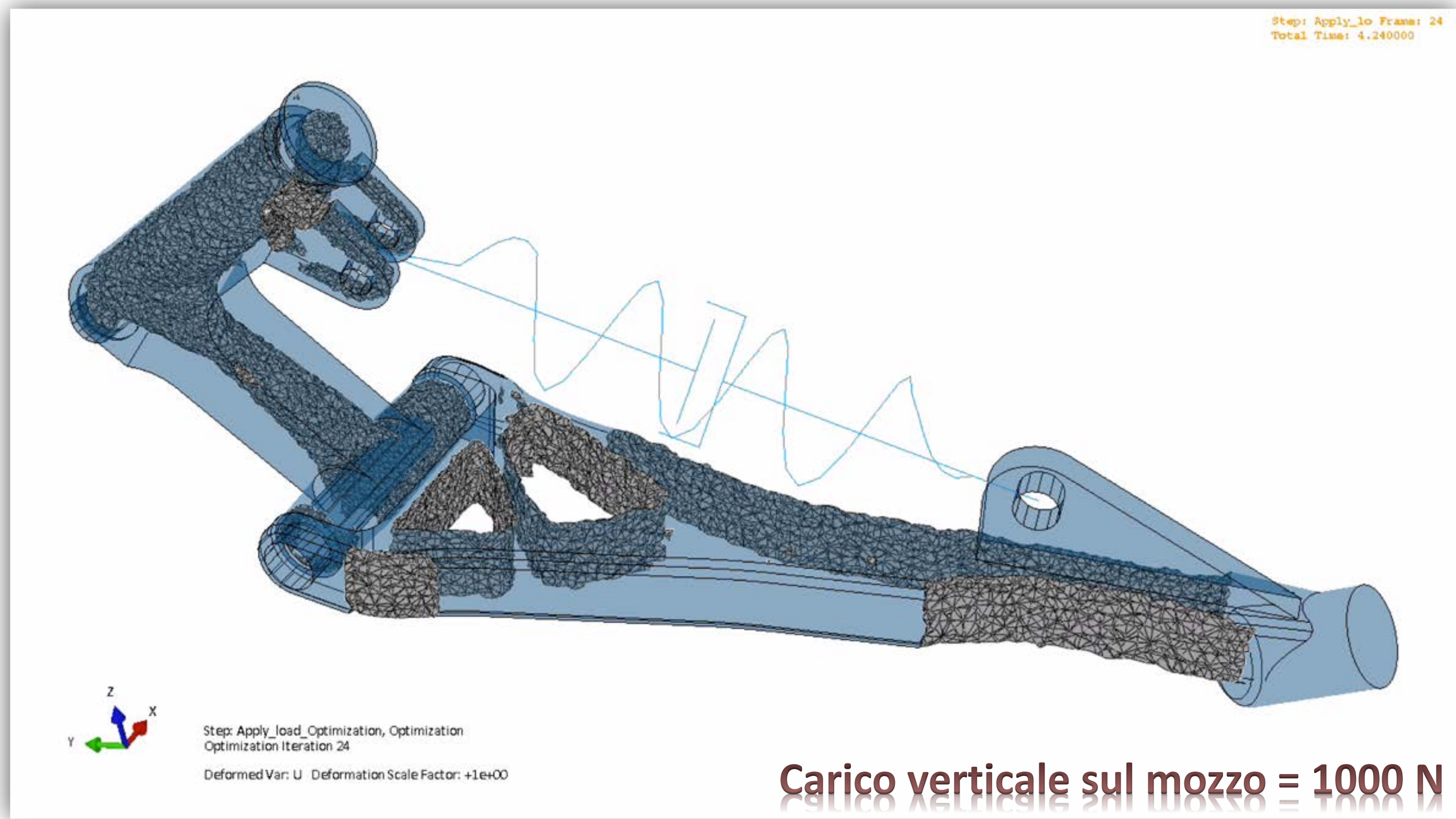
Identificazione di vincoli non modificabili:

- la posizione dei fori;
- le porzioni laterali del carrello che devono accoppiarsi con l'alloggiamento della fusoliera, la porzione terminale del braccetto collegata con il mozzo;
- la posizione e l'orientamento dell'asse della cerniera per non alterarne la corretta cinematica.



Caso di studio – DFAM con Ottimizzazione Topologica

La geometria dei componenti è stata ottimizzata per topologia e forma utilizzando il modulo di ottimizzazione topologica ATOM/TOSCA di Abaqus.



Caso di studio – DFAM con Ottimizzazione Topologica

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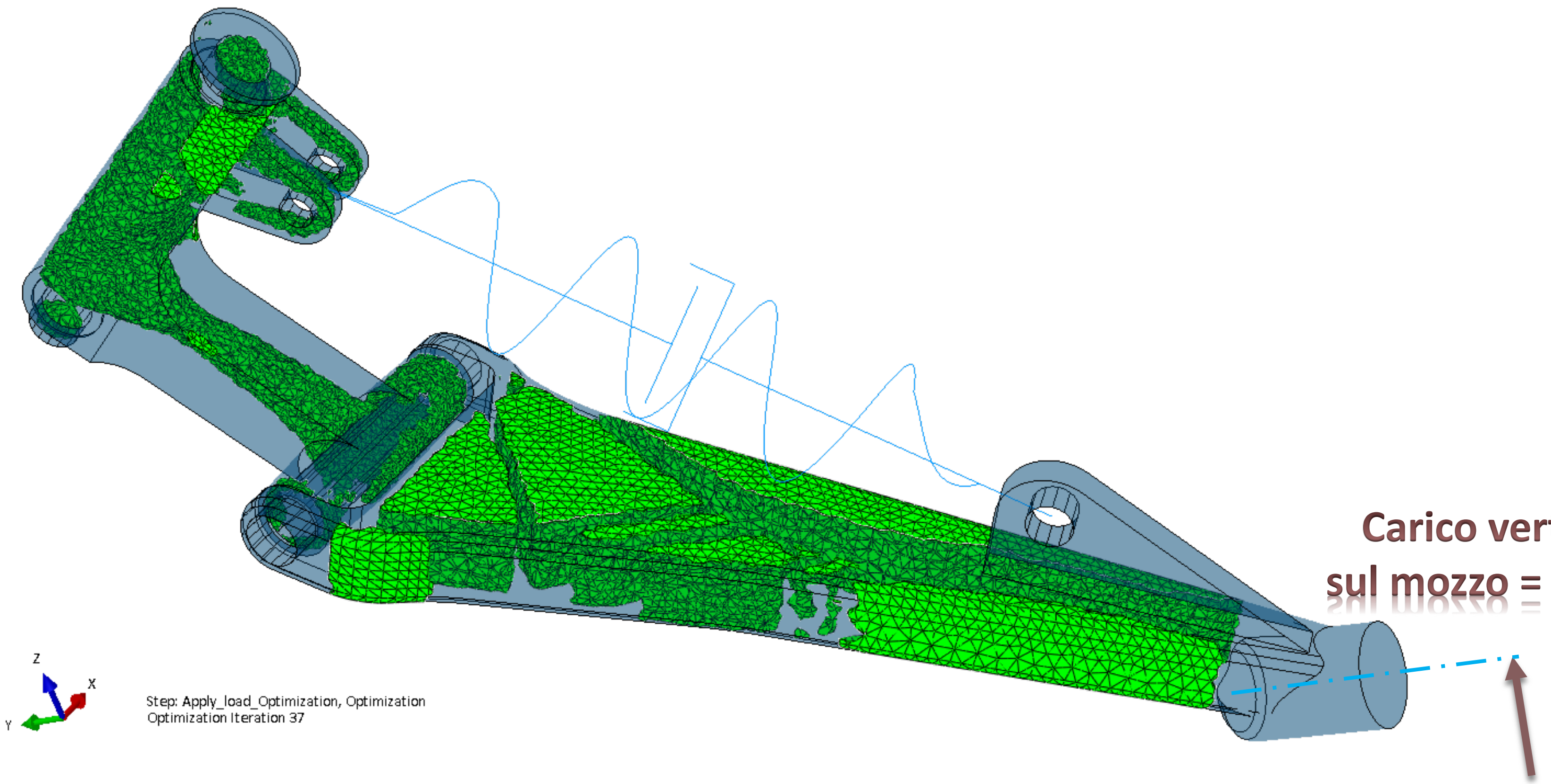
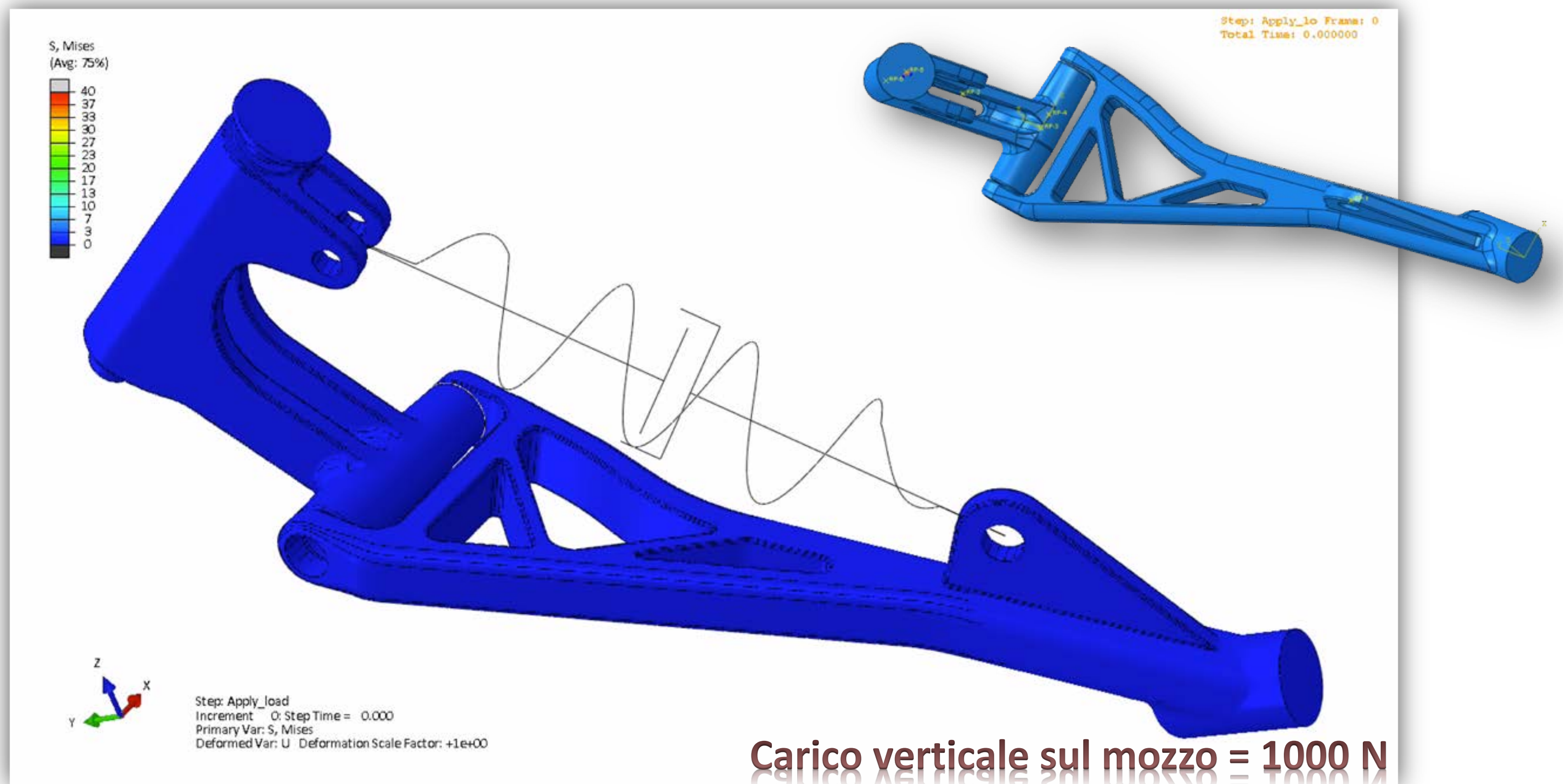


Carico verticale sul mozzo = 1000 N

Caso di studio – DFAM con Ottimizzazione Topologica

Il compomente riprogettato è stato verificato staticamente mediante Abaqus. I risultati numerici confermano che le tensioni sono uniformente distribuite.



Analisi dei costi – Ipotesi e limitazioni

Si suppone che l'intera piattaforma di costruzione del sinterizzatore sia usata per produrre copie dello stesso pezzo, perciò il costo di produzione è una costante.

Se si considera la variazione dei costi relativa ad una specifica tecnologia, devono essere presi in considerazione solo quei fattori che influenzano direttamente il costo del pezzo. In particolare

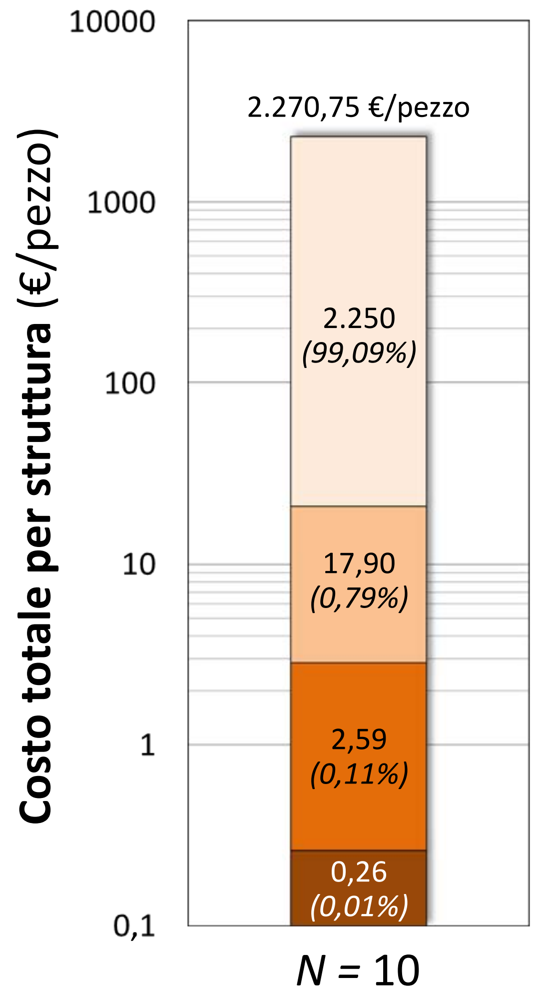
Fattori	**Pressofusione**	**Fresatura**	***FA - SLM***
Grezzo di partenza	lingotto	spezzone	polvere
Attrezzature specifiche	stampi	bloccaggi/utensili	*nessuna*
Fabbricazione			
• **riprogettazione**	*nessuna*	limitata	completa
• **macchina**	pressa	CNC 5-assi	sistema di FA
• **preparazione**	fusione della lega	Programmazione CAM	creazione del job
• **post-trattamento**	smaterozzatura lavorazioni meccaniche finitura	pulizia	trattamento termico rimozione delle parti rimozione dei supporti finitura
Lead time	settimane	giorni	ore

Le spese generali non vengono prese in considerazione.

Poiché il costo del lavoro è fortemente influenzato dalla localizzazione dell'impianto produttivo, in questo studio si ipotizza che la produzione avvenga nell'Europa dell'ovest.

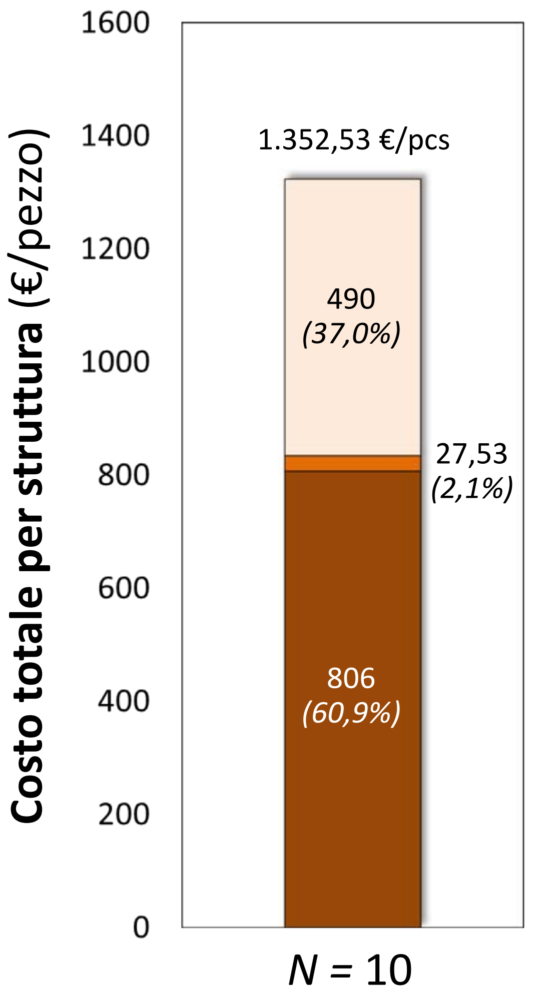
Analisi dei costi – Pressofusione (HPDC)

Dimensione del lotto	**(pezzi)**	***N***
Costo del materiale al kg	(€/kg)	16,00
Peso del pezzo	(kg)	0,162
Costo del materiale	**(€)**	**2,59**
Costo dei componenti standard	(€)	2.500
Costo delle figure e dei carrelli	(€)	16.000
Costi ausiliari	(€)	3.900
Costo dell'attrezzatura	**(€)**	**22.500/*N***
Costo orario della pressa	(€/h)	260,00
Costo orario dell'operatore	(€/h)	35,00
Percentuale del tempo operatore	(%)	10
Tempo ciclo	(h)	0,001
Costo della lavorazione (HPDC)	**(€)**	**0,26**
Costo del trattamento termico	(€)	1,42
Costo di finitura	(€)	13,98
Costo orario dell'operatore	(€/h)	25,00
Tempo dell'operatore	(h)	0,100
Costo di post-trattamento	**(€)**	**17,90**
COSTO TOTALE PER STRUTTURA	***(€)***	***20,75 + 22.500/N***

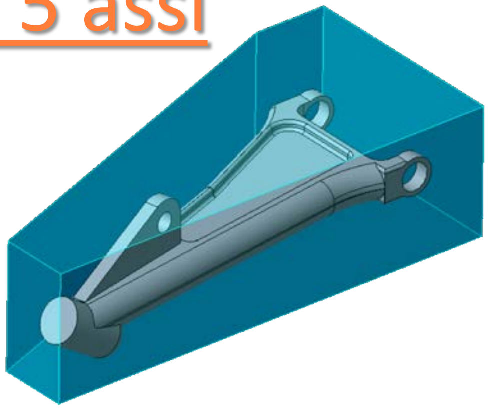


Analisi dei costi – Fresatura a 5 assi

	Dimensione del lotto	**(pezzi)**	***N***
	Costo del materiale al kg	(€/kg)	16,00
	Peso del grezzo	(kg)	1,72
	Costo del materiale	**(€)**	**27,53**
	Costo della fresa Ø10 mm	(€/pezzo)	55,00
	Costo della fresa Ø 6 mm	(€/pezzo)	40,00
	Numero di frese Ø 10 mm	(pezzi)	6
	Numero di frese Ø 6 mm	(pezzi)	4
	Costo dell'attrezzatura	**(€)**	**490,00**
	Costo per la programmazione CAM	(€)	200,00/*N*
	Costo orario della macchina	(€/h)	60,00
	Tempo di attrezzaggio	(h)	1/*N*
	Tempo di taglio	(h)	10
	Tempo improduttivo	(h)	3
	Costo della lavorazione (fresatura)	**(€)**	**780,00 + 260/*N***
	COSTO TOTALE PER STRUTTURA	***(€)***	***1.297,53 + 260/N***



Analisi dei costi – Fresatura a 5 assi



Dimensione del lotto	**(pezzi)**	***N***
Costo del materiale al kg	(€/kg)	16,00
Peso del grezzo	(kg)	1,72
Costo del materiale	**(€)**	**27,53**
Costo della fresa Ø10 mm	(€/pezzo)	55,00
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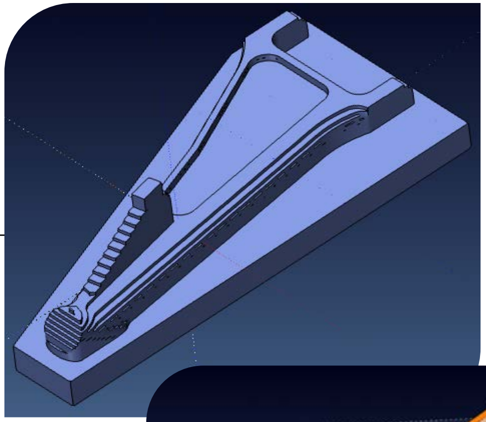
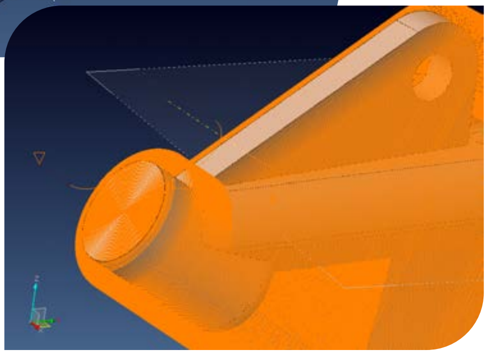
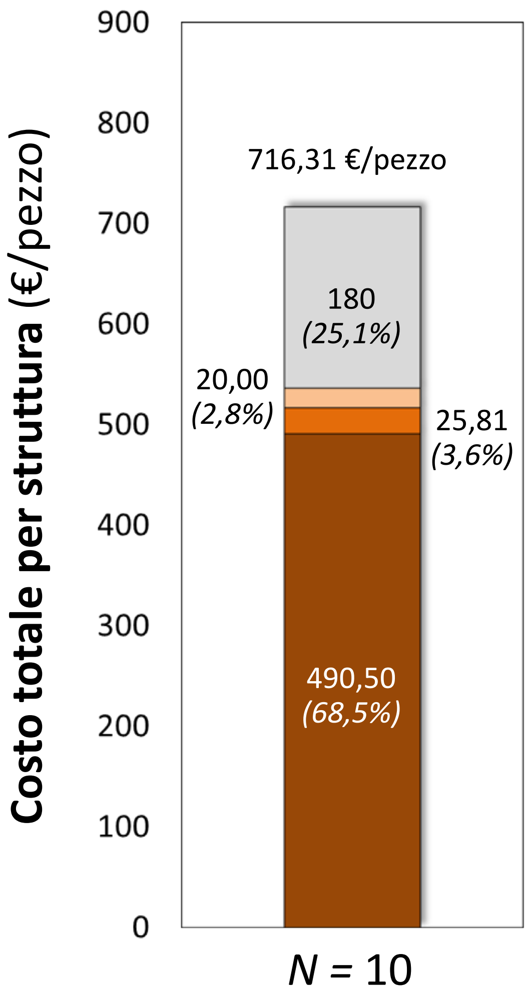
Numero di frese Ø 10 mm	(pezzi)	6
Numero di frese Ø 6 mm	(pezzi)	4
Costo dell'attrezzatura	**(€)**	**490,00**
Costo per la programmazione CAM	(€)	200,00/*N*
Costo orario della macchina	(€/h)	60,00
Tempo di attrezzaggio	(h)	1/*N*
Tempo di taglio	(h)	10
Tempo improduttivo	(h)	3
Costo della lavorazione (fresatura)	**(€)**	**780,00 + 260/*N***
COSTO TOTALE PER STRUTTURA	***(€)***	***1.297,53 + 260/N***



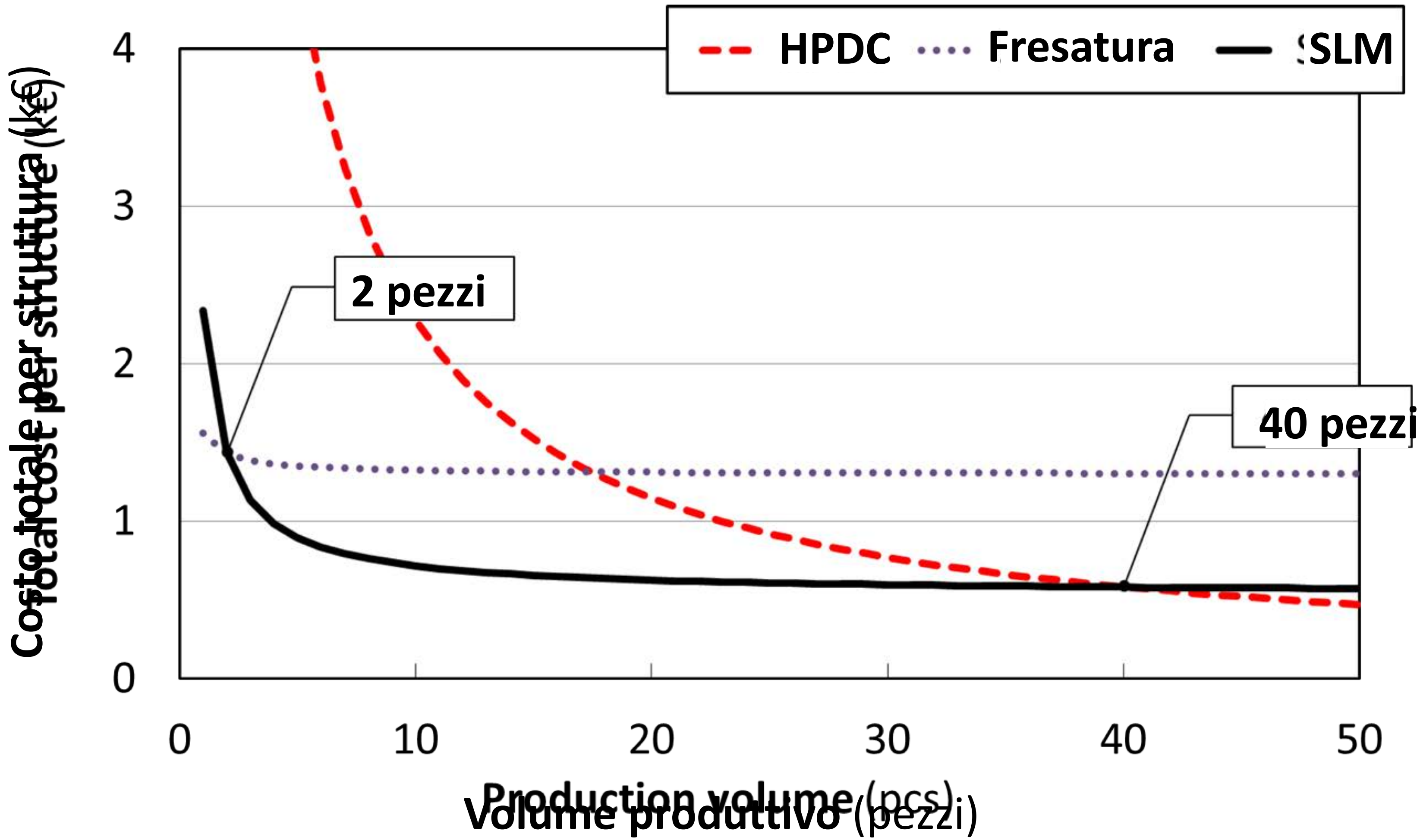


Analisi dei costi – Fabbricazione additiva laser (SLM)

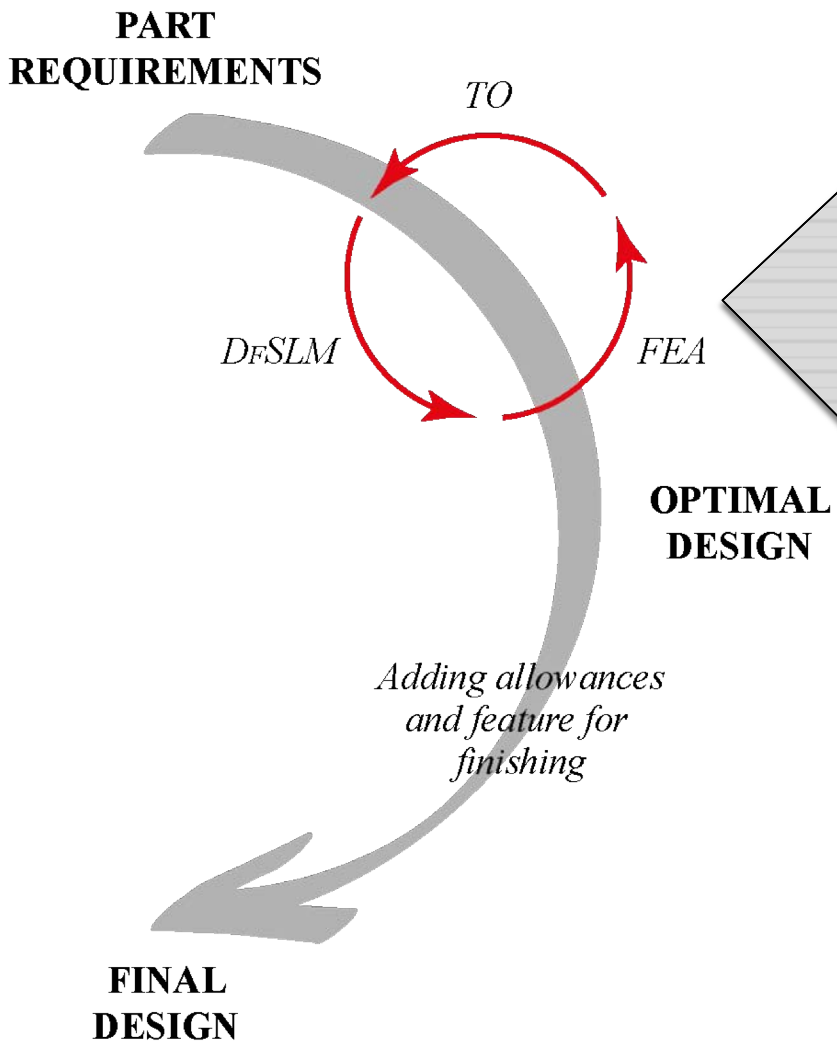
Dimensione del lotto	**(pezzi)**	***N***
Costo della riprogettazione	**(€)**	**1.800,00/*N***
Costo del materiale al kg	(€/kg)	145,00
Peso della parte (supporti compresi)	(kg)	0,178
Costo del materiale	**(€)**	**25,81**
Costo orario della macchina	(€/h)	35,00
Tempo di costruzione	(h)	54
Costo di produzione del *job*	(€/job)	1.890,00
Costo orario dell'operatore	(€/h)	25,00
Tempo di preparazione	(h/job)	1,2
Numero di pezzi per *job*	(pezzi/job)	4
Costo della lavorazione (FA)	**(€)**	**490,50**
Costo orario dell'operatore	(€/h)	20,00
Tempo di post-trattamento	(h/job)	3
Costo del trattamento termico	(€/job)	20,00
Costo del post-trattamento	**(€)**	**20,00**
COSTO TOTALE PER STRUTTURA	***(€)***	***536,31 + 1.800/N***



Analisi di break-even

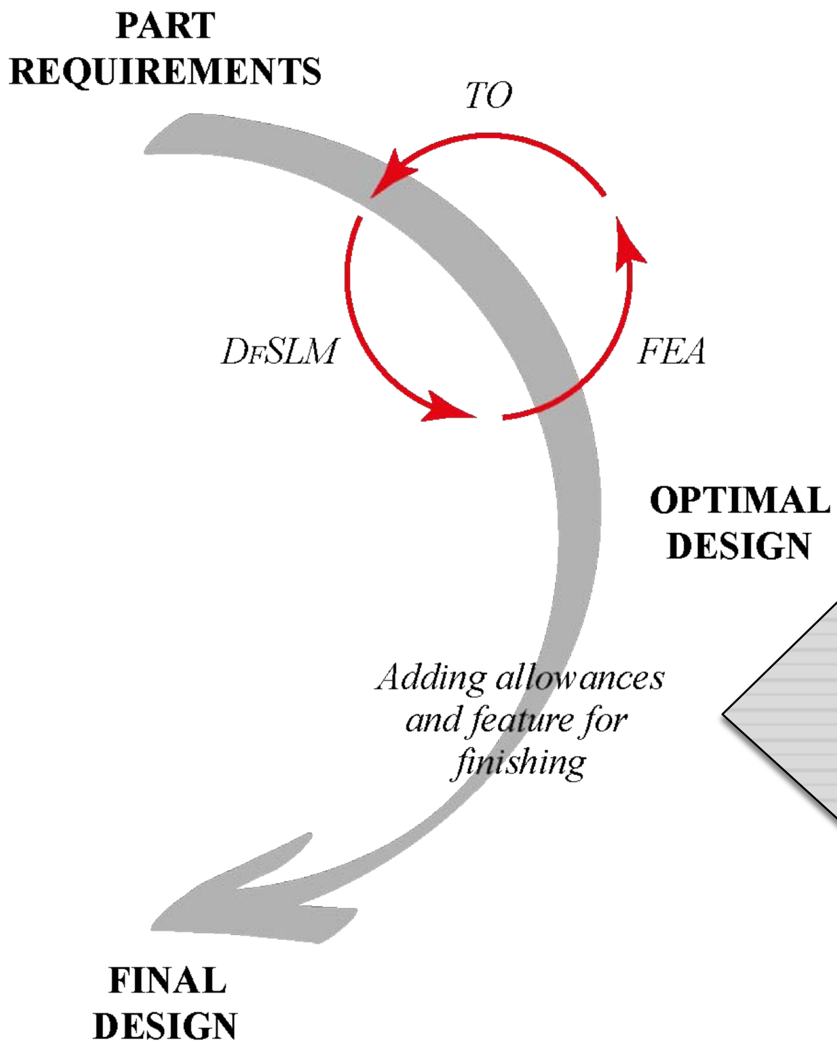


Design methodology for metal AM (DMLS) – 1/2



- The full potential of design freedom can be obtained by making effective use of topology optimization (TO).
- When TO is used to define an optimal shape for AM production, no manufacturing constraints are applied in the TO procedure.
- The design obtained by TO should be revised taking into consideration SLM design rules so as to guarantee an effective production.
- A further step is necessary to validate the optimized geometry according to the set of loads and constraints that define the part requirements.
- This is usually an iterative approach.

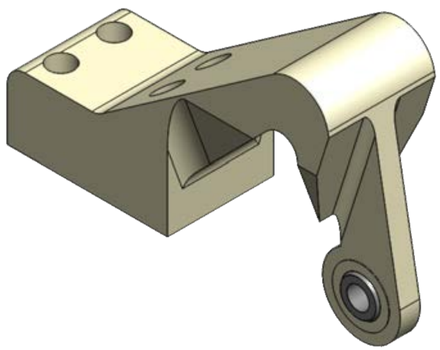
Design methodology for metal AM (DMLS) – 2/2

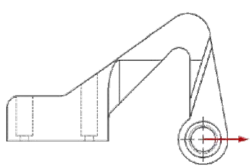


- Finishing operations are often required for functional surfaces, in order to overcome the limitations of the surface quality characteristic of SLM parts.
- Material allowances should be added to the surfaces of the optimized design that has to be finished, in order to compensate for the changes in shape that are a consequence of the finishing process.
- Additional features may be required to hold and refer the part in the finishing apparatus.

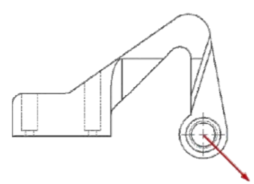
Case Study – Part requirements

Airplane Bearing Bracket Challenge - GrabCAD

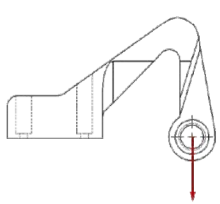




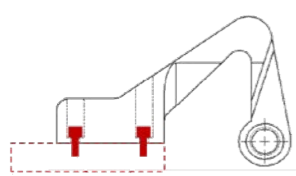
Load Case 1 – 5560N



Load Case 2 – 8340 N



Load Case 3 – 11120 N



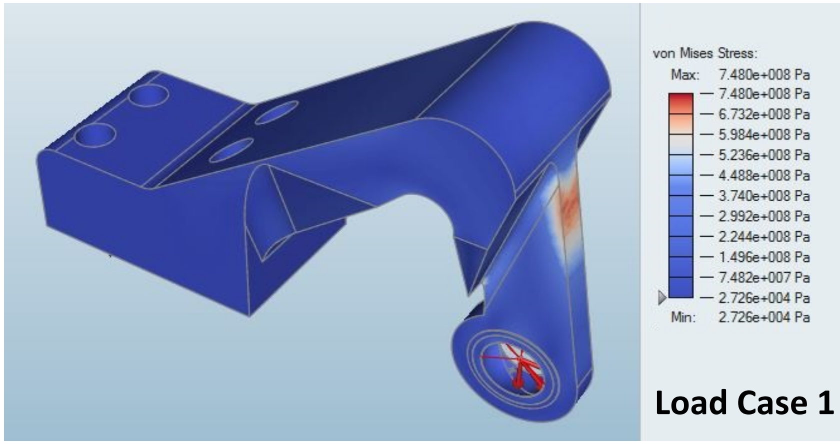
Fasteners – 5000 N

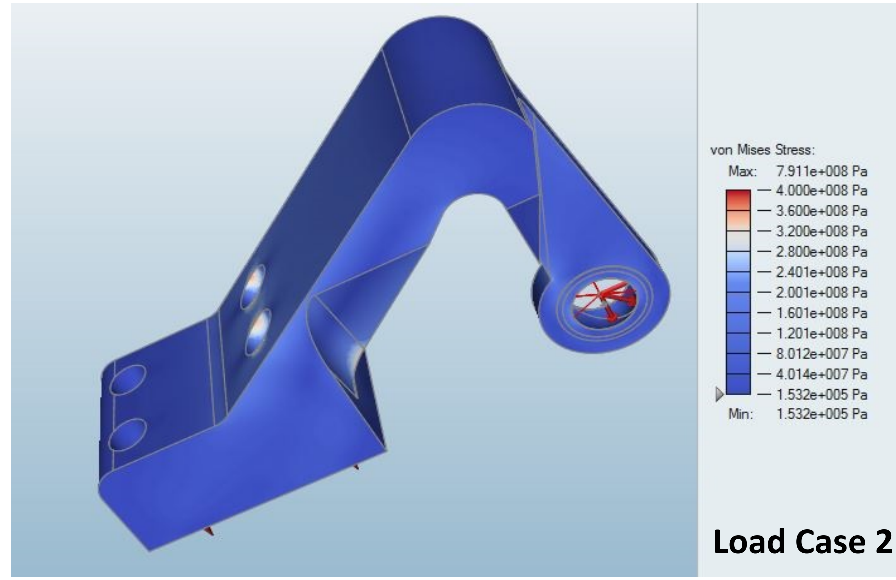
Stainless steel 15-5PH AMS5862

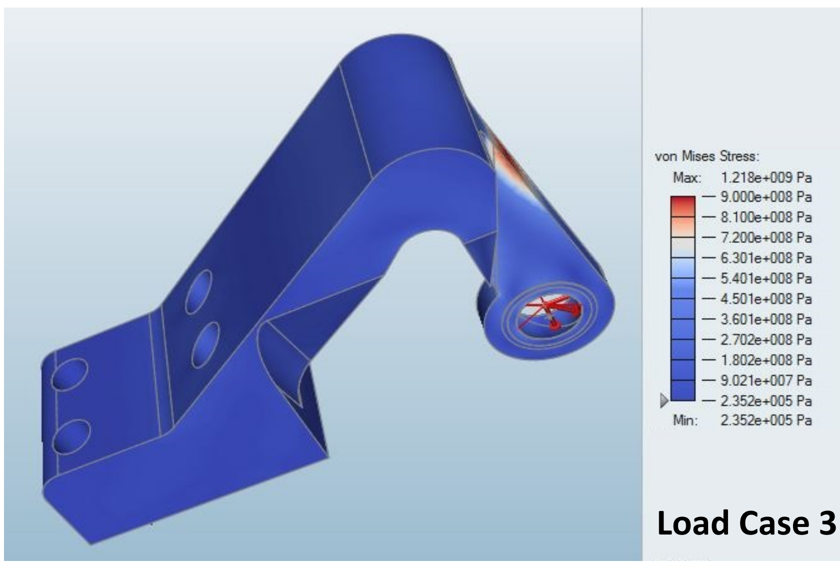
- Elastic Modulus (E) = 200 GPa
- Poisson Ratio (ν) = 0.27
- Yield Stress (σ_y) = 1000 MPa
- Density (ρ) = 7833 kg/m^3
- Material is assumed to be linear elastic

With the given geometry (maximum envelope) the weight of the part is equal to 0.860 kg

Original component – Static analysis

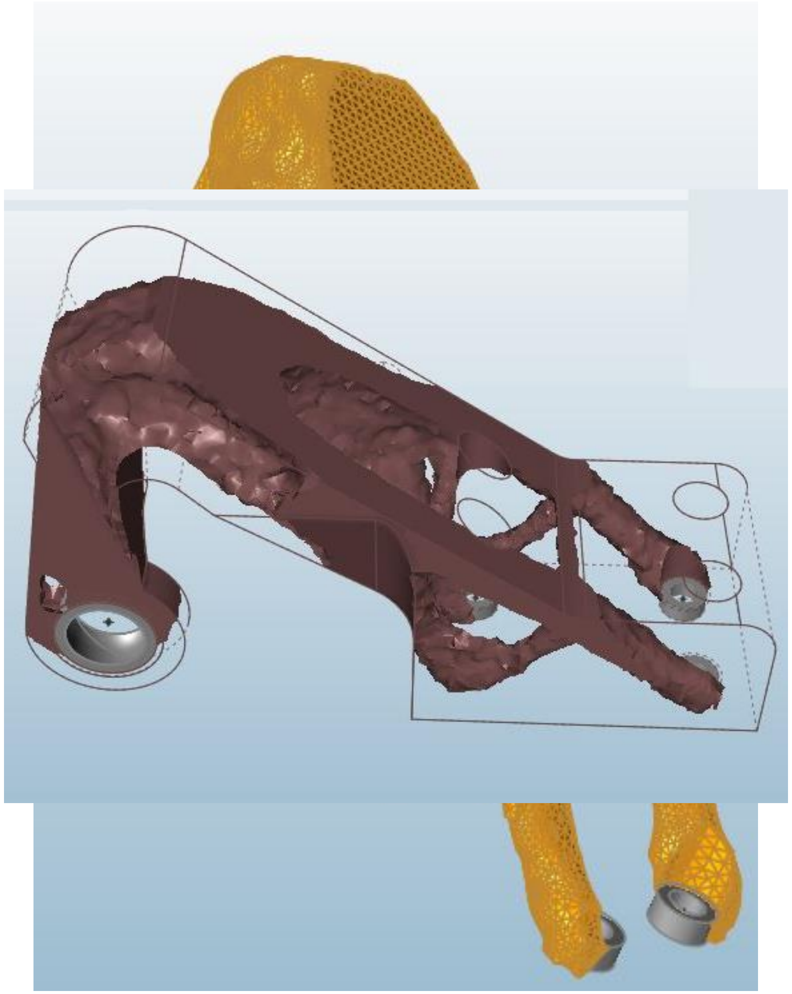






Condition	Von Mises MAX [MPa]	Position of the peak stress
Load Case 1	900	External arm
Load Case 2	400	Supports for the fasteners
Load Case 3	750	External arm

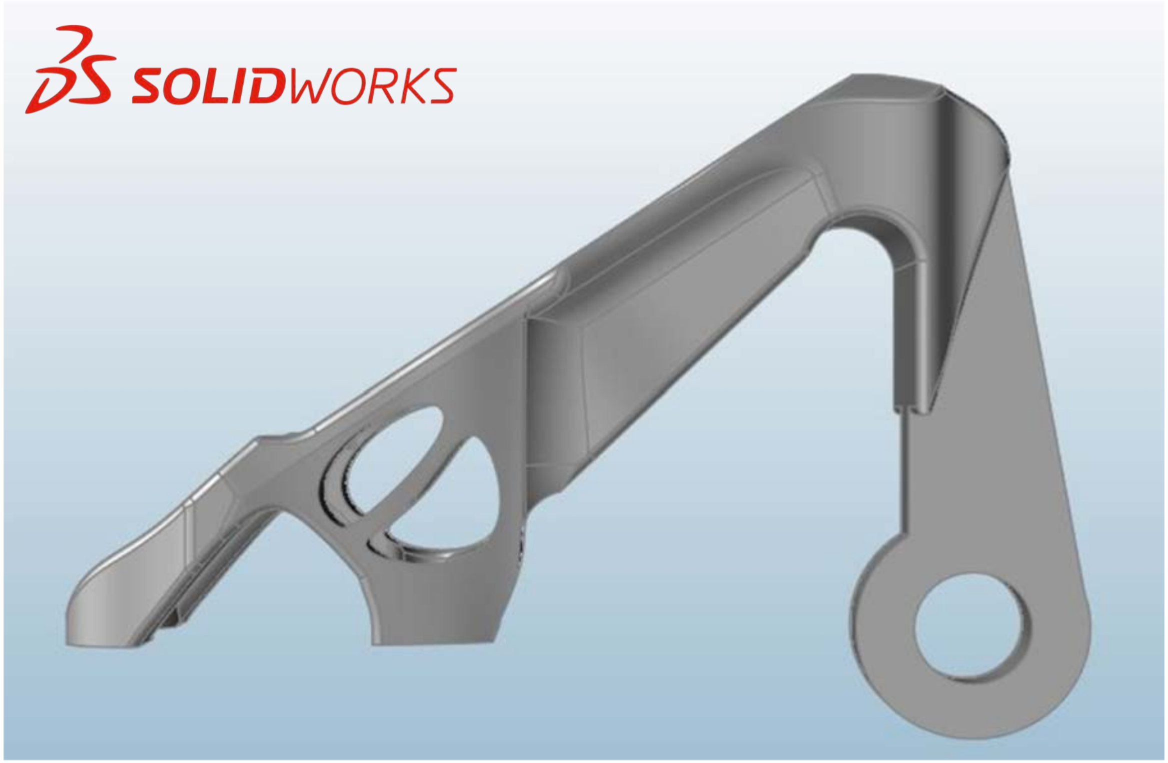
Topology optimization

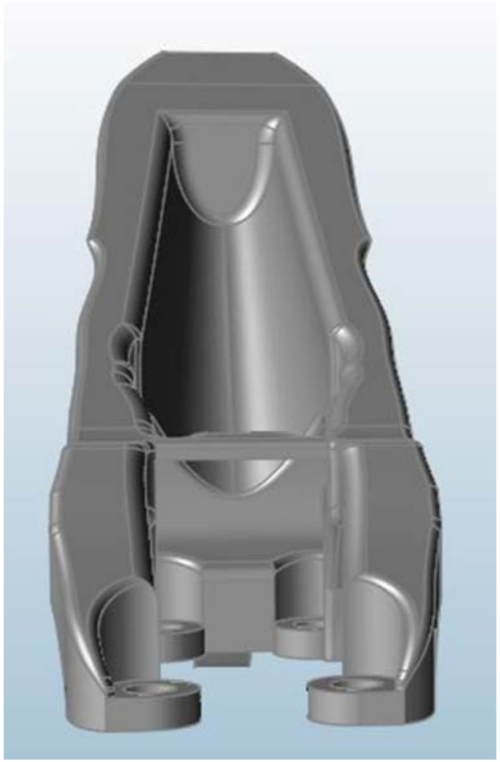


- Objective: minimization of the mass
- Constrain: $\text{VonMises}_{\text{Max}} < \sigma_y$
- Minimum wall thickness: 1.2 mm
- Material: 15-5PH
- Frozen region highlighted in grey
- All three load cases considered
- Smoothing process

3 iterations were required

Redesign bracket – Optimal design

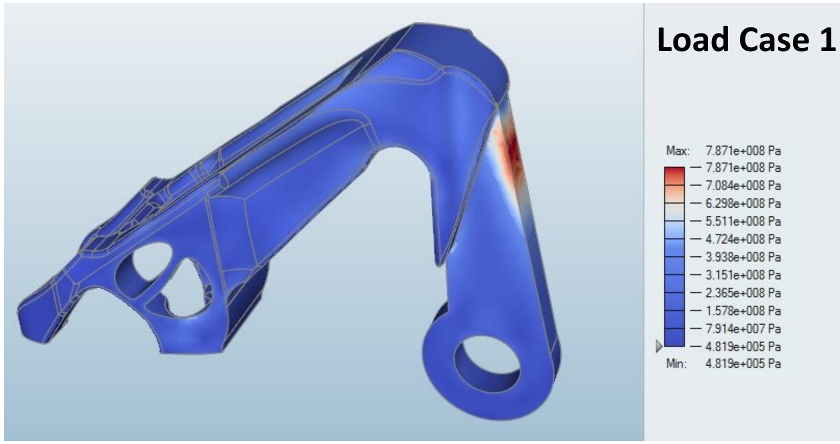


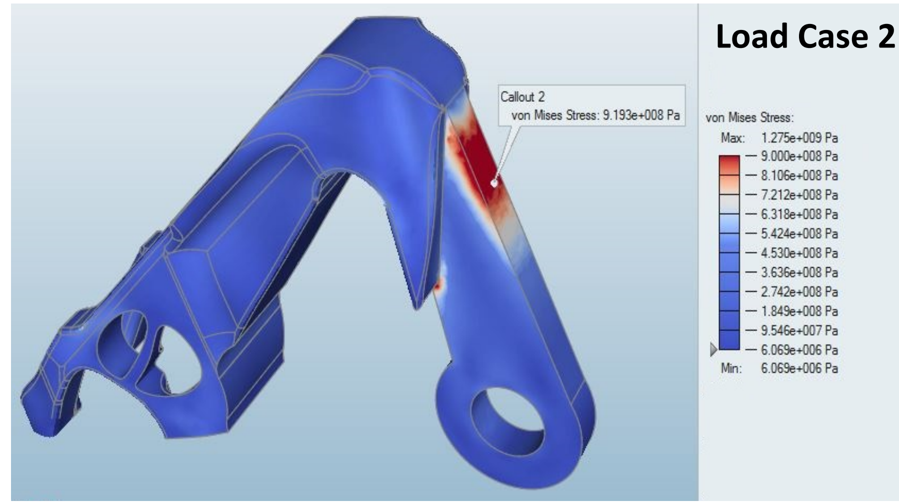


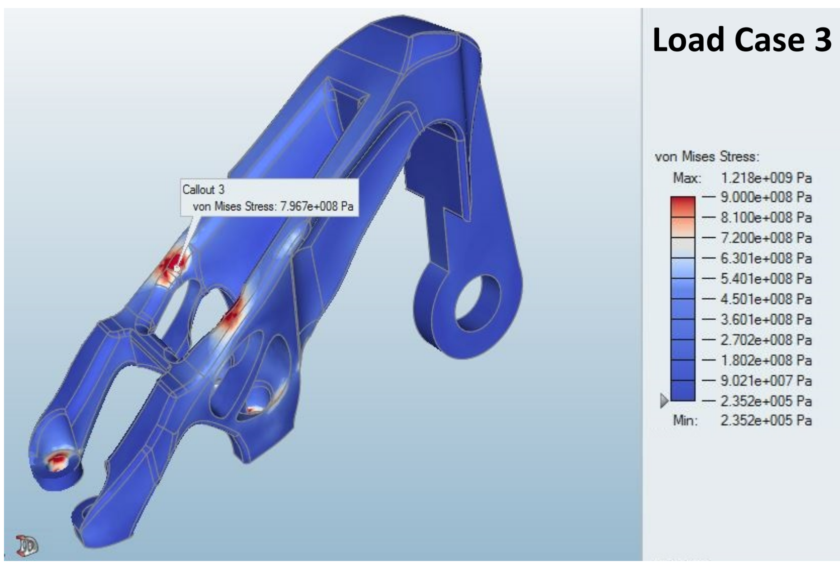
The weight of the optimal design is 0.321 kg

Compared to the initial mass of the bracket corresponding to the maximum envelope, means a reduction in weight of 63%

Redesign bracket – Optimal design (static analysis)

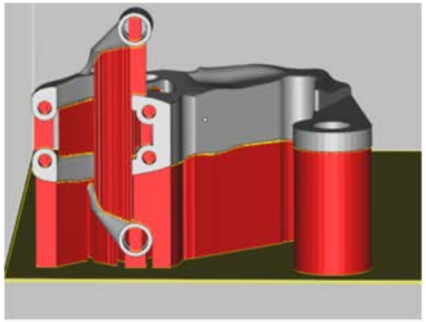






Condition	Von Mises MAX [MPa]	Position of the peak stress
Load Case 1	780	External arm
Load Case 2	920	External arm
Load Case 3	810	Upper branches

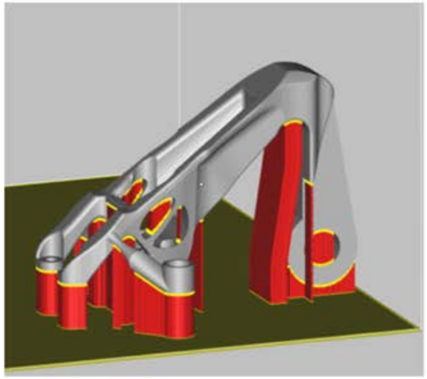
Orientations and support structures



Job height: 91.2 mm
Building time: 17 h
Volume support: 114817 mm^3
Volume part: 42854 mm^3

Horizontal positioning

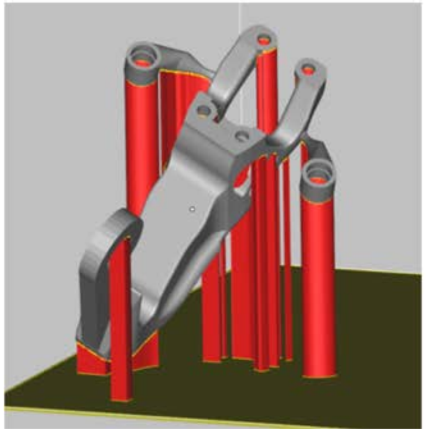
Too many supports
Too hard and dense supports
Supports in functional regions



Job height: 87.5 mm
Building time: 11 h
Volume support: 14731 mm^3
Volume part: 42854 mm^3

Vertical positioning

Less density and hardness of supports
Supports in functional regions

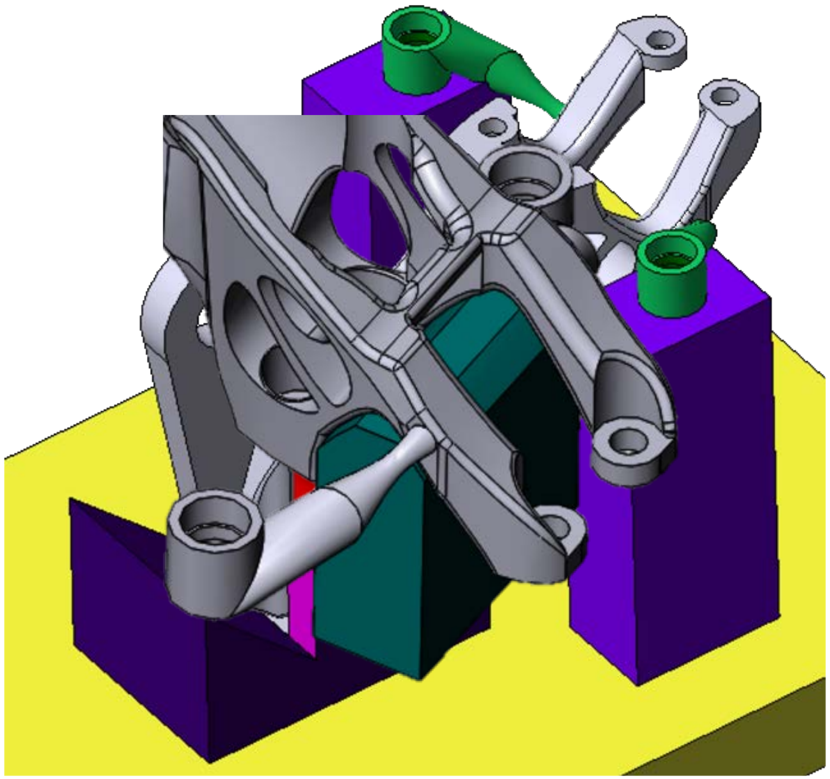


Job height: 116.7 mm
Building time: 15 h
Volume support: 21724 mm^3
Volume part: 42854 mm^3

Tilted positioning

Low number of supports
Low density of supports
Minimum quantity in functional region

Adding allowances and feature for finishing



- An allowance of 1 mm was applied to surfaces involved in couplings with fasteners, joints and bearings.

- Finishing process, realized by means of a 5-axis CNC machine, requires 2 different set-ups

1st setup

- Two additional auxiliary arms (in green) were designed and are used as the main reference
- A conformed base (in purple) together with a sliding cylinder (in red) are used to constrain the remaining degrees of freedom of the part

2nd setup

- The part is rotated 180 degrees, and the same auxiliary arms together with a conformed base are used to hold the bracket during the boring operation

Auxiliary arms and conformed bases are manufactured by AM and mechanically removed at the end

Finishing processes requires only about 30 minutes

Integrated design methodology for SLM – Case study