Blended Intensive Program (BIP) Program:

"Additive Manufacturing: Design and Processing"

Lightweight Structure Design for Additive Manufacturing

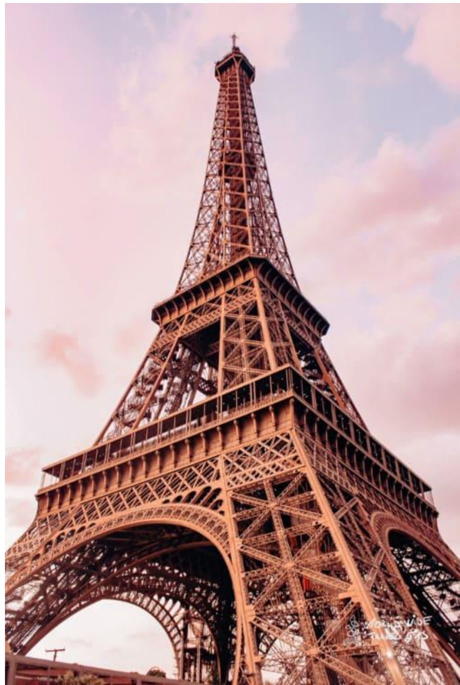
Ioannis Ntintakis
Lecture

"The art of structure is where to put the holes"

Robert Le Ricolais (1894-1977)

The "father of space structures."

structural engineer and architect



Generative Design

Generative design is an iterative design process that involves a program that will generate a certain number of outputs that meet certain constraints, and a designer that will fine tune the feasible region by selecting specific output or changing input values, ranges and distribution

GD mimics nature by using algorithms inspired by the way in which bones grow in animals

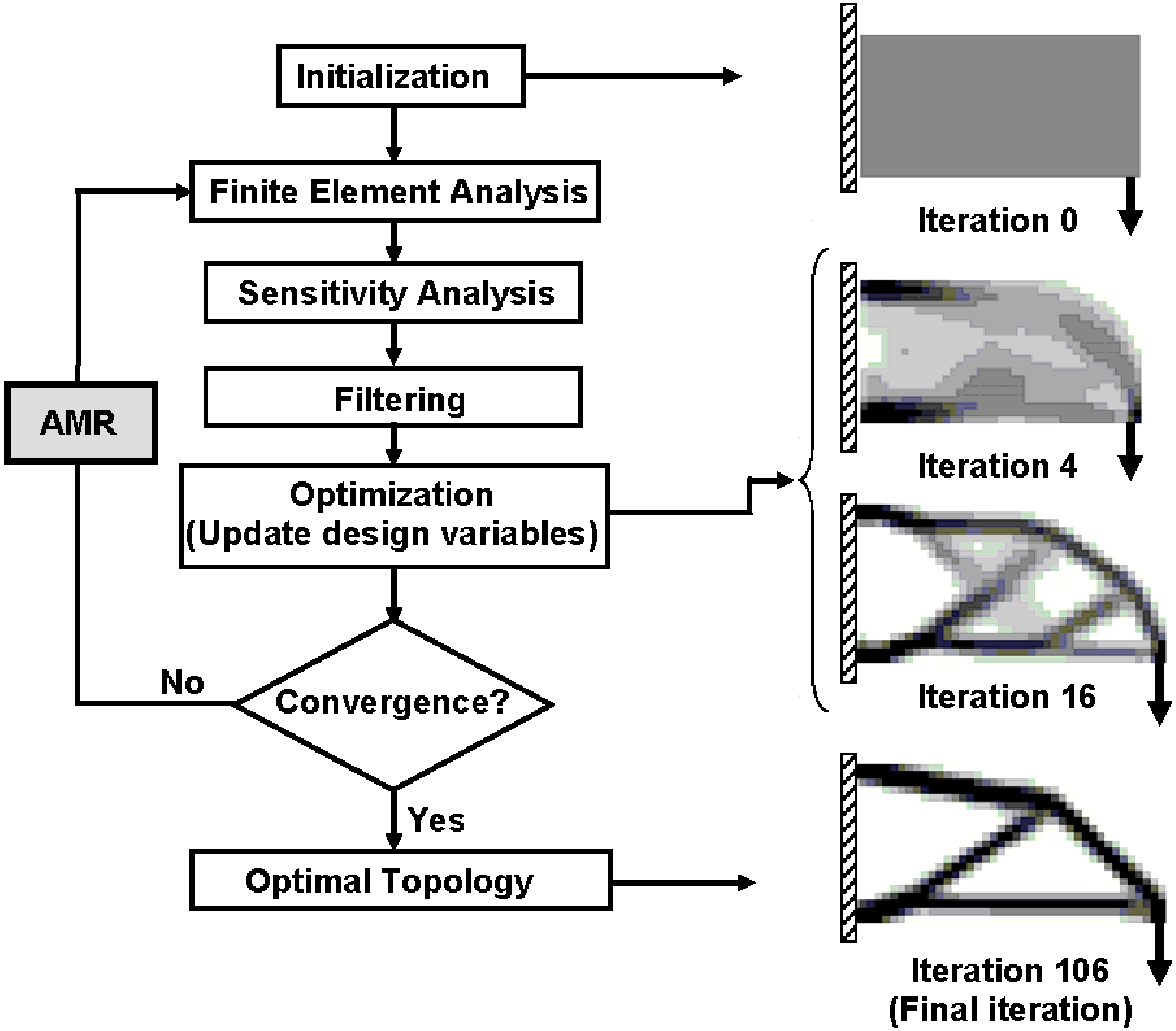
Why Generative Design

- Need for mass reduction and lightweight structures
- Mimic nature
- Compatible models for Additive Manufacturing
- A significant tool for concept design stage
- Use of Artificial Intelligent algorithms
- Structure Topology Optimization
- Generated models meet certain constrains and boundary conditions

Why Generative Design

- Add or remove material from the domain
- Generation of potential solutions
- Human – machine design methodology
- Minimize timetable for ready to use products

Topology Optimization Algorithm (T.O.)

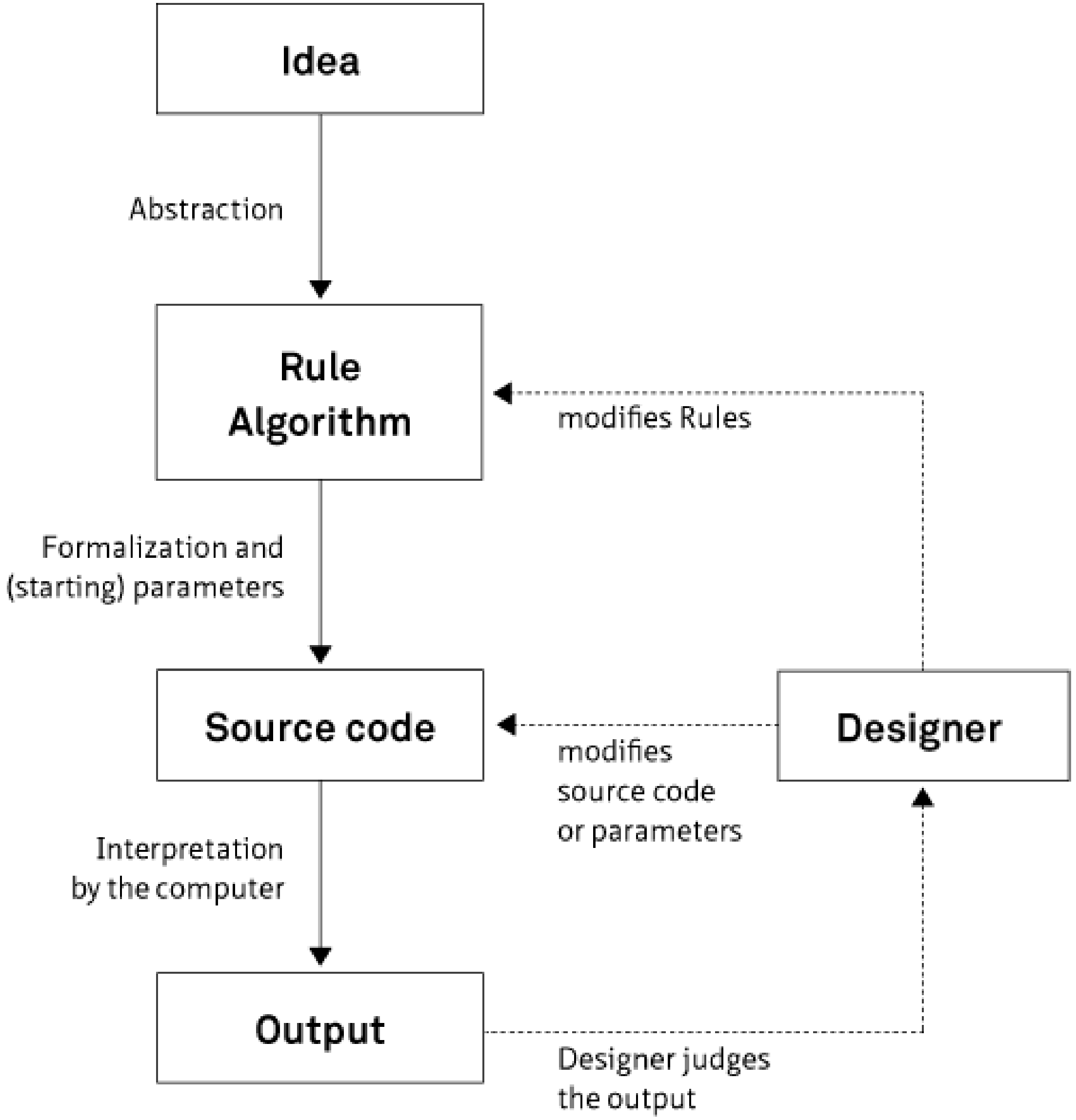


$$\min_{\forall e\ \rho_e \in [\rho_0, 1]} \mathbf{f}^T \mathbf{u}$$

$$\text{s.t.} \begin{cases} \mathbf{K}(\boldsymbol{\rho})\mathbf{u} = \mathbf{f} & \text{for } x \in \Omega \backslash \Omega_0, \\ \mathbf{u} = \mathbf{u}_0 & \text{for } x \in \Omega_0, \\ \sum_e \rho_e V_e \leq V_0, \end{cases}$$

Source: Proceedings of the 6th IASS-IACM 2008, Ithaca2008, Cornell University, Ithaca, NY, USA

Generative Design Process



Topology Optimization Vs generative Design

T.O. creates only one design that's been optimized for structural integrity based on existing criteria

G.D creates lots of designs in an evolutionary way

Topology Optimization is suitable when you have a set space and overall idea and just need the computer to make it as lightweight as possible

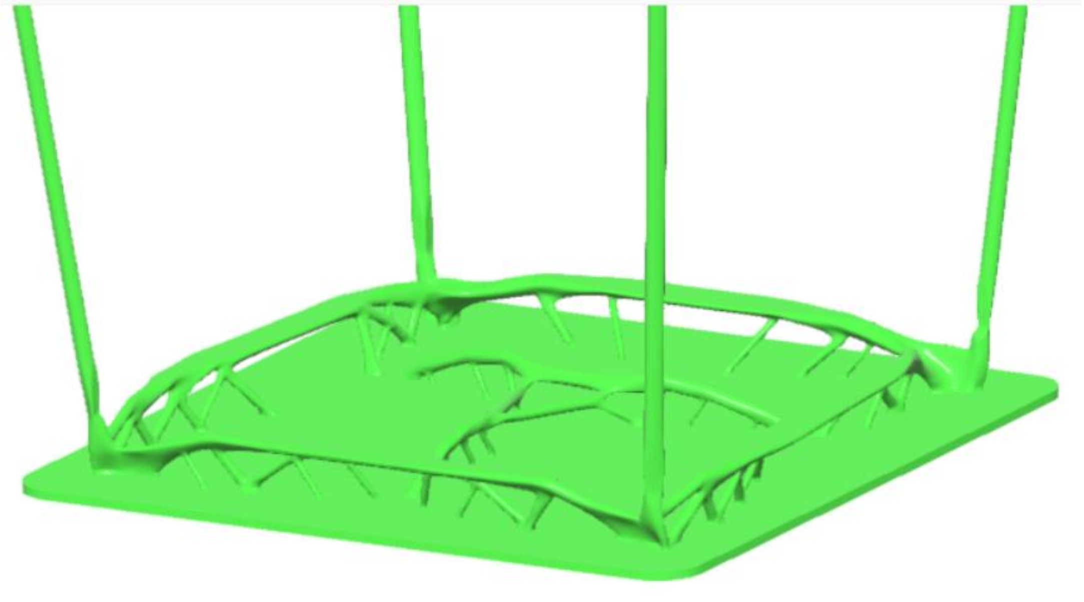
Generative Design is mainly used when the whole shape is unknown so the program will give us a lot of options, taking into consideration things like the desired material and manufacturing method.

-The A.I. chair-

Source: Designboom

Source: createdigital

T.O. Furniture

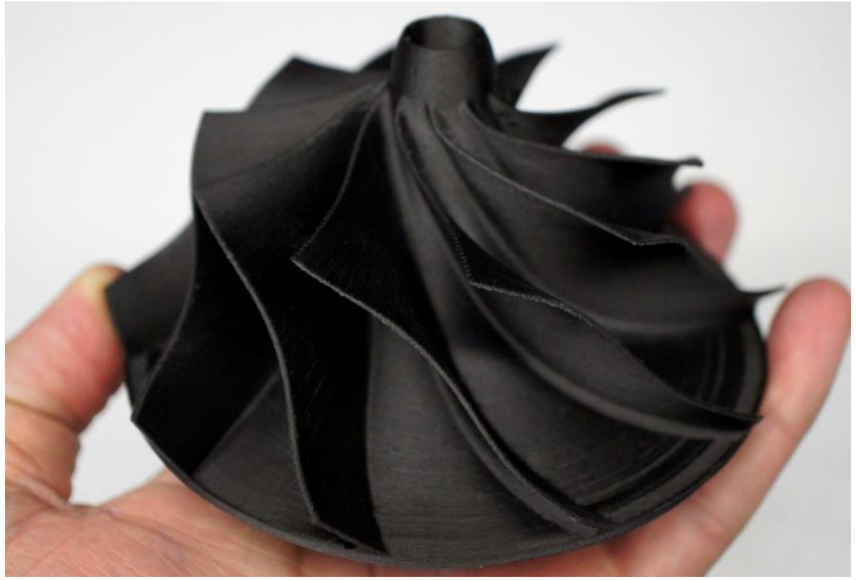






I. Ntintakis, G.E. Stavroulakis (2020)

T.O. Mechanical Parts
The 'Chaos' Project



Source: Spyros Panopoulos

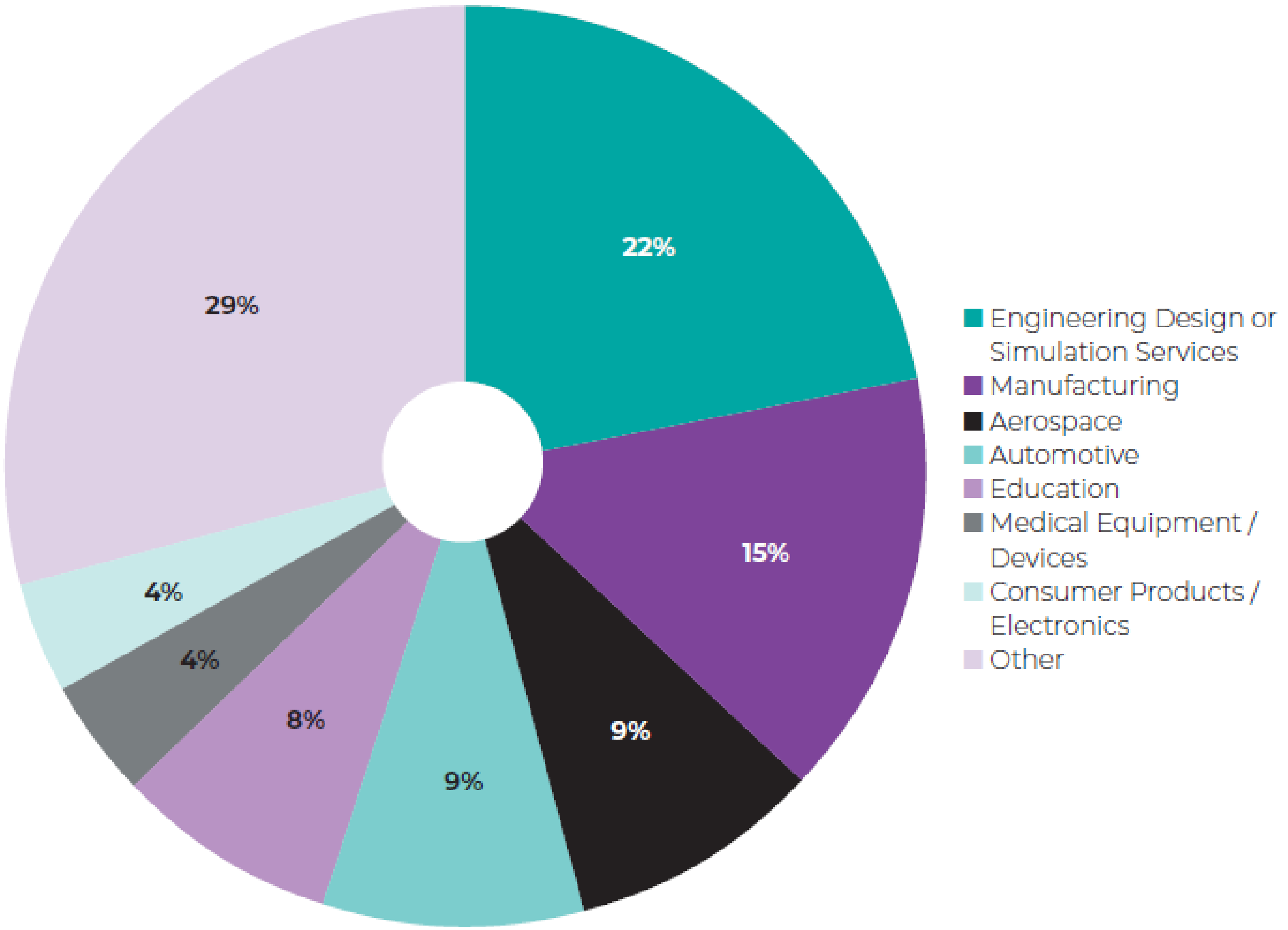
The Present and the Future of Lightweight Design

A survey :Lightweighting with Generative Design

Source: engineering.com (April 2021)

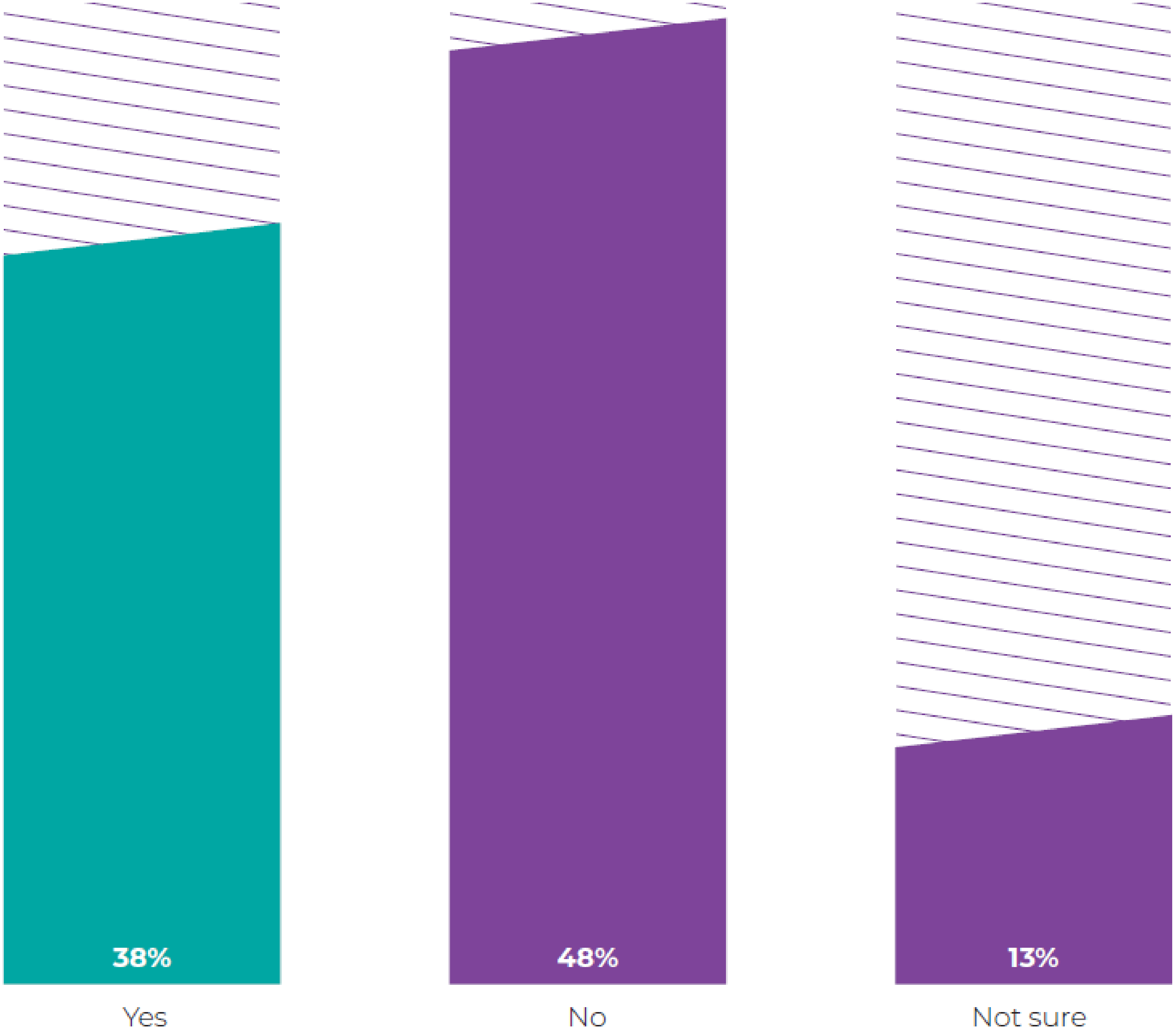
Who use Generative Design and Topology Optimization Today???

Though respondents work in a diverse range of industries, the largest industries represented here are Engineering Design or Simulation Services (22%),
Manufacturing (15%),
Aerospace (9%),
Automotive (9%),
Education (8%),
Medical Equipment/Devices (4%) and
Consumer Products/Electronics (4%).



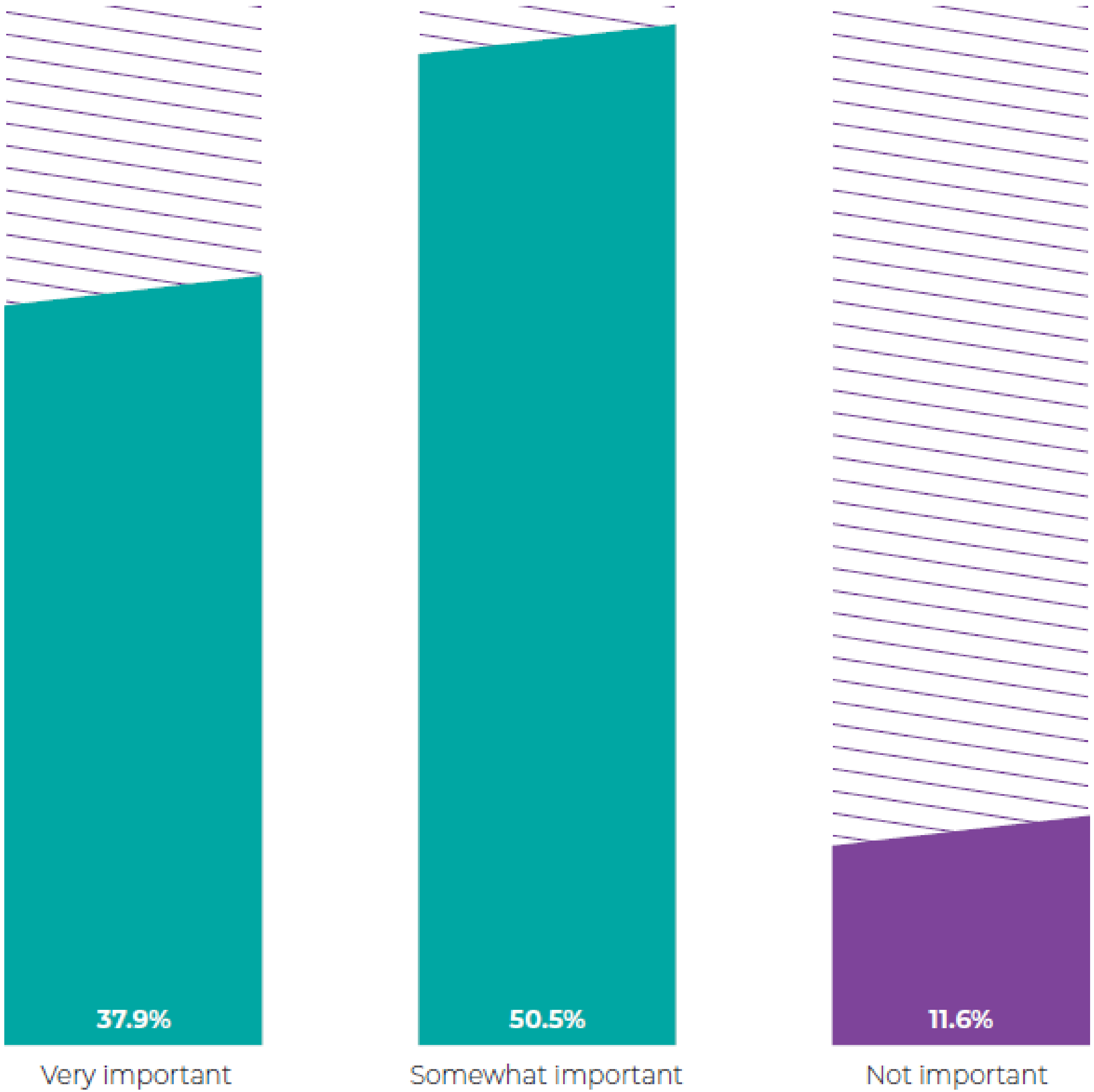
Are generative design and topology optimization technologies being used?

Despite the benefits of generative design and topology optimization technology, 61% of survey takers still have not tried it.
The minority (38%) that has used generative design and topology optimization
technology marks an opportunity to educate users about the advantages of topology optimization as a design tool



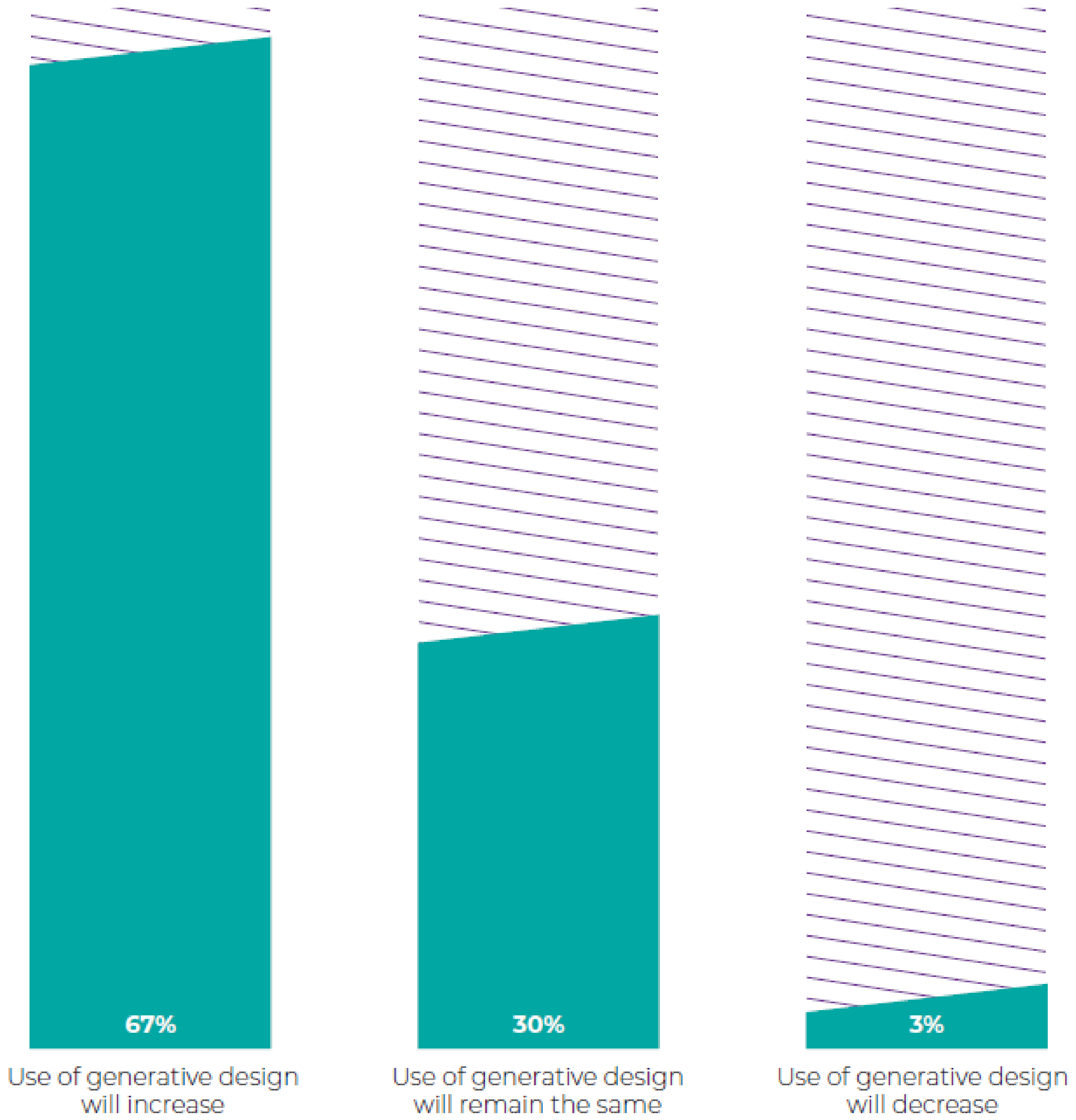
How important is light weight in your product design?

Most (88%) are interested in reducing the weight of their products.
Only a small subset (12%) of the respondents don't consider weight important.



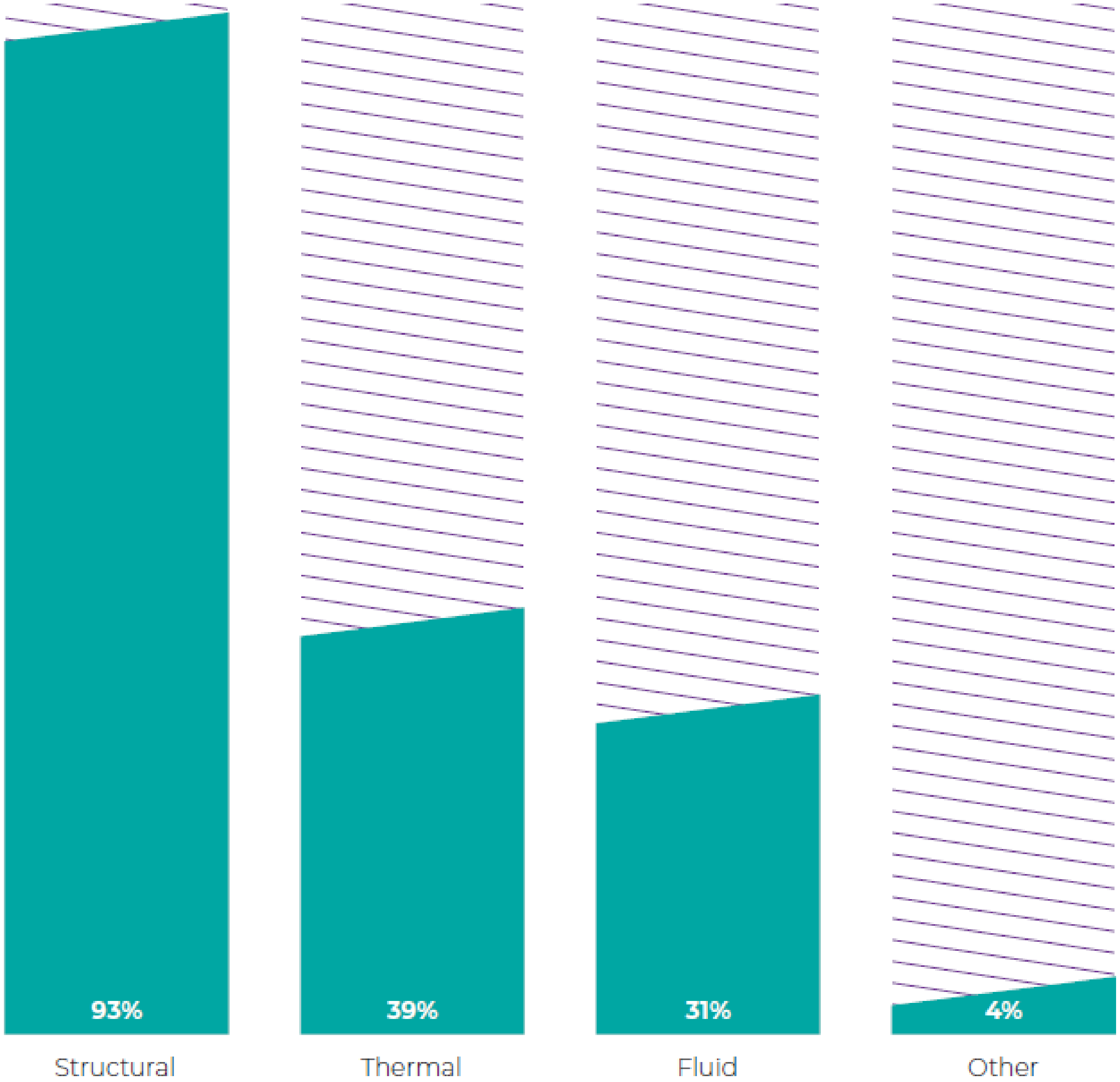
Will generative design technology be popular five years from now?

The majority (67%) of those surveyed believe that software usage will increase over the next five years. A third believe that it will continue as-is, and only 3% believe that generative design will decrease in the next five years.



What type of analysis do engineers prefer for design optimization?

By and large, the vast majority (93%) of users prefer structural analysis, but there are still those who rely on thermal (39%) and fluid (31%) methods of analysis.

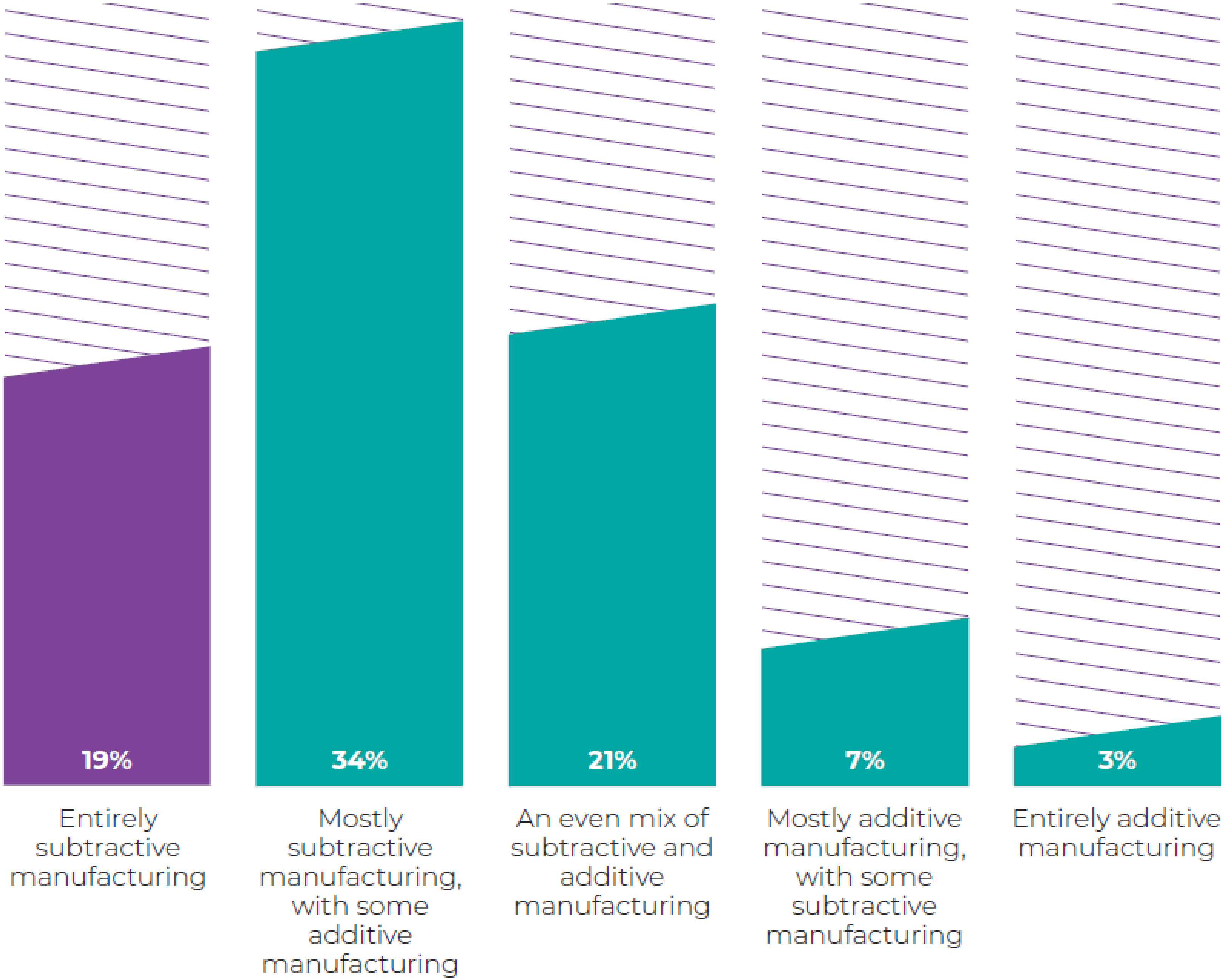


What do users think about generative design software?

- Over half (57%) of respondents believe that the software is too expensive to buy or use; only 9% disagreed.
- A large percentage (41%) of respondents are not able to incorporate the generative design solution into their design and 39% find it too difficult. Only 20% don't see this as an issue.
- The majority (41%) of respondents are concerned that generative design takes too long to set up and/or run. Only 27% are okay with the setup time.
- Likewise, the majority (45%) also have trouble manufacturing their designs.
- When it comes to robust value, respondents were split—31% feel that the software is not robust enough and 40% are unsure. Only 29% are satisfied.

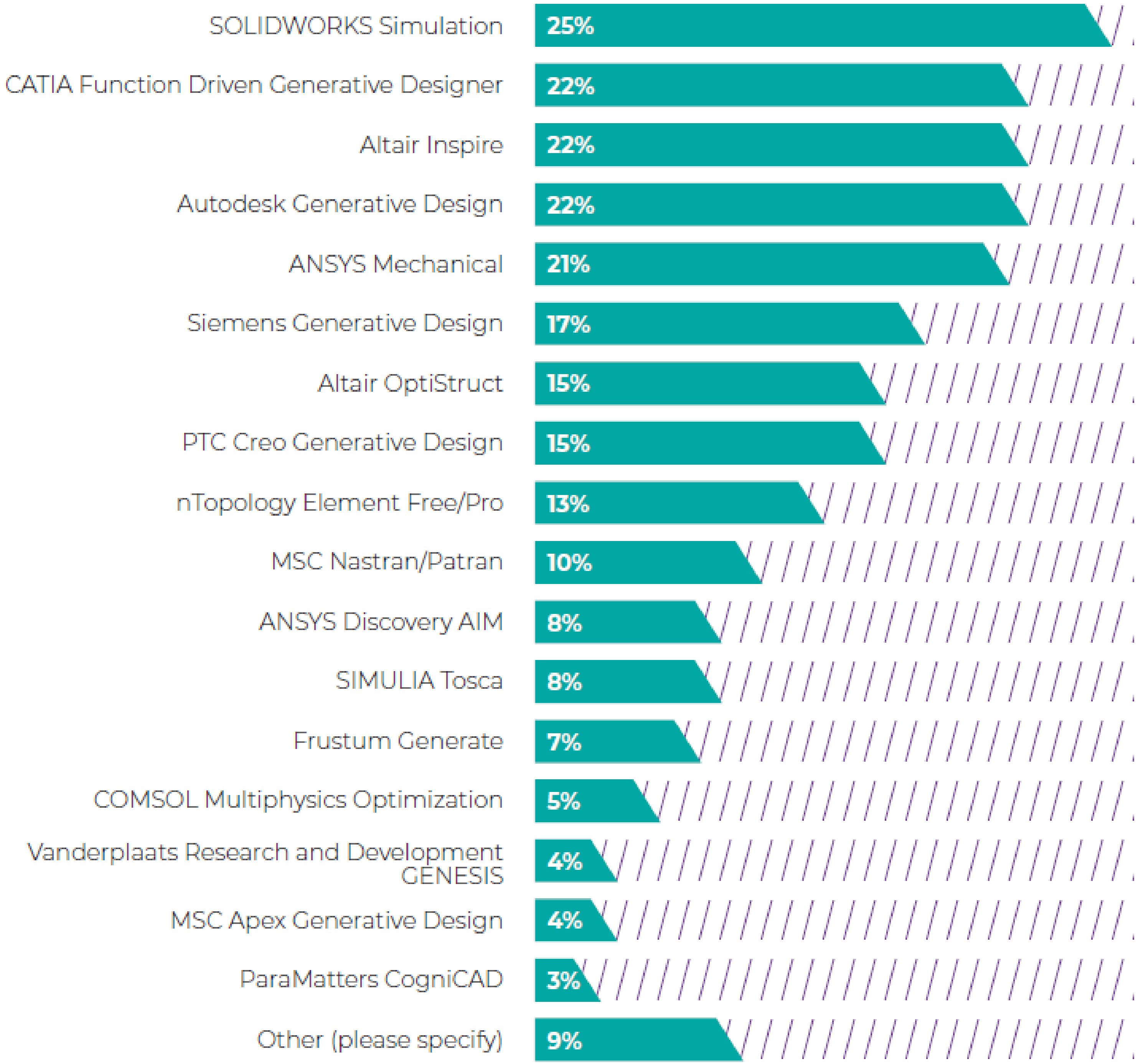
The need to use additive manufacturing hindering the use of generative design

19% rely entirely on subtractive methods and 34% rely on them mostly.
Just over a fifth of respondents use an even mix of subtractive and additive manufacturing methods.
A much smaller portion (3%) relies entirely on additive manufacturing,
and 7% use mostly additive with some subtractive manufacturing.



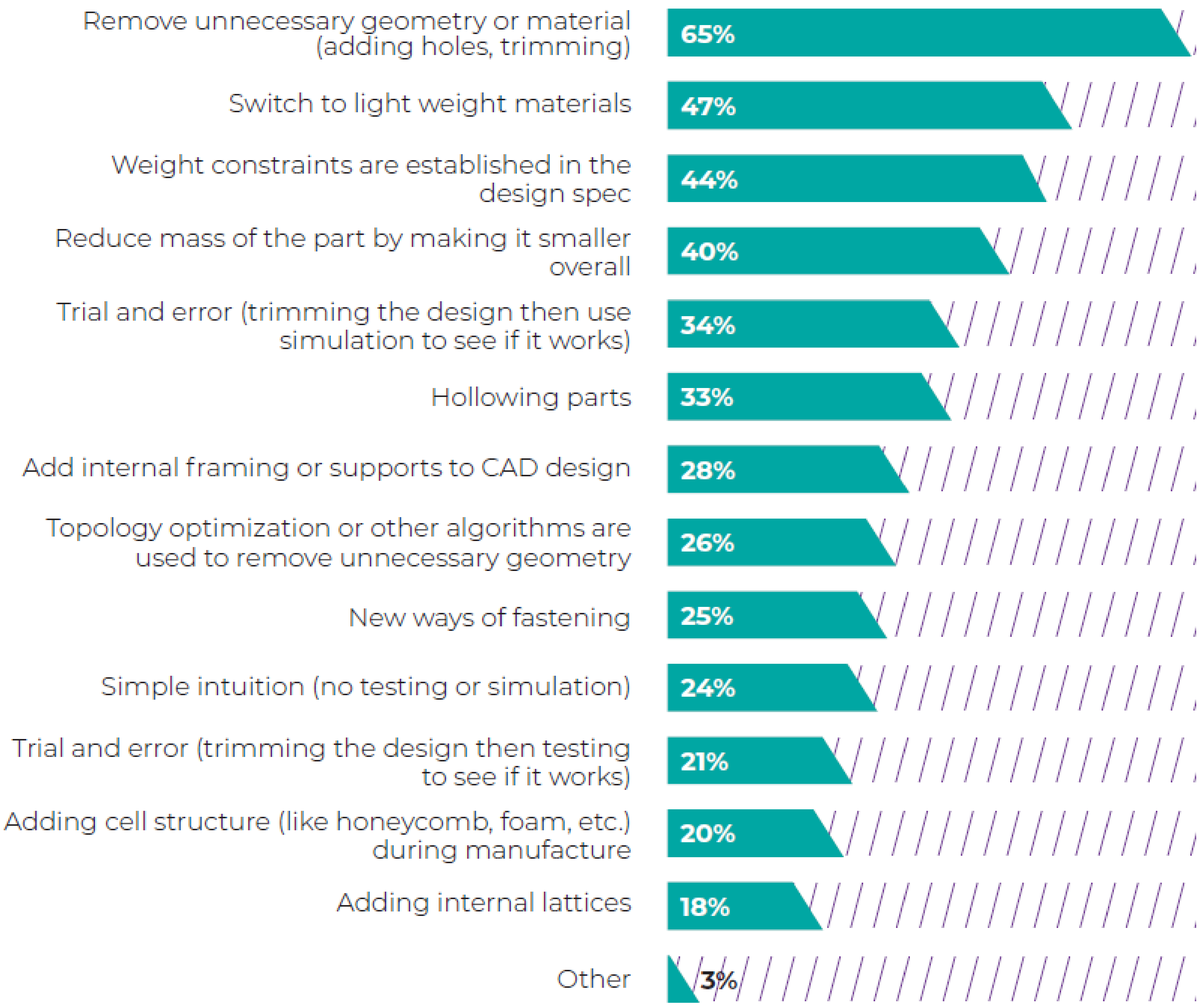
What are the popular applications for generative design and/or topology optimization?

SOLIDWORKS Simulation (25%), Altair Inspire (22%), Autodesk Generative Design (22%), CATIA Generative Design (22%), CATIA Function Driven Generative Design (22%) and
ANSYS Mechanical (21%).



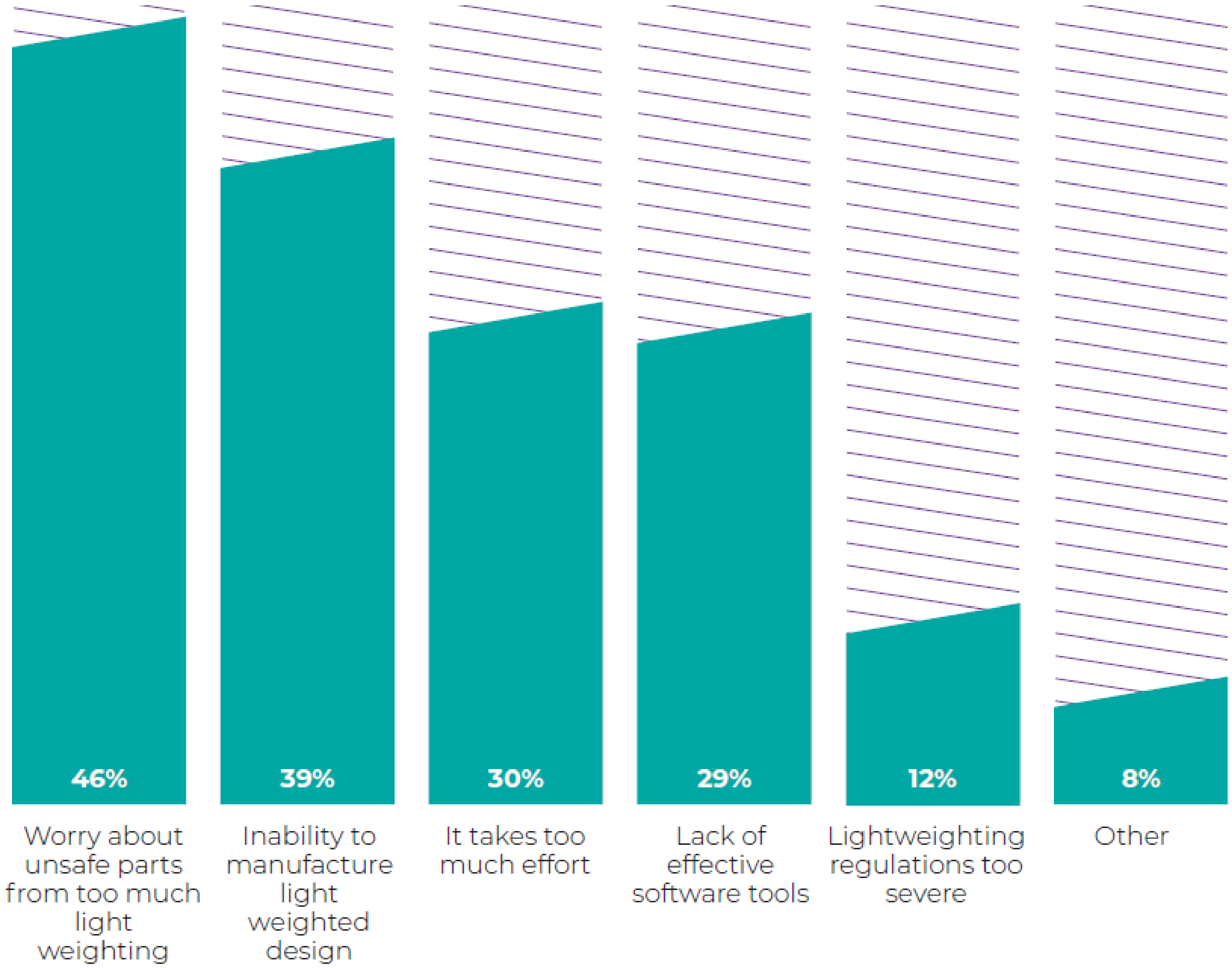
How do engineers approach lightweighting?

The most popular lightweighting methods include removing unnecessary geometry or material (65%), switching to lighter materials (47%), setting weight limits in the design specs (44%) and reducing mass by making the part smaller overall (40%).
The least popular methods involve adding internal lattices (18%), adding cell structure such as honeycomb and foam during manufacturing (20%), trimming the design then testing to see if it works (21%) and relying on intuition (24%).



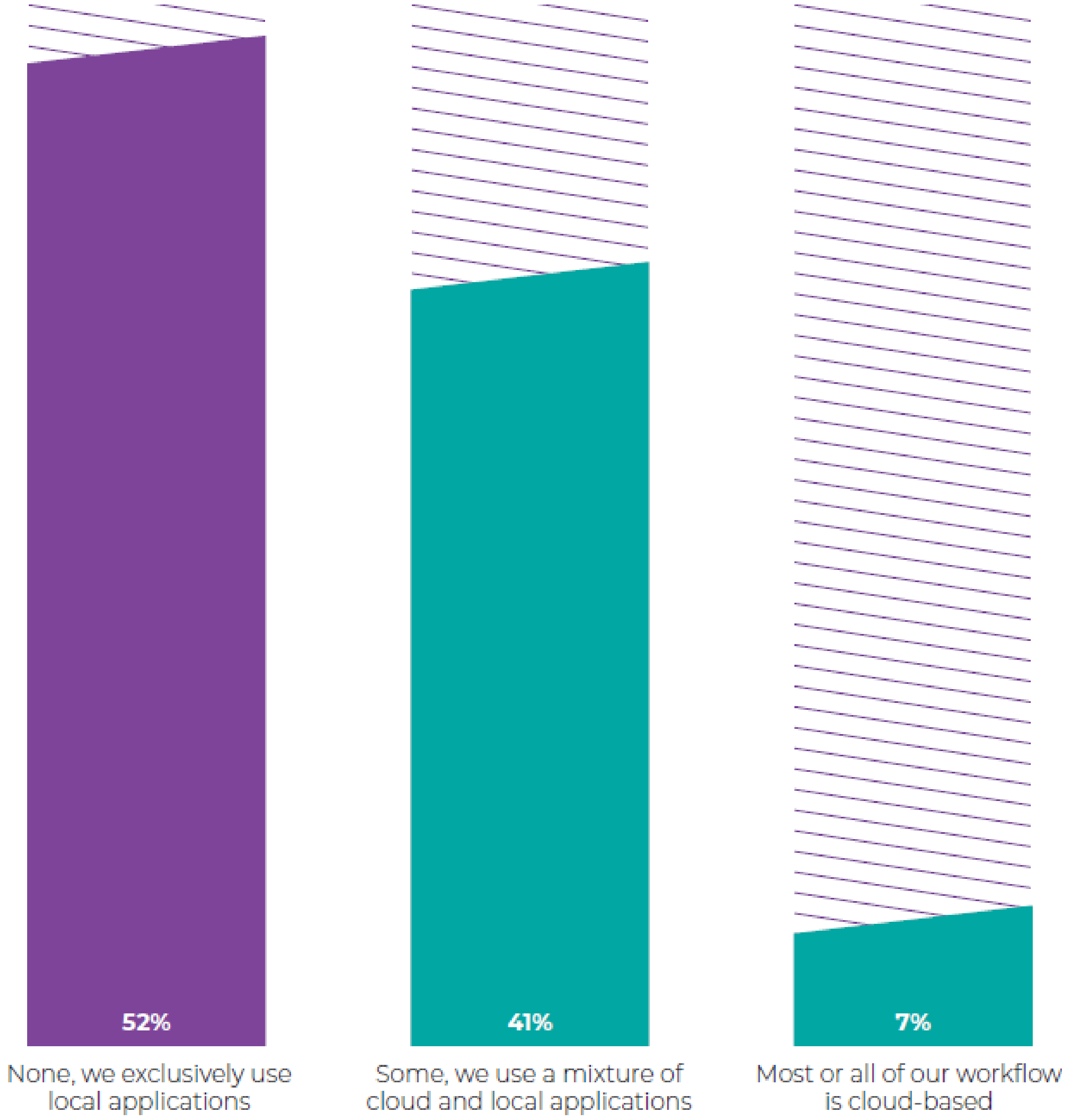
What are the obstacles to lightweighting designs?

A large subset (46%) worry that lightweighting will make parts weaker, leading to safety and liability issues.
(39%) don’t have the ability to manufacture a part that has been lightweighted using generative design.
A third of our respondents note that lightweighting takes too much effort (30%) or that they lack effective software tools (29%).
Only 12% of respondents consider regulations for lightweighting to be a hindrance.



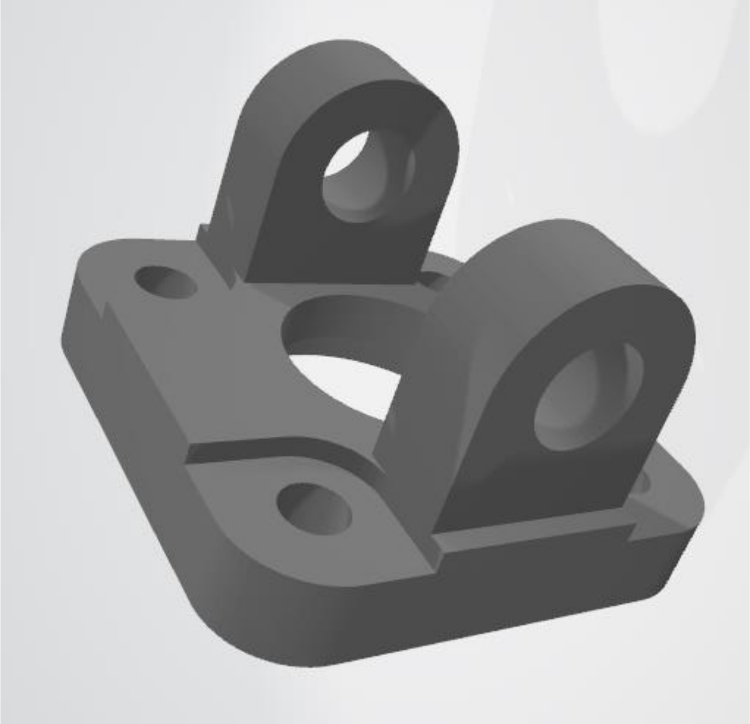
Cloud-based workflow strategies gaining popularity

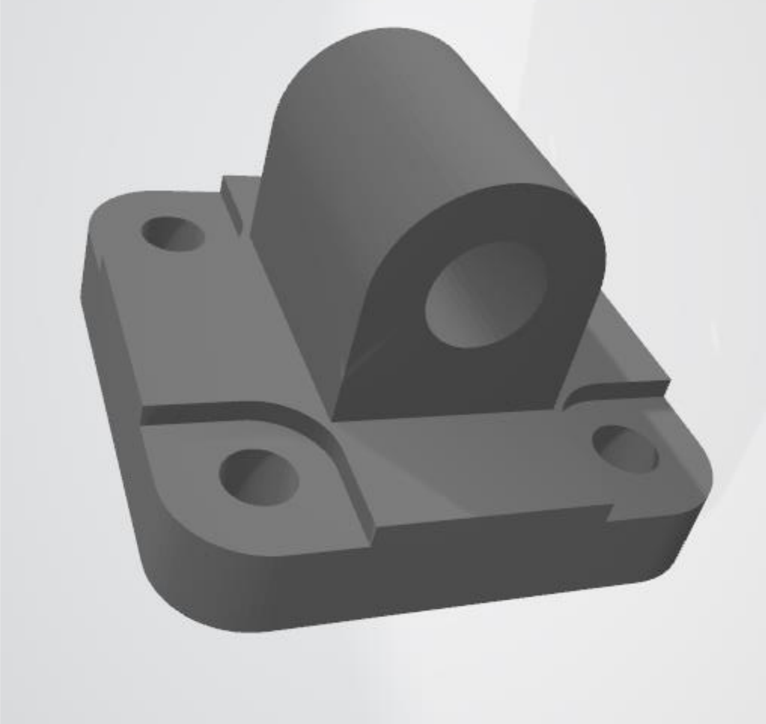
Are engineers relying more on cloud-based systems to streamline their workflow? Our survey results point to mixed usage. Less than half (41%) of our respondents use some mixture of cloud and local applications, and only 7% have fully adopted cloud-based workflows.



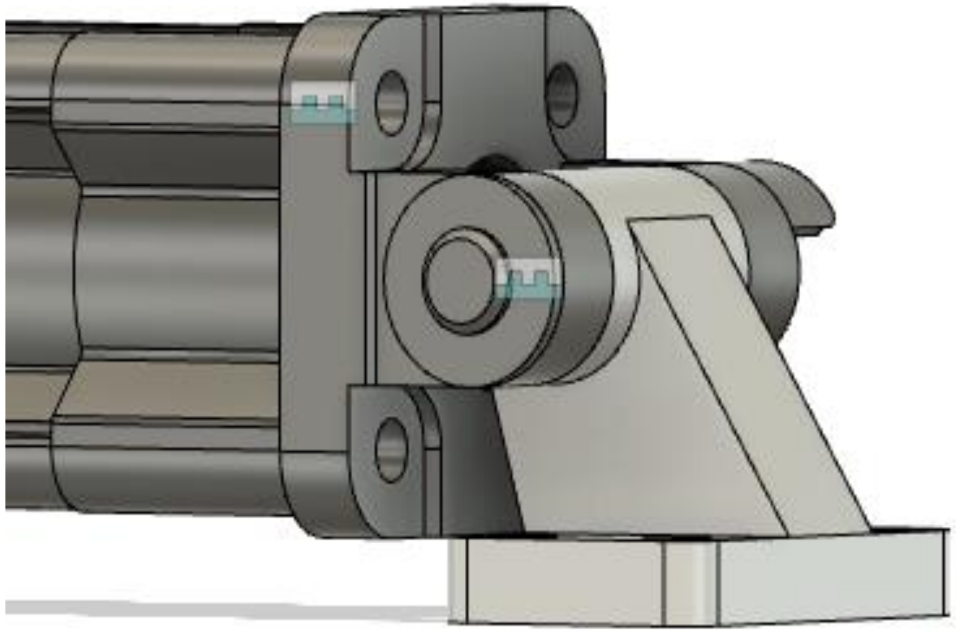
Generative Design Process –Examples-

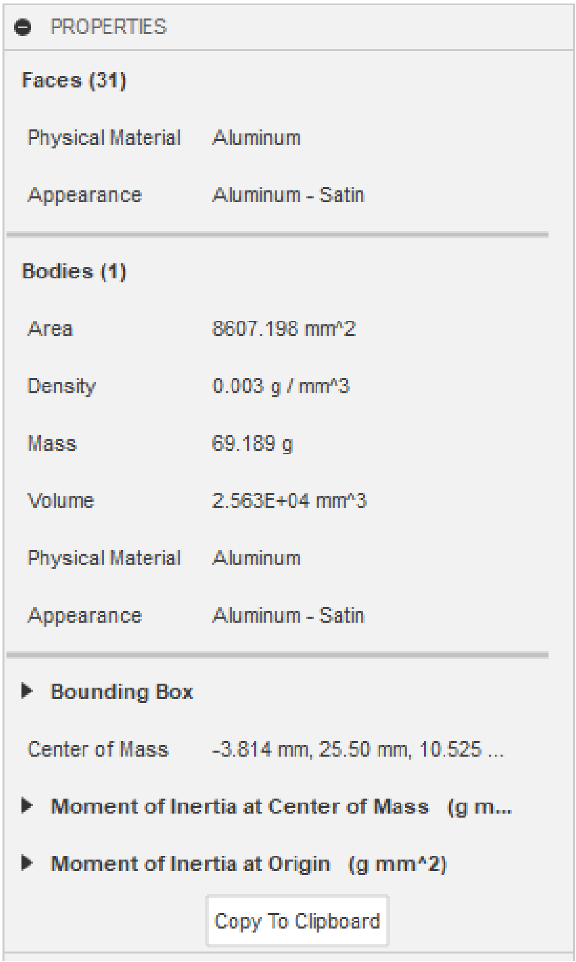
Bases of pneumatic cylinder Φ32 ISO15552





1st Part
The part is made of aluminum alloy and weighs 69.13gr





Boundary Conditions

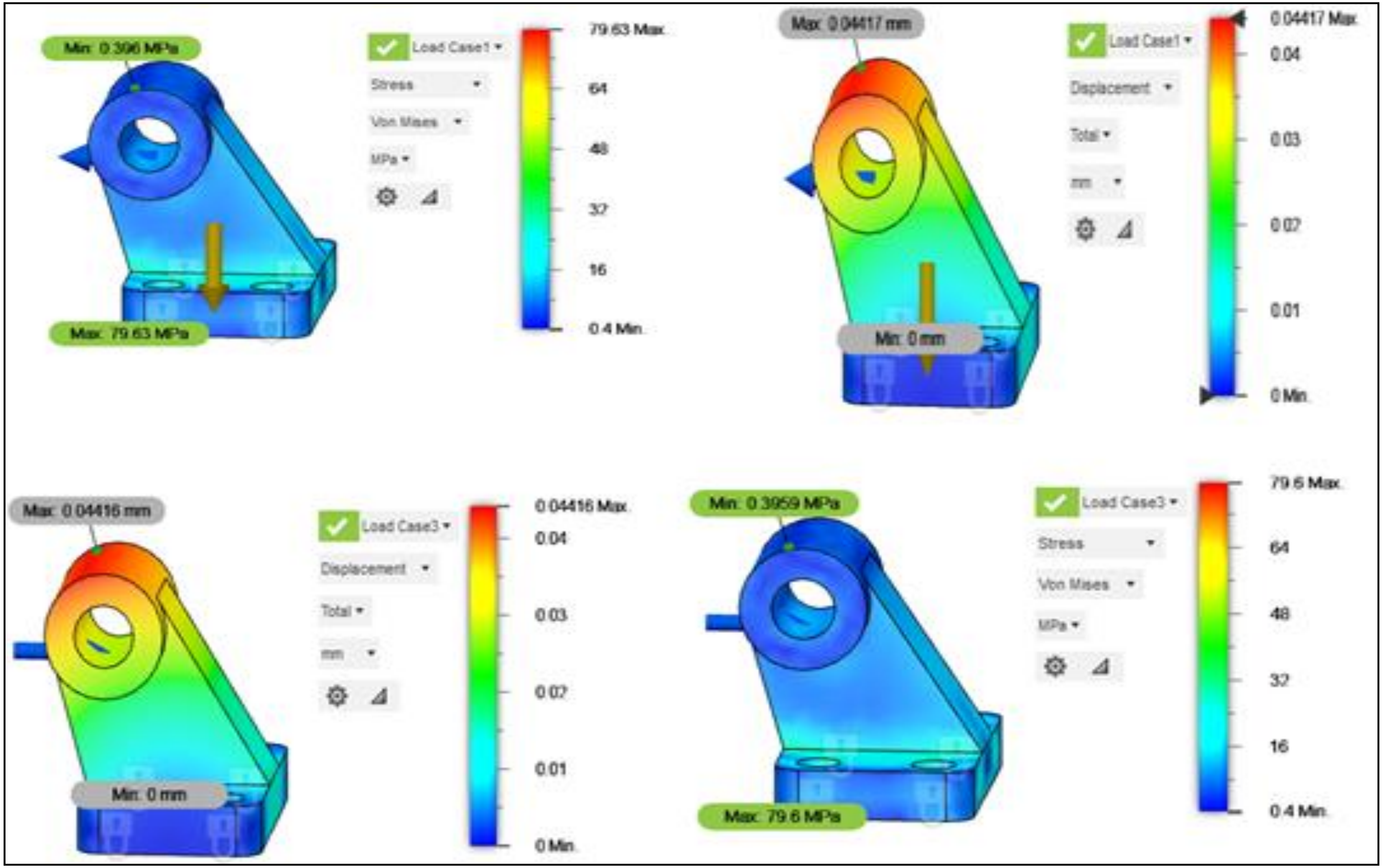
Technical Data

Cylinder forces

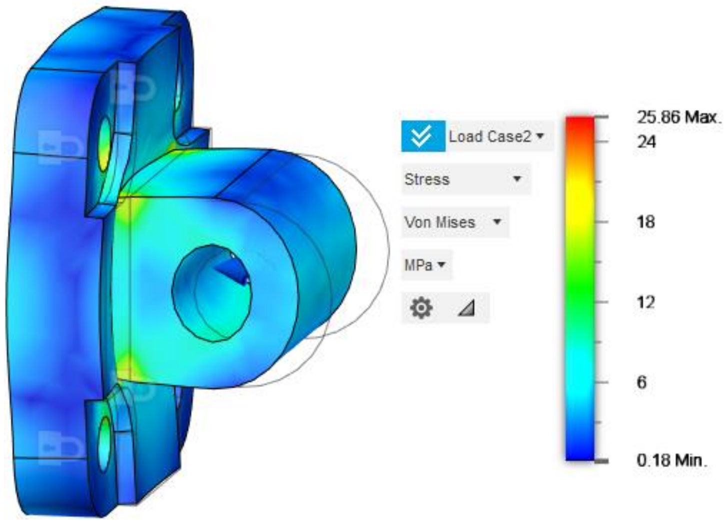
Bore/piston rod [mm]	Stroke	Surface area [cm²]	Max theoretical force in N in relation to applied pressure in bar 1	2	3	4	5	6	7	8	9	10
32/12	+	8.0	80	161	241	322	402	**483**	563	643	724	804
	-	6.9	69	138	207	276	346	**415**	484	553	622	691
40/16	+	12.6	126	251	377	503	628	**754**	880	1005	1131	1257
	-	10.6	106	211	317	422	528	**633**	739	844	950	1056
50/20	+	19.6	196	393	589	785	982	**1178**	1374	1571	1767	1964
	-	16.5	165	330	495	660	825	**990**	1155	1319	1484	1649
63/20	+	31.2	312	623	935	1247	1559	**1870**	2182	2494	2806	3117
	-	28.0	280	561	841	1121	1402	**1682**	1962	2242	2523	2803
80/25	+	50.3	503	1005	1508	2011	2513	**3016**	3519	4021	4524	5027
	-	45.4	454	907	1361	1814	2268	**2721**	3175	3629	4082	4536
100/25	+	78.5	785	1571	2356	3142	3927	**4712**	5498	6283	7069	7854
	-	73.6	736	1473	2209	2945	3682	**4418**	5154	5891	6627	7363
125/32	+	122.7	1227	2454	3682	4909	6136	**7363**	8590	9818	11045	12272
	-	114.7	1147	2294	3440	4587	5734	**6881**	8027	9174	10321	11468

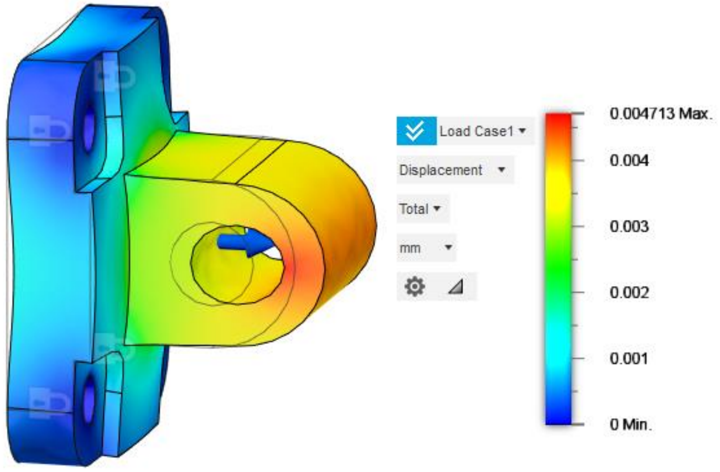
+ = outward stroke
- = return stroke

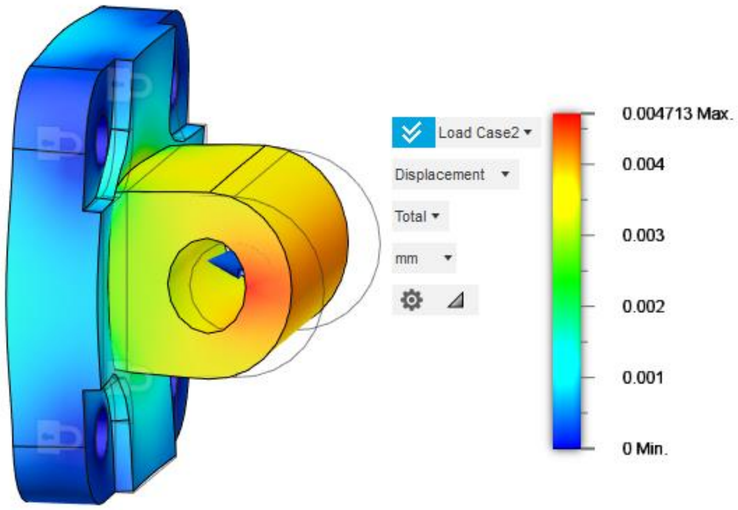
1st Part FE Analysis

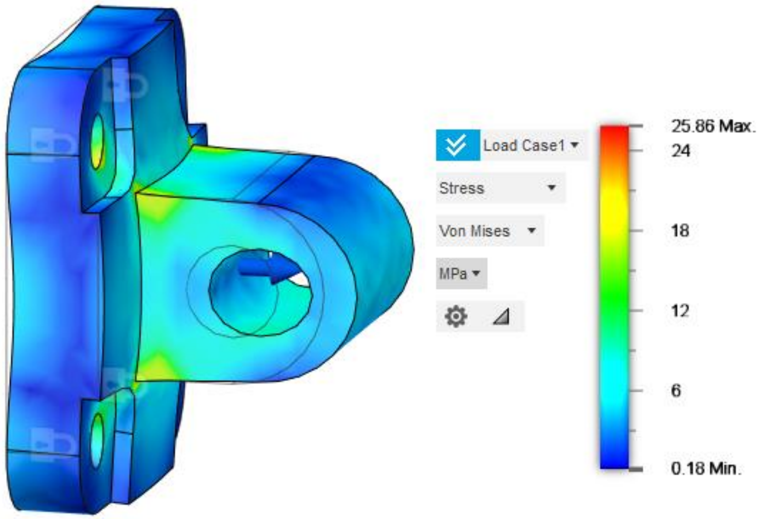


2nt Part
FE Analysis

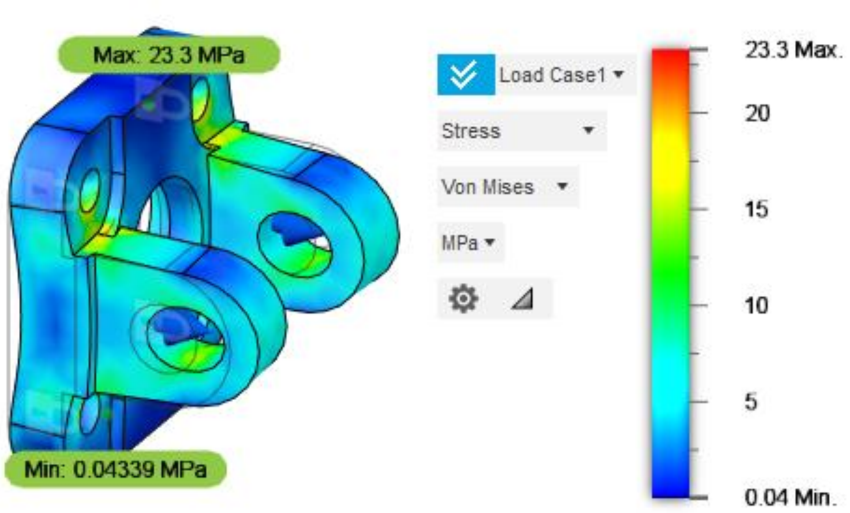


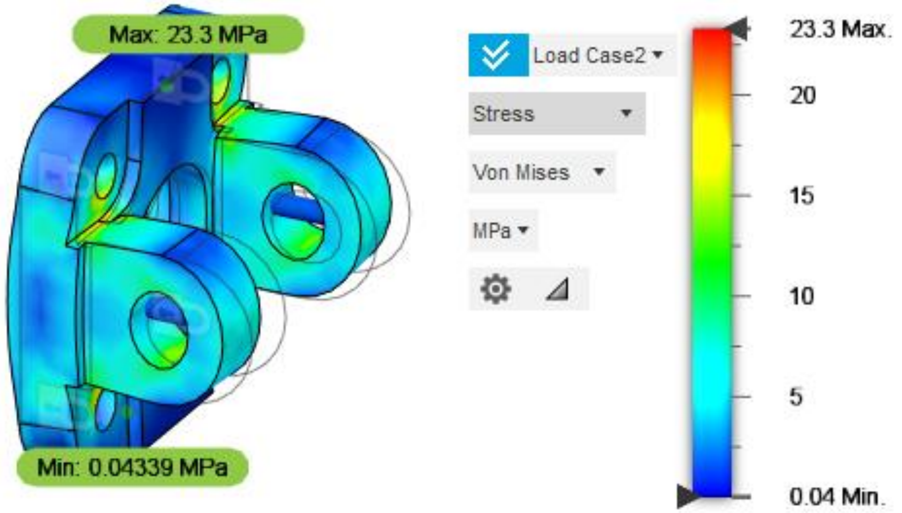


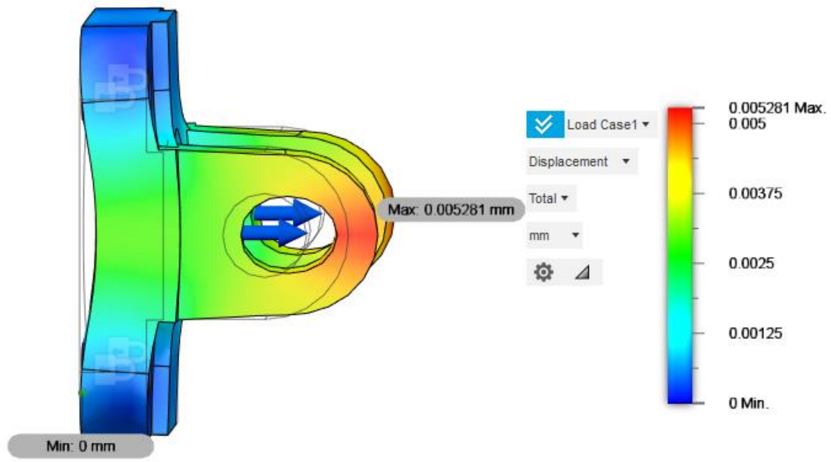


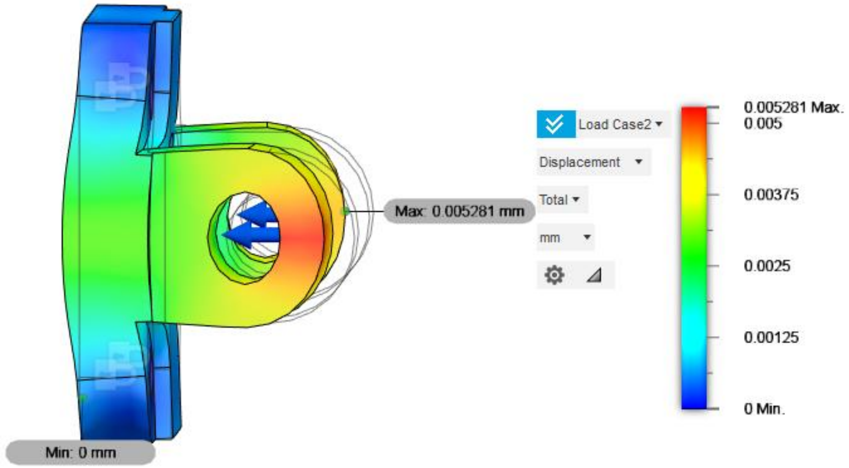


3rd Part FE Analysis









G.D. Study

A generative study is a set of data that describes a design problem you want to define using generative design

In the generative study you can input specific design objectives, including functional, manufacturing, and mechanical requirements. You can also define material type and performance criteria. Once the study setup is defined, you can generate a set of designs that meet these requirements

Define Objectives

Optimization objectives and limits must be defined, so that the outcomes should have to satisfy

In the generative study we have to input specific design objectives, including functional, manufacturing, and mechanical requirements

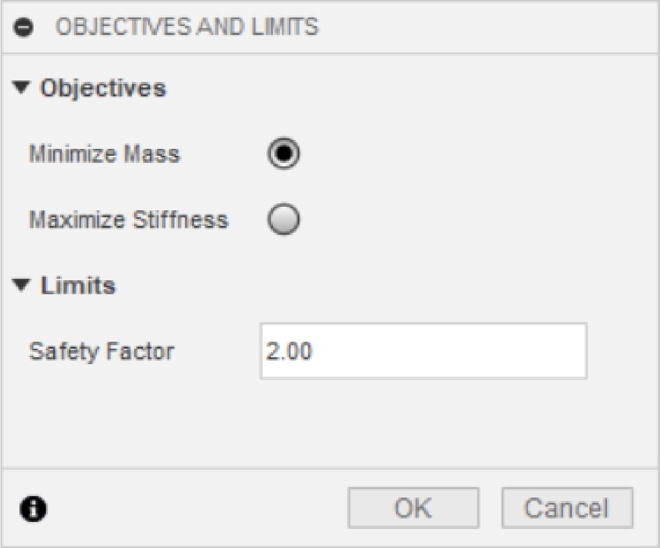
Also, to define material type and performance criteria. Once the study setup is defined, a set of designs that meet these requirements will be generated

Define Objectives

Maximize stiffness - to achieve the maximum possible stiffness of the design for a given mass. You need to specify the value of the mass target for this objective

Minimize mass - to achieve the minimum possible mass of the design. The solver removes mass through an automatically set number of iterations

Optimization limits enable you to specify other requirements that the outcomes should satisfy. The solver tries to achieve the limits, though sometimes it may not be possible



Study materials in a generative study

The selection of materials is a very important part of the design requirements in a generative study and influences the final shapes of outcomes.

You need to select materials from which your design can be manufactured. You can select from one to seven materials for each manufacturing method. You can select materials to all methods or specific materials to a specific manufacturing process in your study. Each activated manufacturing method in the generative study, must include at least one material.

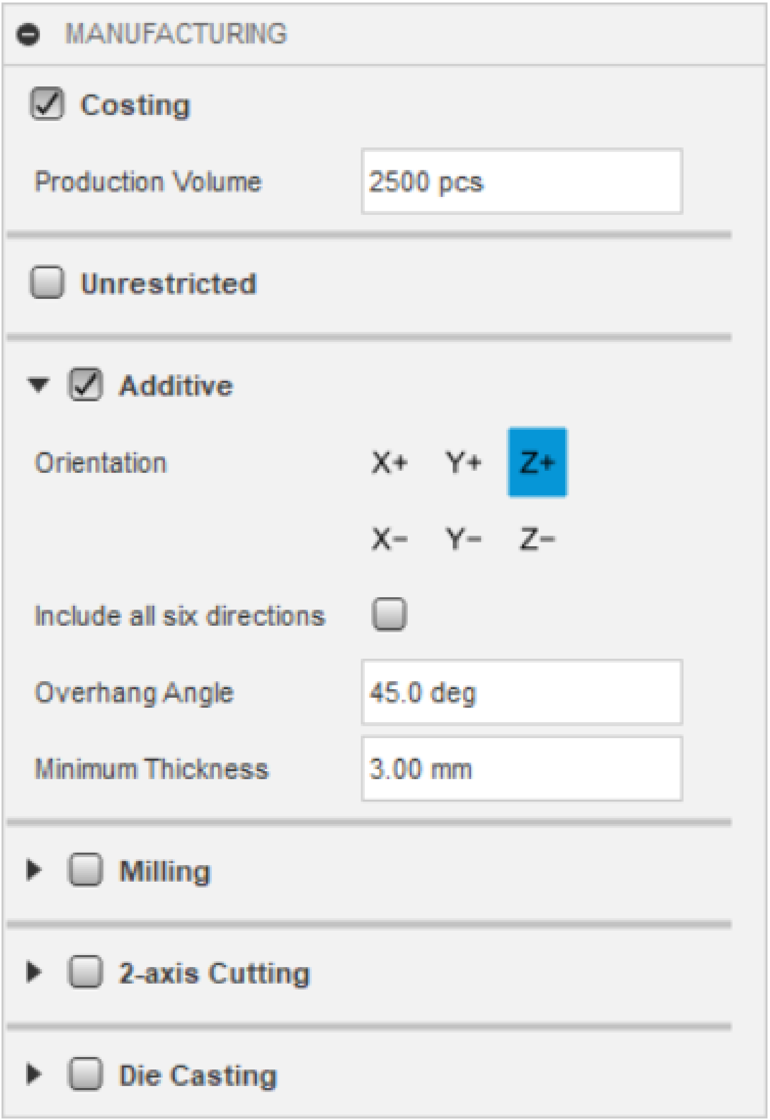
Manufacturing methods in a generative study

G.D. study enables you to specify manufacturing constraints that outcomes should satisfy

Multiple options are available. For each option selected, you obtain a set of outcomes showing the design problem solved with that manufacturing method in mind

If you specify a production volume, you receive estimated manufacturing costs for outcomes

It enables you to explore tradeoffs between performance, cost, and aesthetics between designs which can be manufactured using each manufacturing method



Preserve geometry -Why it is necessary to define a preserve geometry in a model?-

Preserve geometry should represent the minimum geometry which you need in the final shape of your design. It should include sections of geometry which are essential for the performance and functionality of your design

A preserve geometry can include:

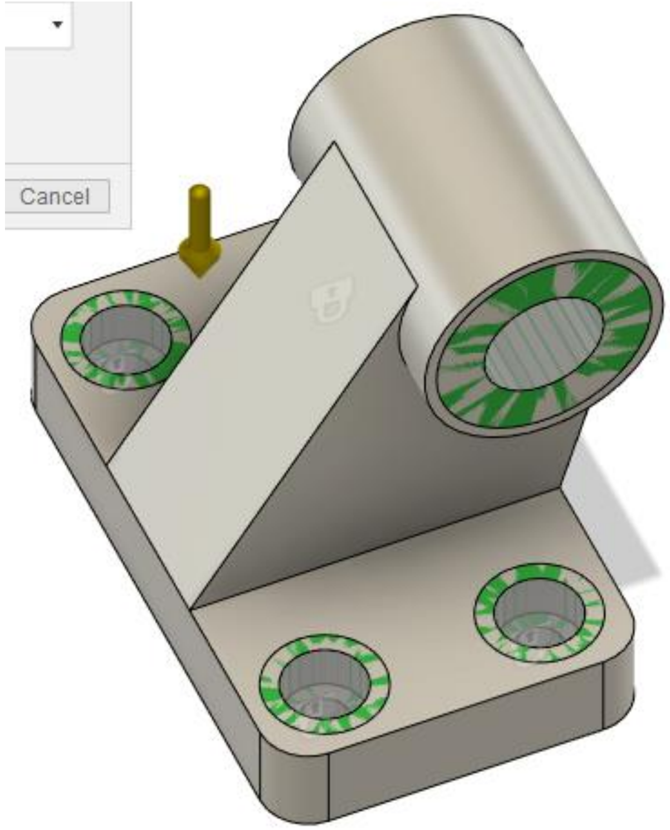
1. A connection to attach a design to other objects, like bolt holes
2. A part of the design you interact with, like handles or handlebars

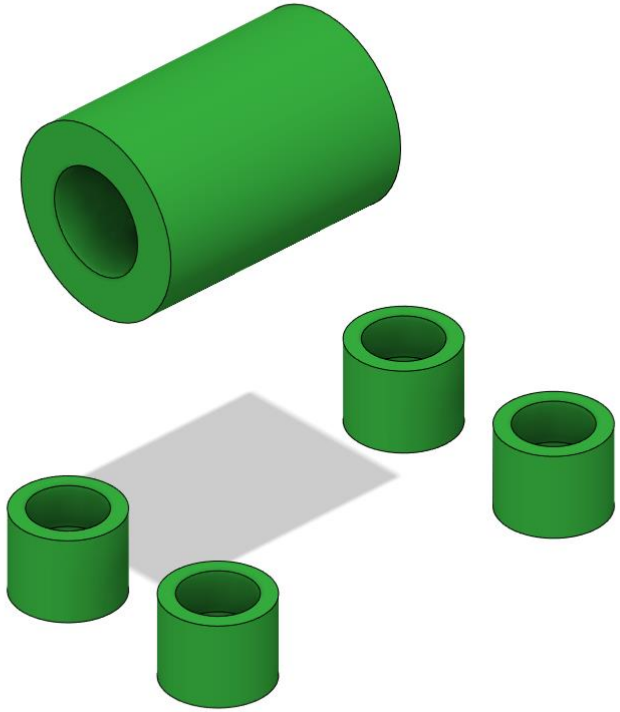
The preserve geometry is where you apply any loads and constraints

It ensures that the design is suitable for use in its intended environment

Preserve geometry

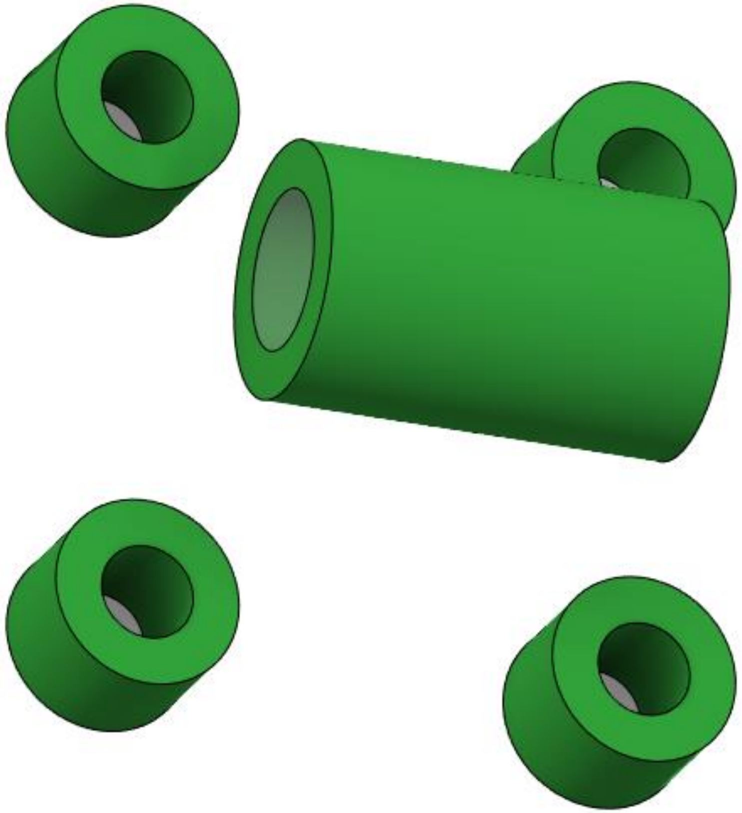
A preserve geometry is one of the geometry types in the design space. You assign it to bodies to incorporate them in the final shape of the design.

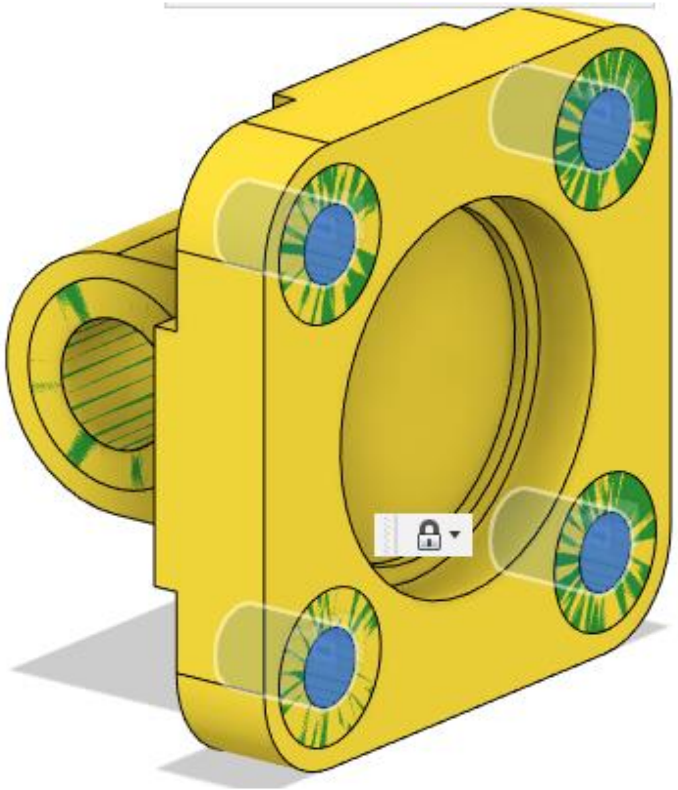




Preserve geometry

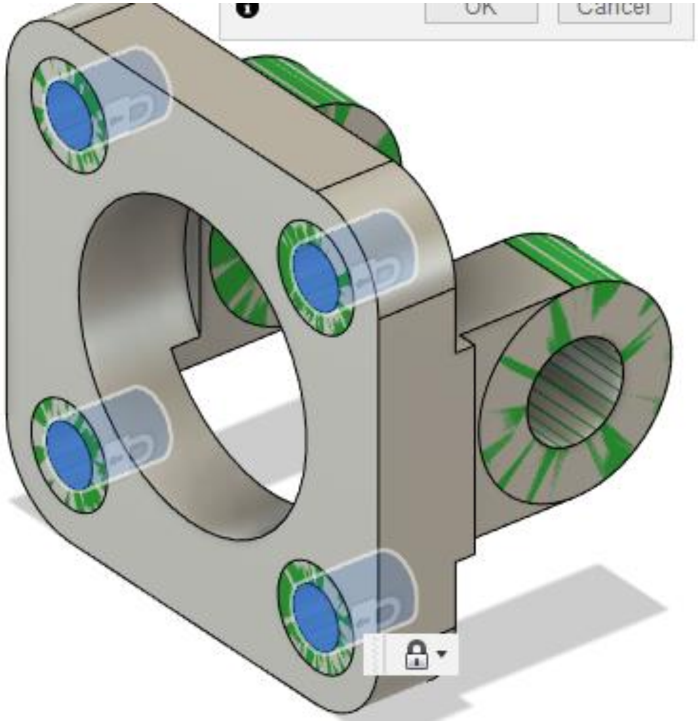
Bodies assigned a preserve geometry display in green on the canvas. They don't change during the generation of outcomes.

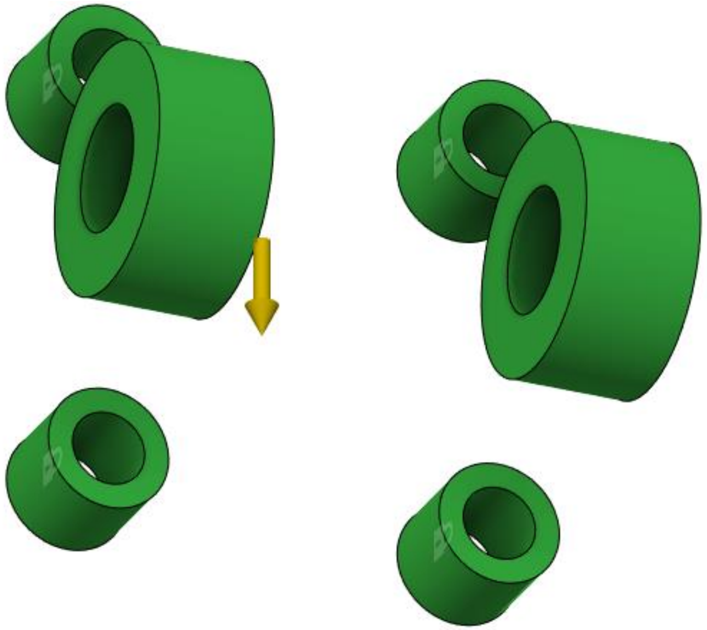




Preserve geometry

To generate outcomes, your model needs at least one body used as the preserve geometry.



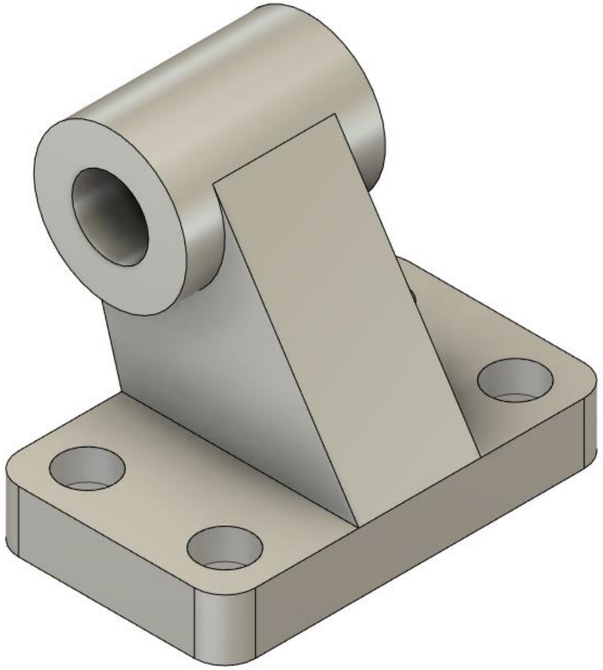


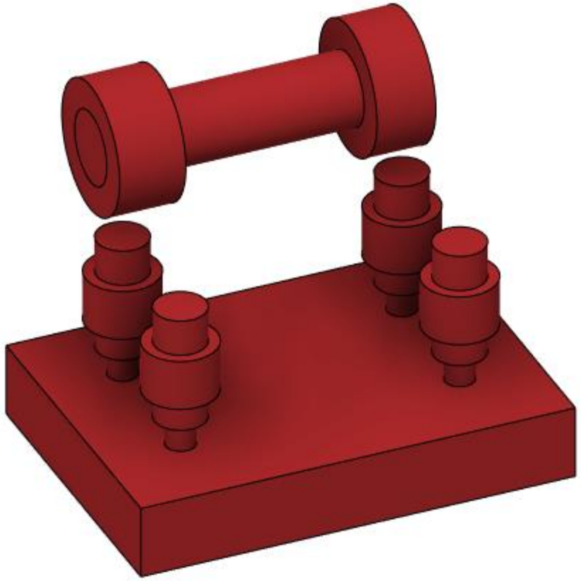
Obstacle geometry- Why you need the obstacle geometry in your model?-

- When your design attaches to other objects, use the obstacle geometry to prevent the design from extending into and interfering with, other objects
- When objects attaching to your design are moving, use the obstacle geometry to represent this range of motion. For example, when setting up the design problem for a bike frame, you need to avoid creating material which could collide with the moving pedals, or the turning front wheel
- Use the obstacle geometry at connection points. For example, in a bolted connector, use the obstacle geometry to:
  - Keep the hole for a bolt free from material.
  - Represent the freedom of movement to enable placing the bolt into the hole freely.

Obstacle geometry

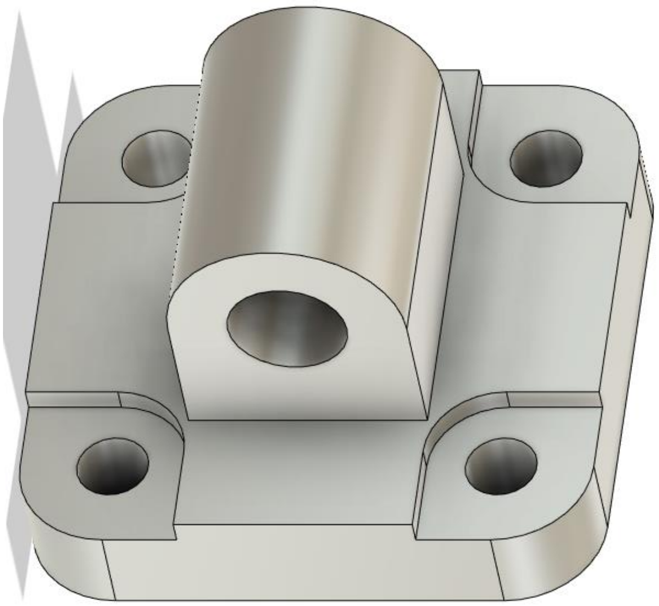
An obstacle geometry is one of the geometry types in the design space. You assign it to bodies to represent spaces that you want to avoid in the design

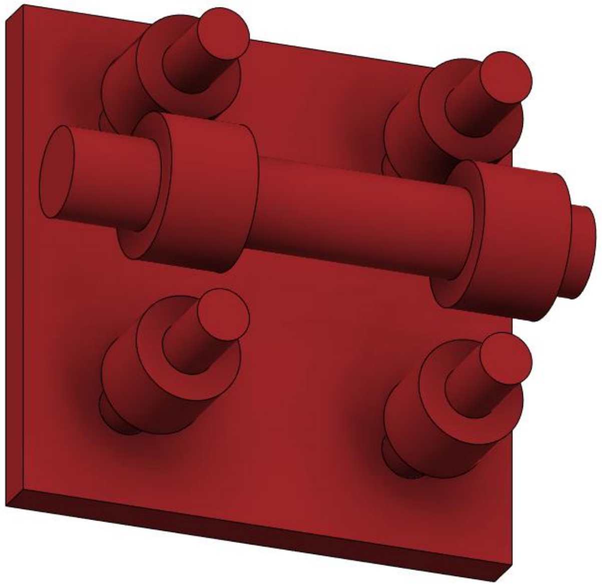




Obstacle geometry

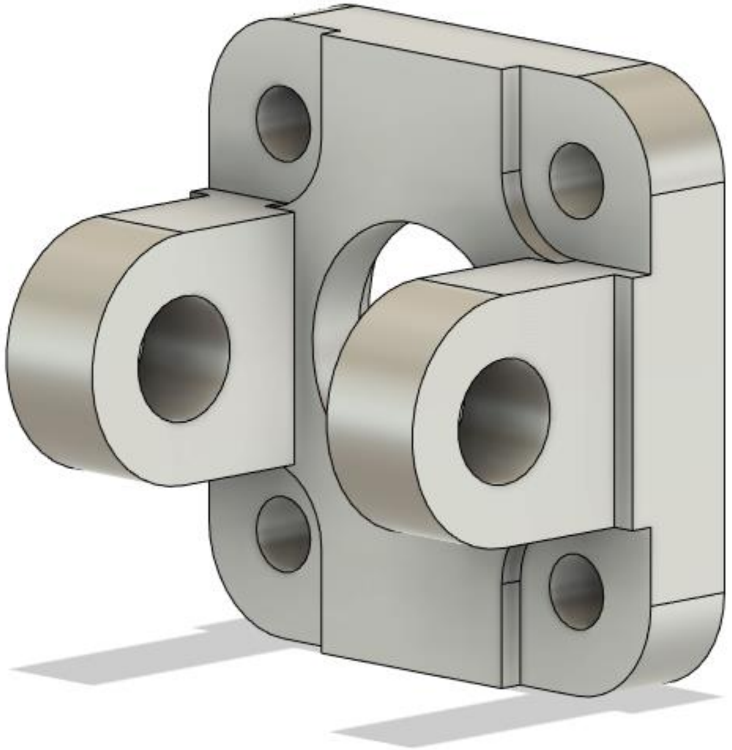
Bodies assigned an obstacle geometry display in red on the canvas. They represent empty spaces where material isn't created during the generation of outcomes

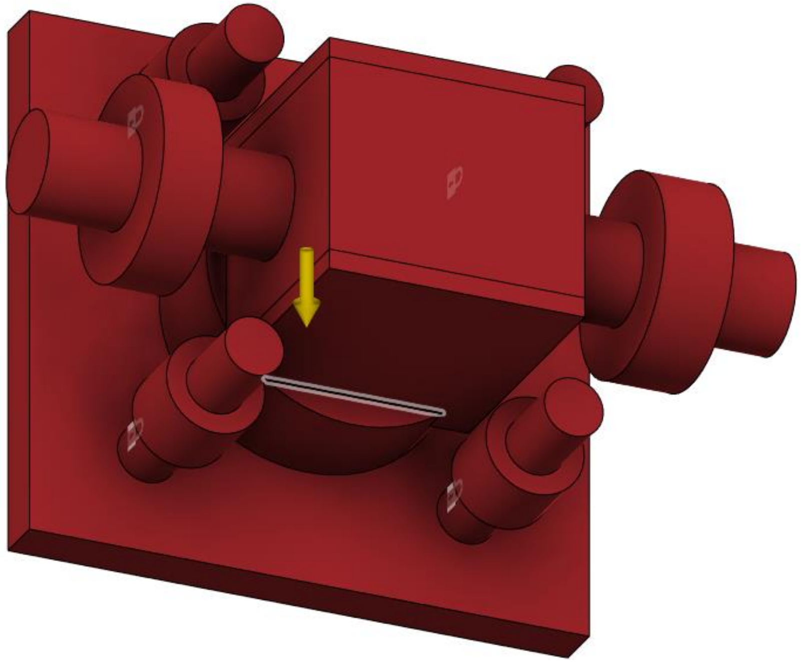




Obstacle geometry

You can generate outcomes without the obstacle geometry body in your model.





Starting shape

An initial shape is the shape generated in the initial stage of the design process

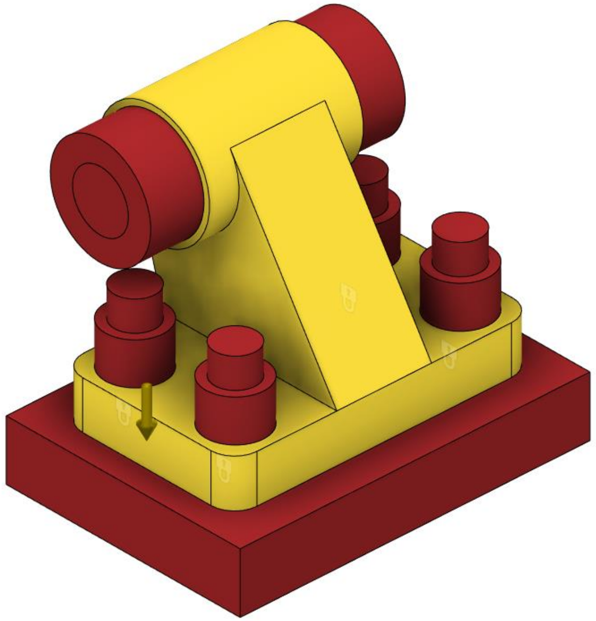
It is determined by all important points given in the definition of the design problem

The outcome generation is performed based on this shape. If a model includes a starting shape, it is the initial shape for the generation process

If the model doesn't include the starting shape, the initial shape is defined based on the preserve geometry.

Starting shape

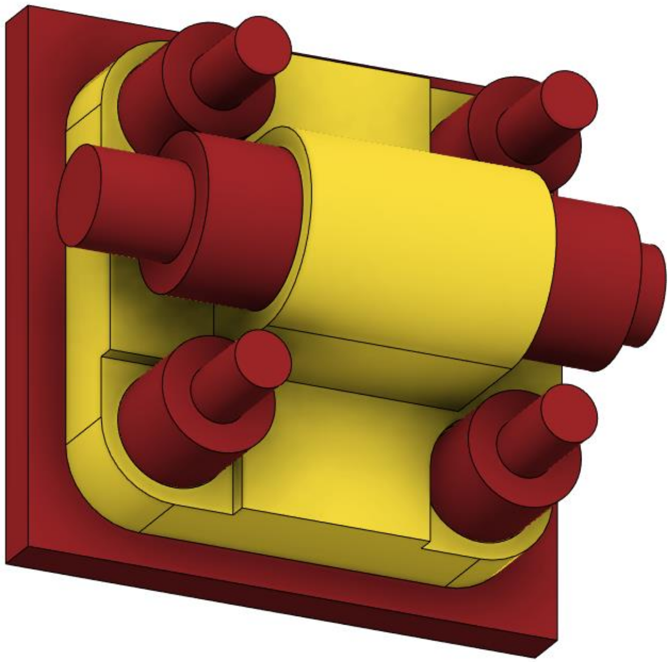
A starting shape is one of the geometry types in the design space. You assign it to a body to optimize an existing design or influence the shape of the generated design



Starting shape

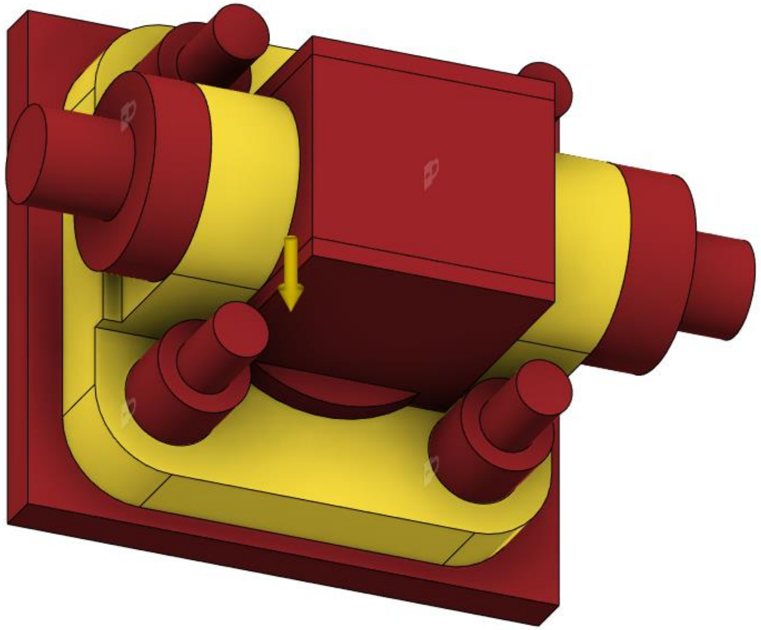
A starting shape is optional. If you don't use it, you receive more variation in outcomes

The starting shape body displays in yellow on the canvas



Starting shape

You can assign the starting shape to only one body in your study. It must be in contact with all preserve geometry bodies

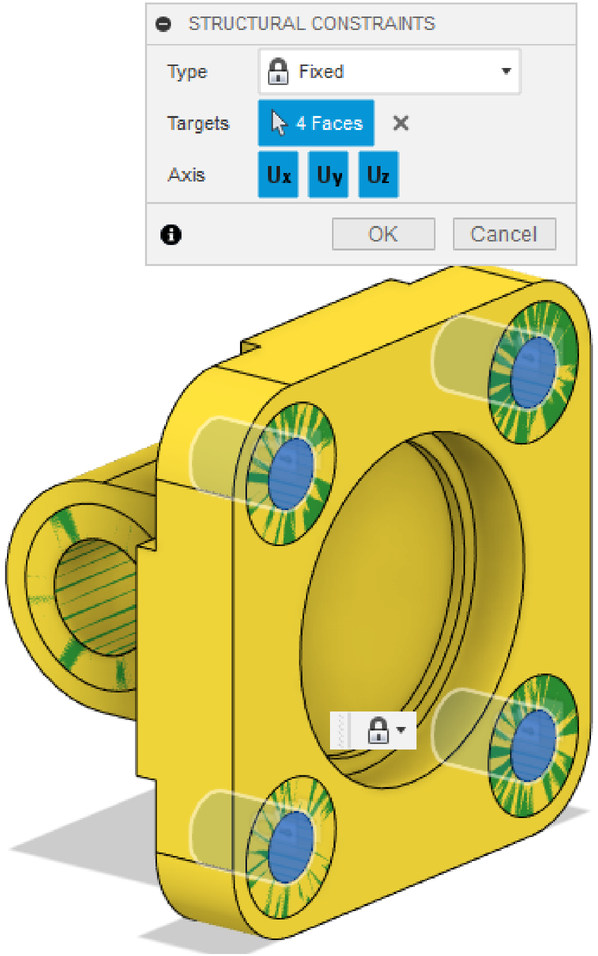


Structural constraints in a generative study

Constraints enable you to define how the design interacts with the objects not included in the model and how it is fixed. Constraints are applied to the model to prevent it from moving in response to applied loads

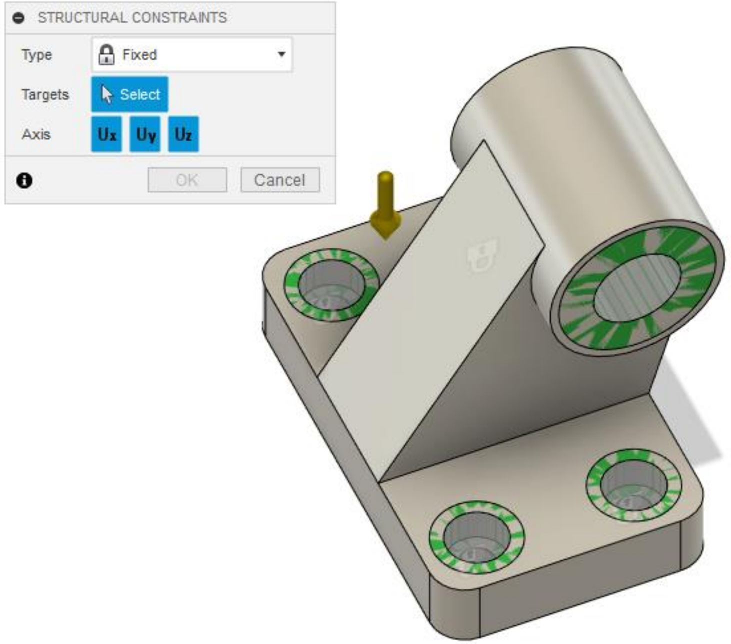
You can apply constraints to the preserve geometry only

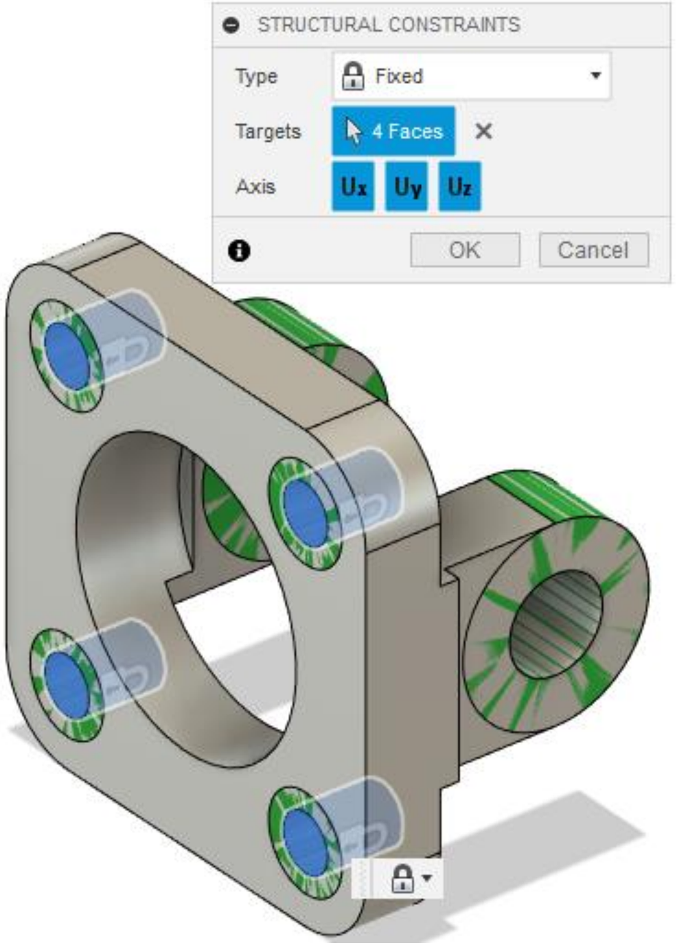
It is displayed in green on the canvas



Structural constraints in a generative study

It is a critical part of the design requirements in a generative study and influences the final shapes of outcomes. You must apply at least one constraint to a preserve geometry body

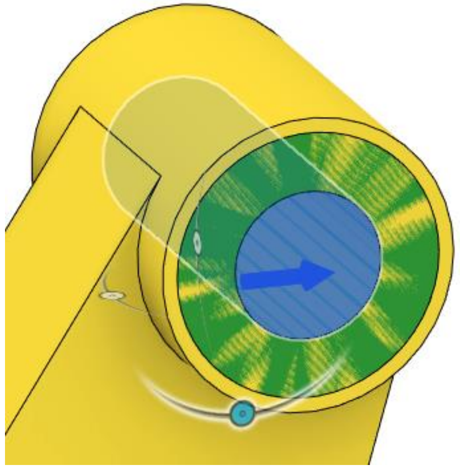


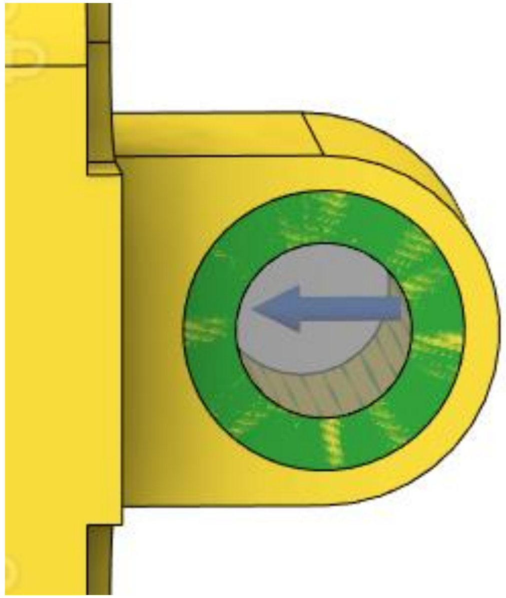


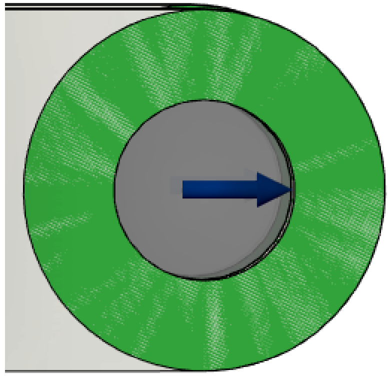
Structural loads in a generative study

Loads enable to simulate pushing, pulling, and twisting forces that the design should withstand

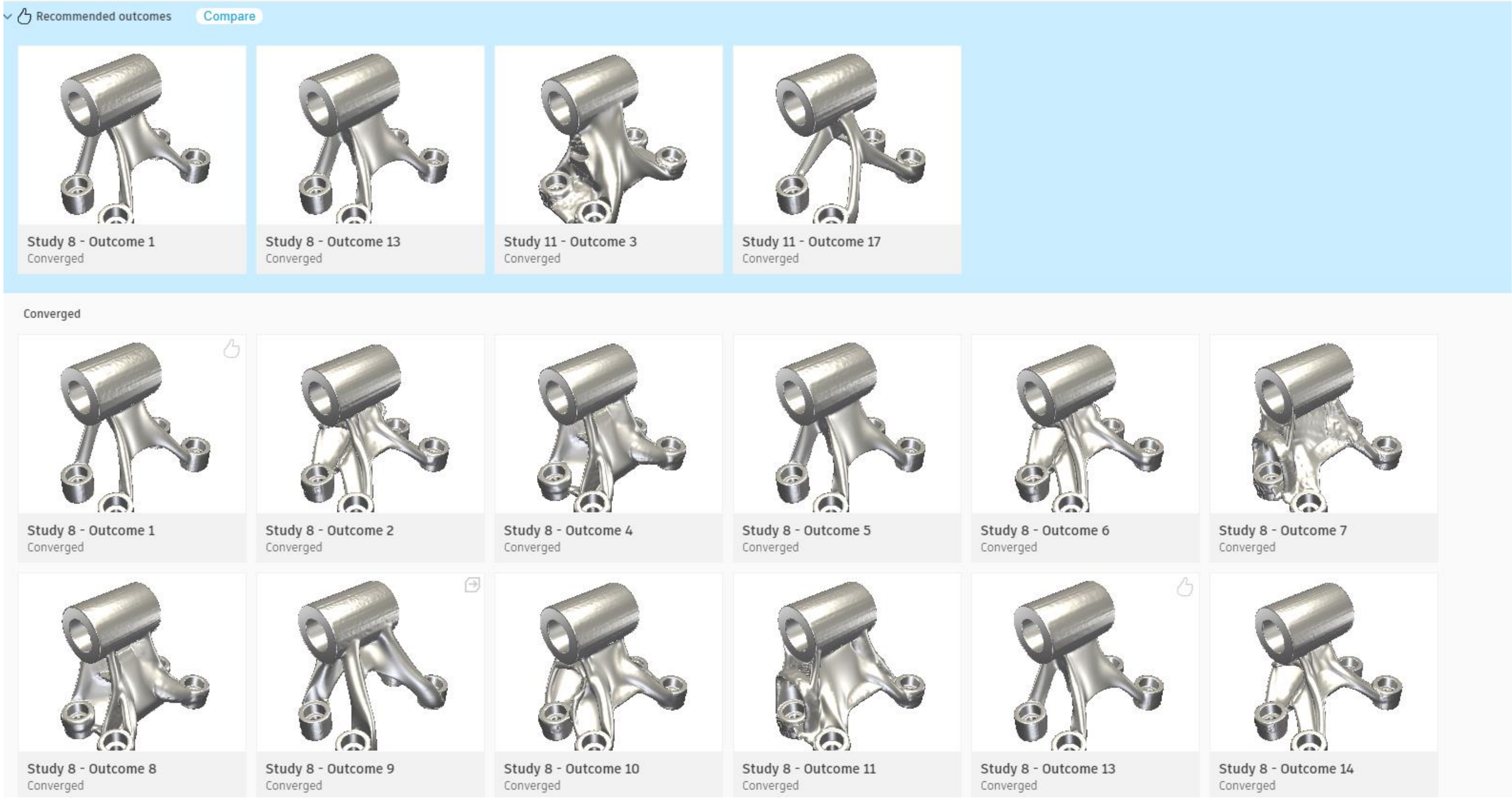
Defining loads enables you to specify expectations towards a design strength. It is a critical part of the design requirements in a generative study and influences the final shapes of outcomes. At least one load must be defined to a preserve geometry body. A load and constraint can't be on the same face, edge, or vertex





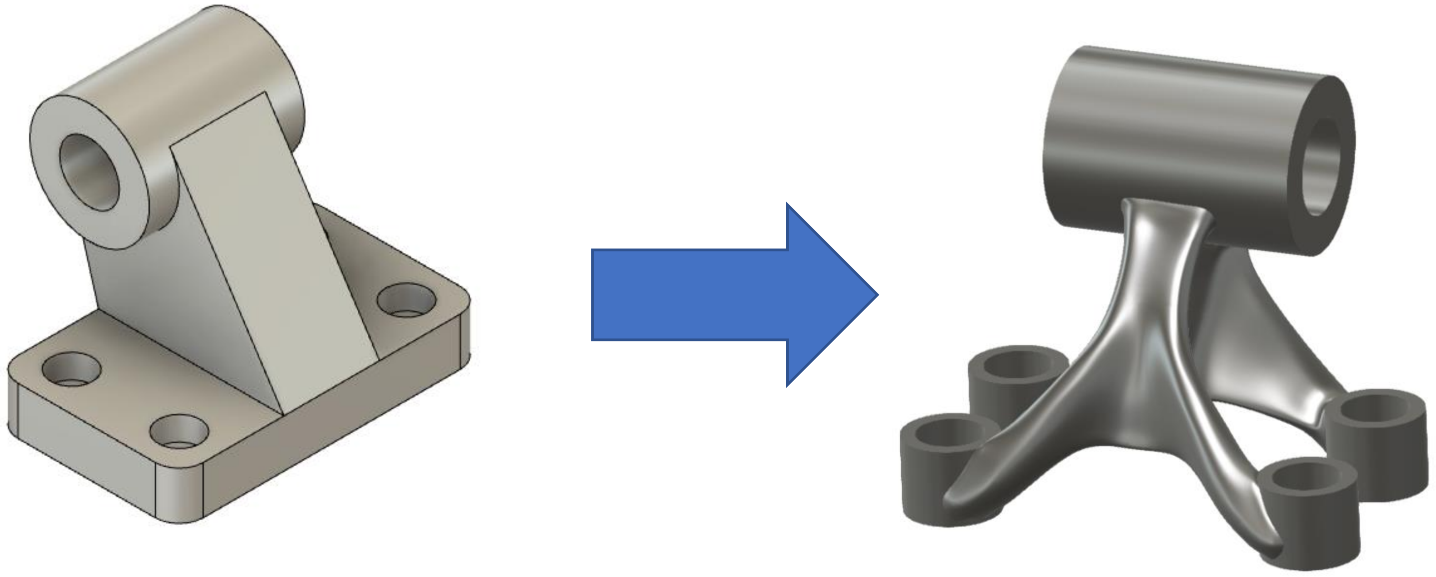


Potential Results #1



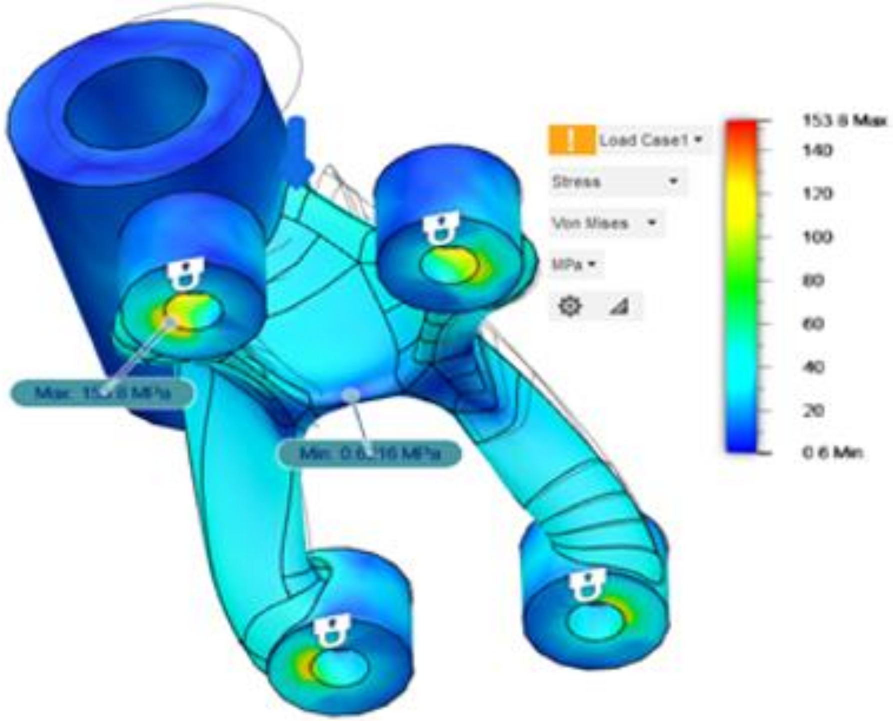
Selected Result after 21 iterations and Post Processing stage

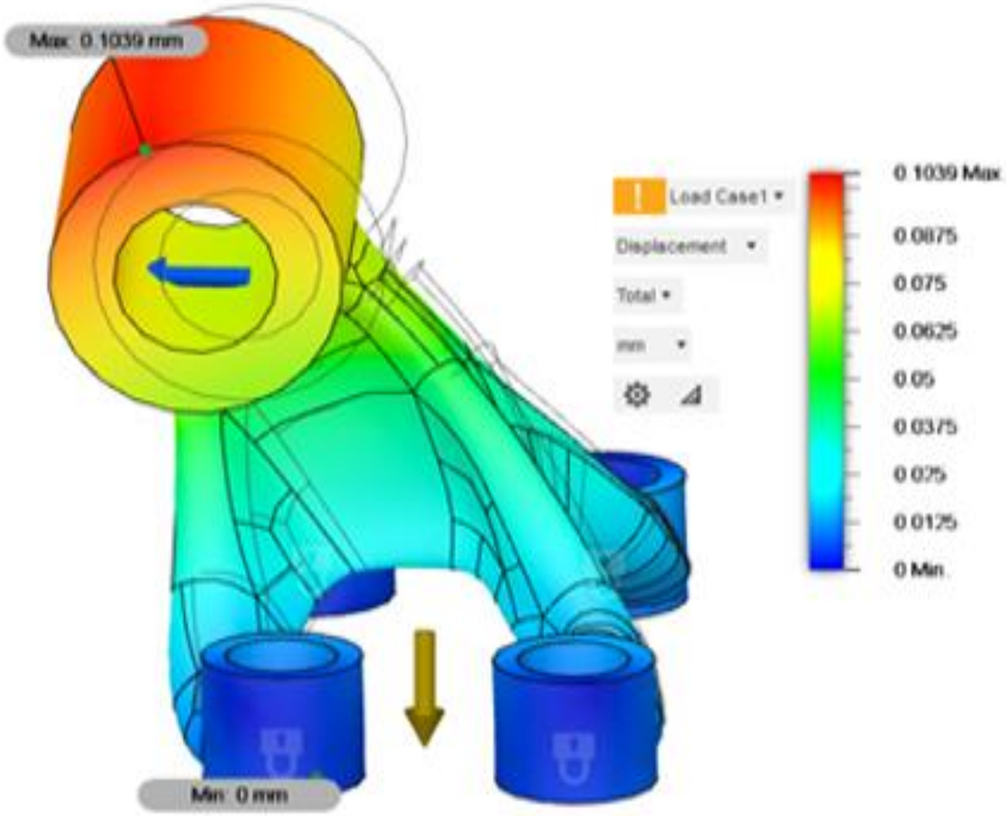
Initial design weight 69,16g
Generative Design model weight 24,58g
Therefore, the weight was reduced by 64,5%



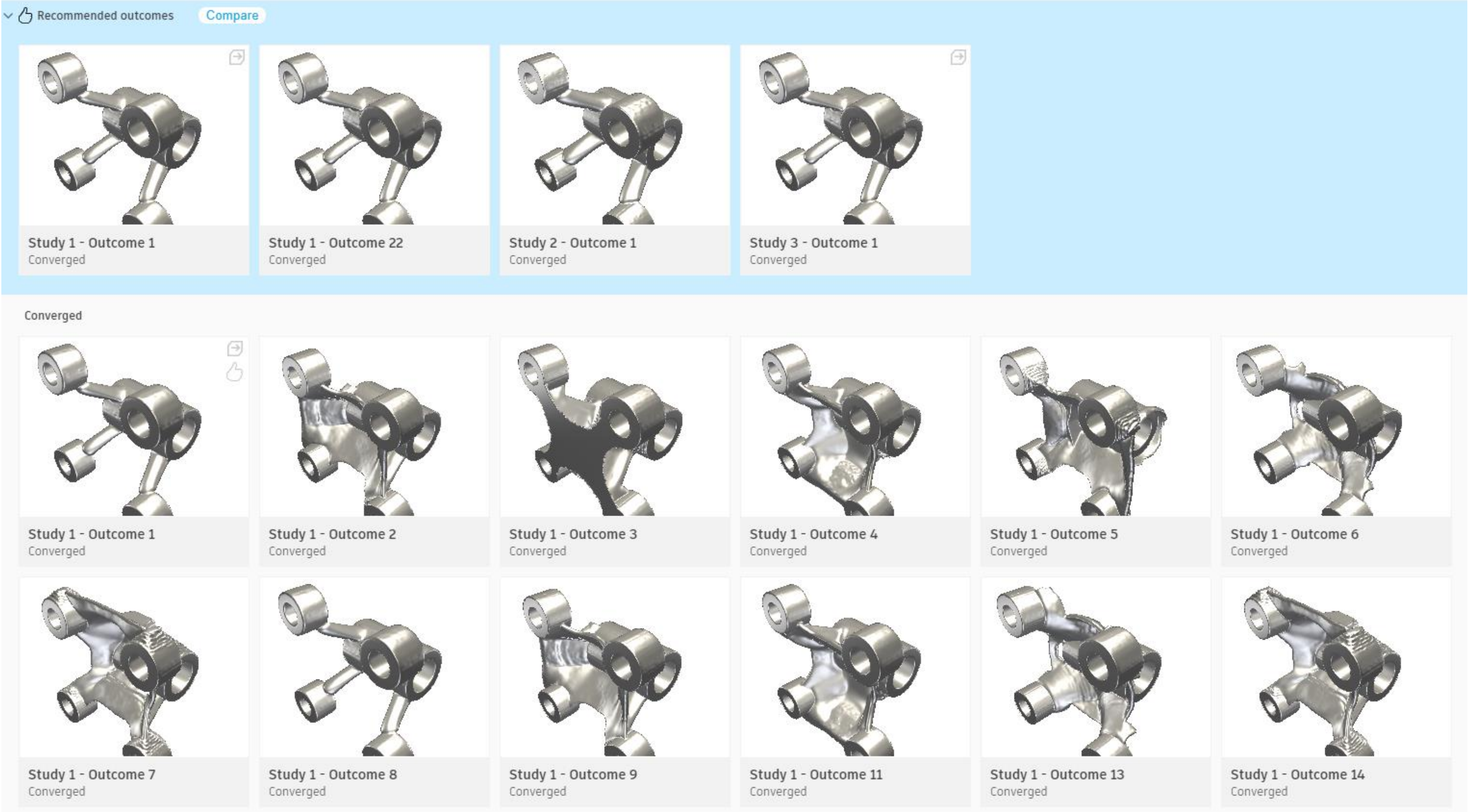
FE Analysis of GD Model

Von Misses stress increased from 79.63 to 153.8 MPa
Total Displacement increased from 0,04 to 0,1039 mm



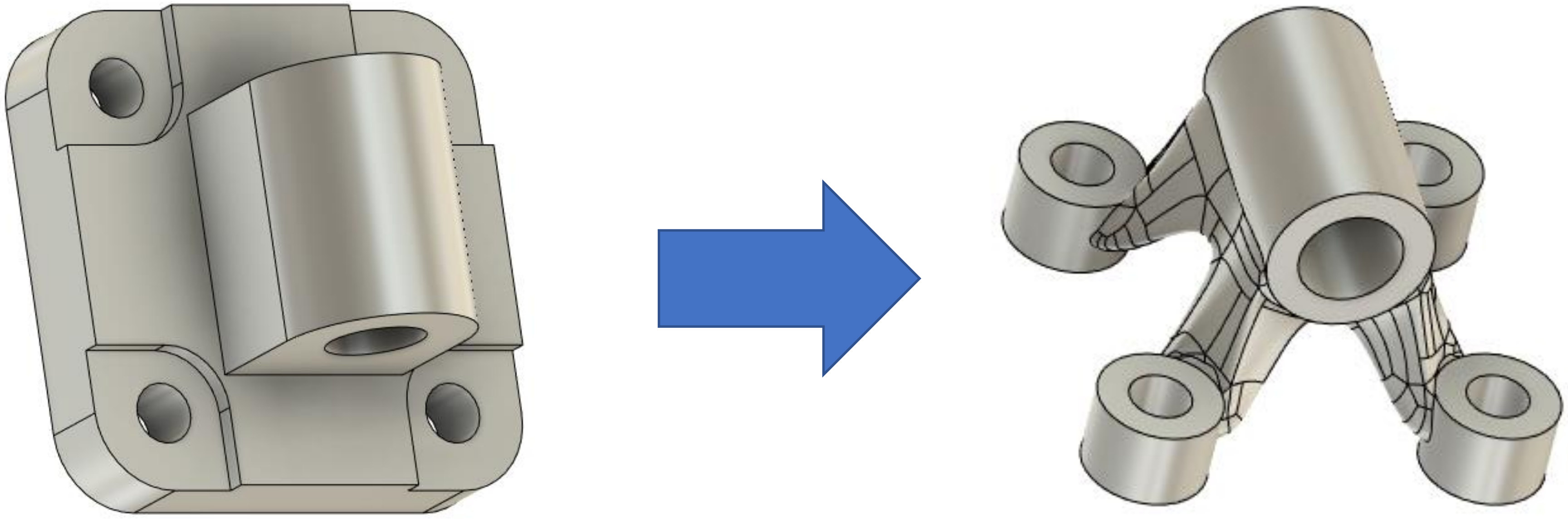


Potential Results #2



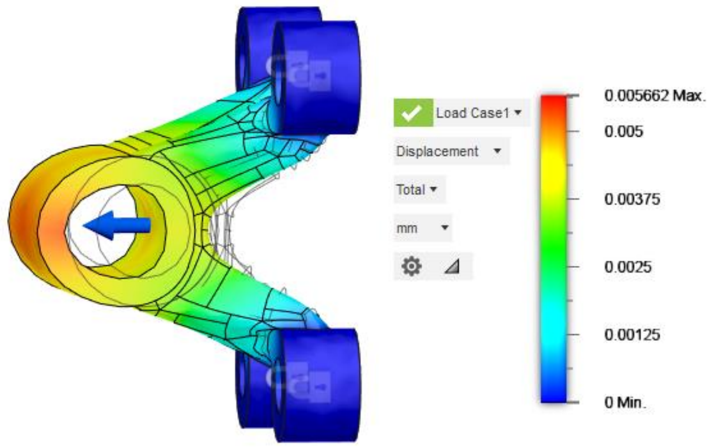
Selected Result after 21 iterations and Post Processing stage

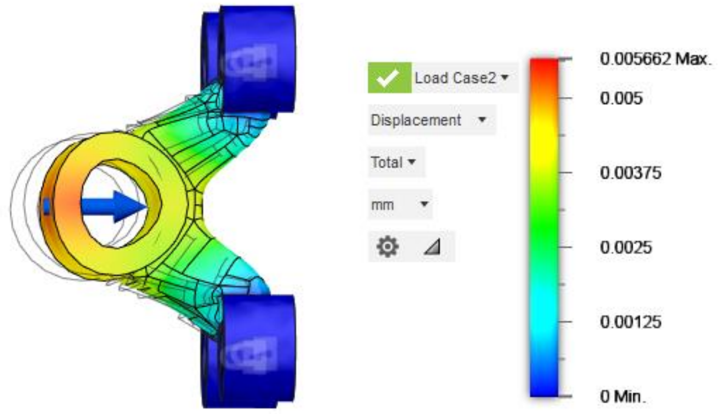
Initial design weight 65,72gr
Generative Design model weight 25,55gr
Therefore, the weight was reduced by61,1%

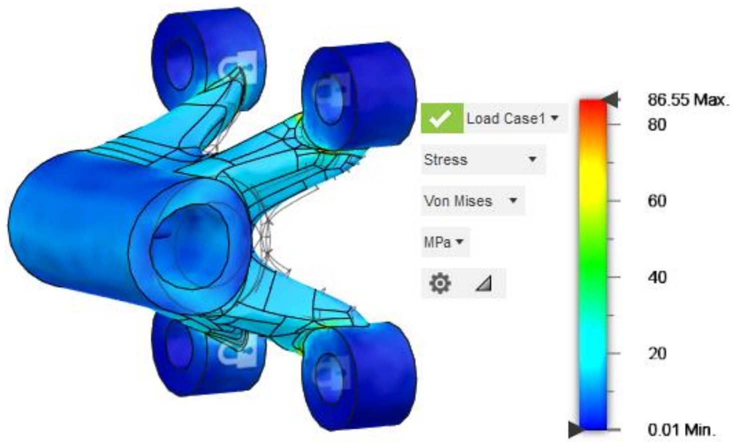


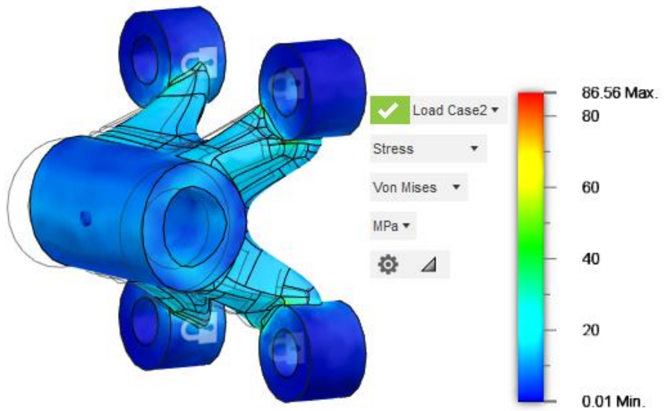
FE Analysis of GD Model

Von Misses stress increased from 25.86 to 86.55 MPa
Total Displacement increased from 0,004 to 0,005 mm

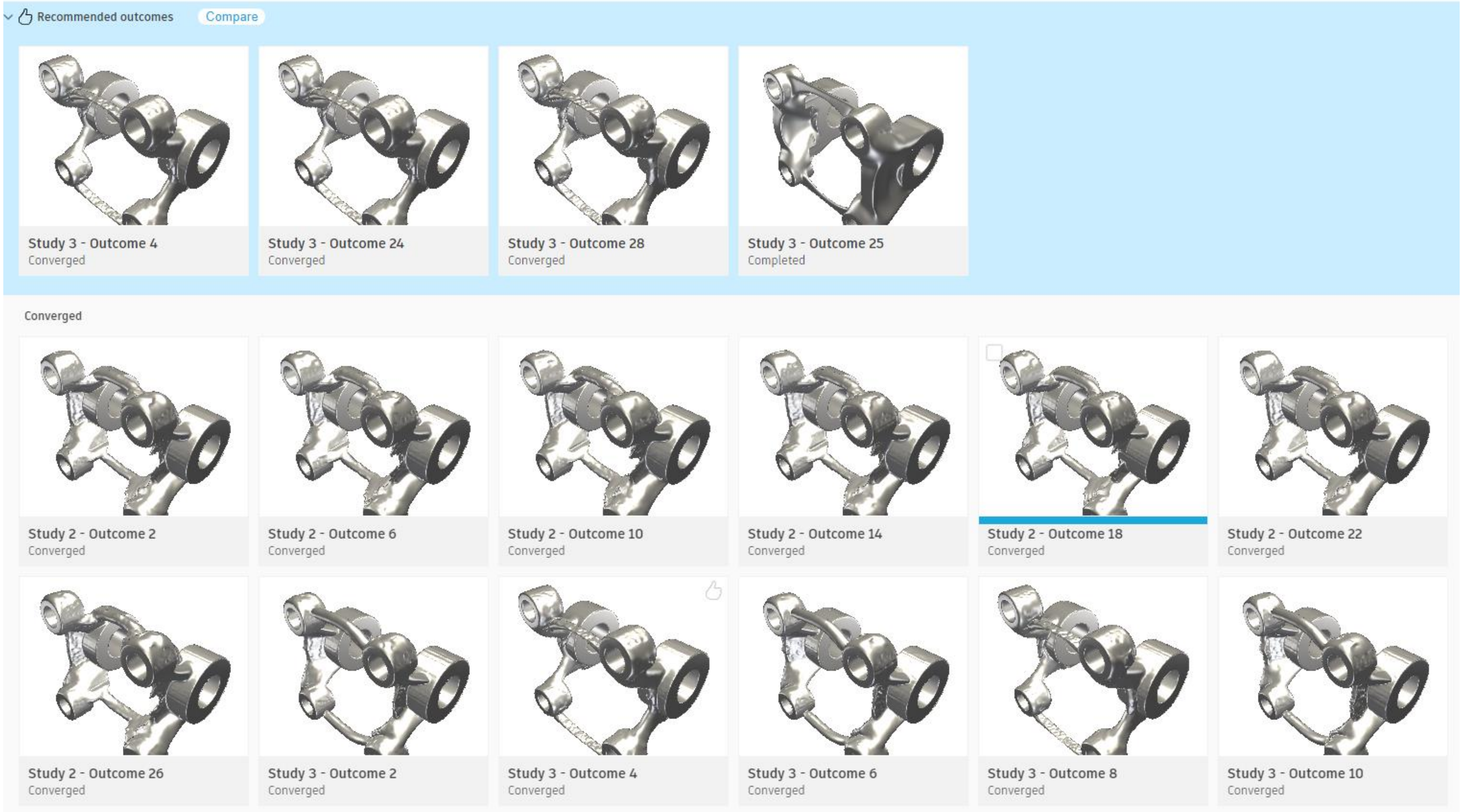






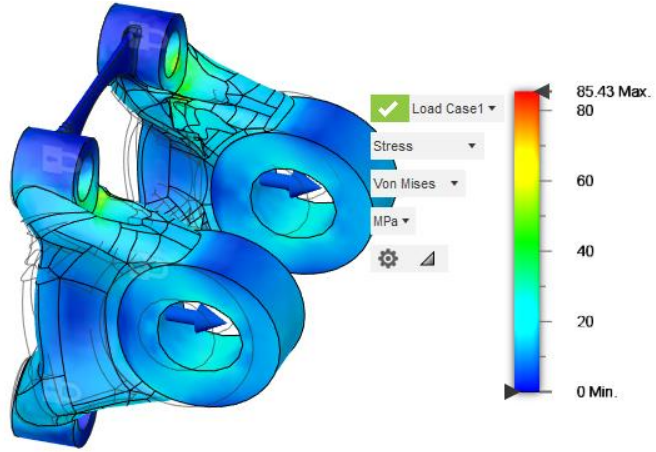


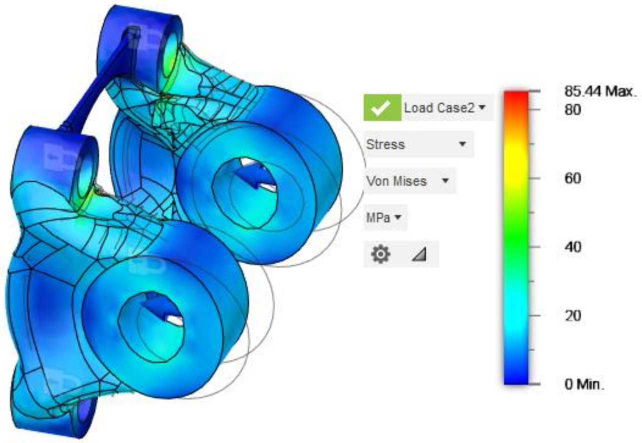
Potential Results #3

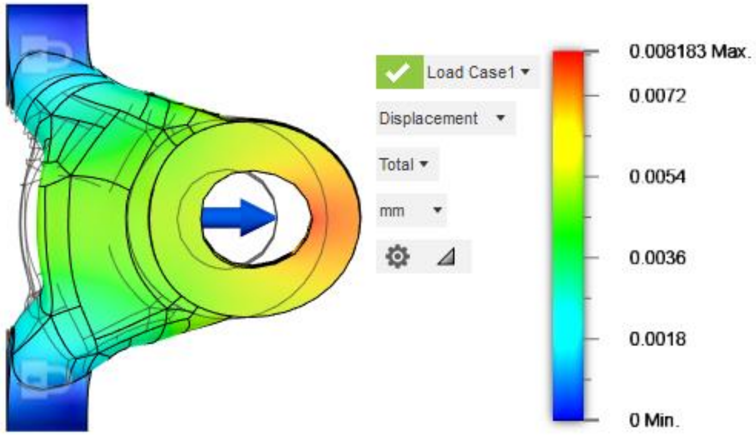


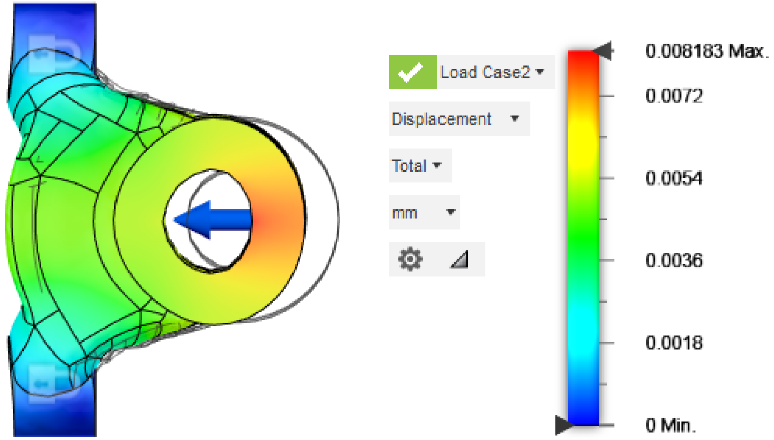
FE Analysis of GD Model #3

Von Misses stress increased from 23.3 to 85.43 MPa
Total Displacement increased from 0,005 to 0,008 mm



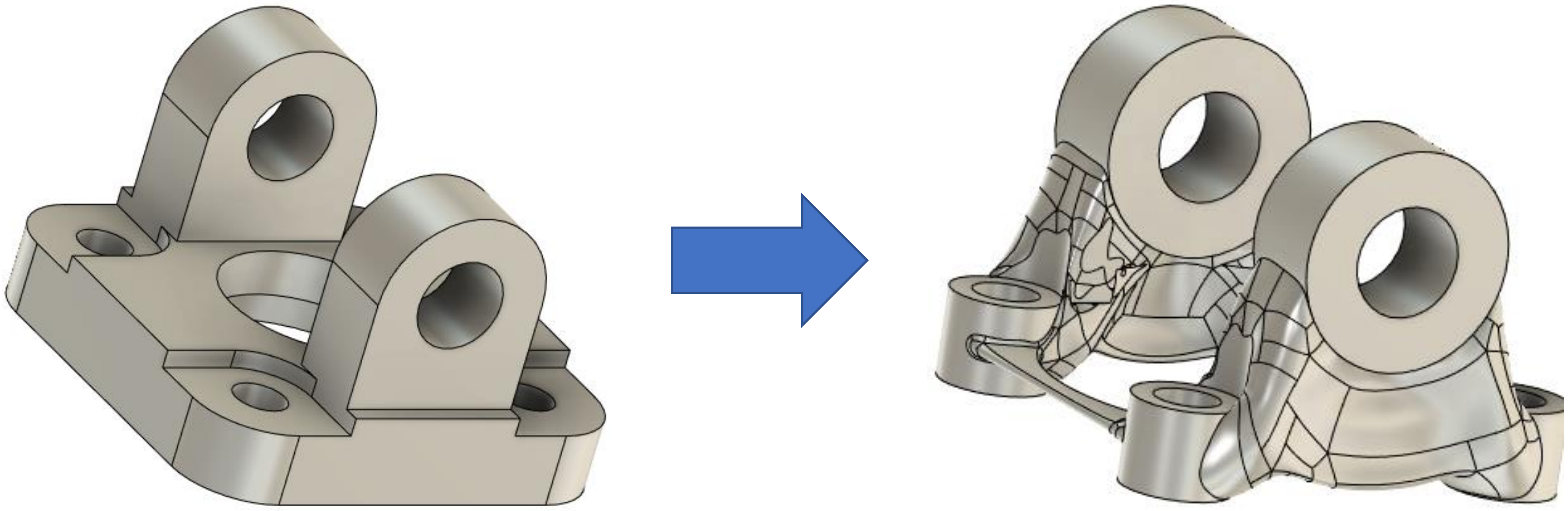






Selected Result after Post Processing stage

Initial design weight 58,43g
Generative Design model weight 30,63g
Therefore, the weight was reduced by 61,1%



Final Assembly of G.D. parts