# TOPOLOGY OPTIMIZATION OF A HELICOPTER PITCH ARM

**Podugu Appalanarasayya*, M.Y.Prasada Rao****

**,**Department of Mechanical Engineering, MVGR College of Engineering, Vizianagaram, Andhra Pradesh, India*

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***Abstract:*** *In today's engineering world, optimization is critical. Advanced optimization techniques and algorithms are used in today's Finite Element and CAD Software to find efficient and cost-effective solutions to difficult engineering challenges. For this work, the popular Finite Element programme ANSYS 2021R1 was used as the baseline optimization package. To evaluate the performance and capabilities of contemporary optimization software, a series of escalating complexity cases pertinent to the domains of Mechanical and Aerospace Engineering are selected and then optimised. In addition, for each of the study scenarios studied, a simulation-style methodology is built with step-by-step definitions and recommendations for the optimization process.*

***Keywords:***. *Ansys2021R1, optimization module, topology optimization module , finite element software , cad software.*

## 1. INTRODUCTION

Scientists and engineers are always looking for more rigorous decision-making processes, such as optimization, to keep up with the rising need to efficiently cut manufacturing costs in order to survive global competitiveness. Techniques for designing and manufacturing goods and systems that are both cost-effective and efficient are extensive, with new optimization approaches still being researched. Finite-element (FE) based design optimization is now a well-established engineering design process. Continual improvements in software and computer speed have made the whole design process more adaptable, reducing the hundreds of hours traditionally devoted in an engineering design to a few, depending on the type of study. With the fast advancement of computer technology, the number of engineering issues that may be solved utilising optimization approaches continues to grow. Optimization techniques are used in conjunction with contemporary computer-aided design (CAD) tools to improve the process of conceptual analysis and detailed design of engineering systems. While there are a plethora of optimization techniques available, Only a few approaches are chosen and implemented in FE and CAD software out of the many methods and algorithms now available and under investigation. The current research focuses on demonstrating modern finite element software's optimization capabilities using a few engineering-related examples of increasing complexity. ANSYS® 2021R1 was chosen as the analysis' baseline Finite Element software. Furthermore, the chosen information delivery technique is a simulation approach that provides a detailed explanation of the processes required to complete each of the optimization analyses. In comparison to earlier work, the current study takes a more illustrated and descriptive approach to engineering optimization.

### SCOPE AND OBJECTIVES

The scope of this study is detailed in Table 1.

Table 1: Scope of the study

| In Scope | Out of Scope |
|---|---|
| ○ Finite element optimization performed in FE software ANSYS® 2021R1.<br>○ Topological and Parametric optimization modules are explored.<br>○ Mechanical and Aerospace Engineering related optimization cases are considered.<br>○ Post-processing is applied to optimized results.<br>○ Simulation description of optimization process. | ○ Optimization using a different FE or CAD Software.<br>○ Other optimization methods or algorithms not specified.<br>○ Optimization cases relevant to other fields or subjects.<br>○ Manufacturing analyses, mass production and other post processing methods.<br>○ Description of CAD generation process. |

Additionally, a number of assumptions are considered for this study including:

- The reader has a sound knowledge or has been previously exposed to Finite Element Analysis (FEA) software and specifically ANSYS® version 2021R1.

- The reader is familiar with basic Mechanical and/or Aerospace engineering topics, concepts and applications as well as essential optimization principles.

## 2. LITERATURE REVIEW

Previous literature asserts that optimization techniques have reached a substantial degree of maturity in recent years and are being implemented in an ever-increasing spectrum of industries. A thorough past literature analysis has been carried out in order to comprehend the extent of this project and thus, better understand the topic and potential advantages of the outcomes. The review focuses on engineering optimization from the early concepts to modern techniques and methods employed globally. In addition, the analysis focuses on optimization in the selected baseline software Ansys® 2021R1 and what milestones have been currently reached regarding the capability and potential of the algorithms implemented.

### HISTORY AND EVOLUTION OF OPTIMIZATION

Table 2: Optimization Evolution

| *Period* | *Date* | *Events* |
|---|---|---|
| ***Antiquity*** | 300 bc | euclid considers minimum distance between a point and a line. |
| | 100 bc | heron postulates that beams of light always take the shortest path. |
| ***17th Century*** | 1636 | fermat shows that light travels between two points in minimal time. |
| | 1687 | newton studies the body of minimal resistance. |
| ***18th Century*** | 1712 | j.s. konig shows that the shape of a honeycomb is optimal for the application. |
| | 1754 | lagrange formulates the problem of minimal surfaces. |
| ***19th Century*** | 1806 | legendre presents the least squares method for optimization. |
| | 1847 | a. l. cauchy presents the gradient method. |
| | 1857 | j. w. gibbs shows that chemical equilibrium is an energy minimum. |
| ***20th Century*** | 1917 | h. hancock publishes the first book on optimization. |
| | 1917 | d. w. thompson applies optimization to analyse the forms of living organisms. |
| | 1947 | g. dantzig presents the simplex method for solving linear programming problems. |
| | 1951 | h. markowitz presents his theory based on quadratic optimization. |
| | 1954 | optimal control theory begins to develop, and the space race gives additional boost to the optimization field. |
| | 1957 | r. bellman presents the optimality principle. |

| | | |
|---|---|---|
| | 1980's | polynomial algorithms for optimization problems are developed. |
| | 1990's | computers become more efficient and algorithms for global optimization are developed (heuristic). |
| ***21st Century*** | modern algorithms are developed, and optimization software rapidly gains popularity. | |

**OPTIMIZATION METHODS**

There is not a sole optimization technique available for efficiently solving all engineering problems. therefore, a series of optimization techniques have been developed for solving different types of optimization cases. there is an increasing number of available optimization methods ranging from century old mathematical models to modern algorithms still under research. optimization techniques can be classified as mathematical programming or traditional techniques that involve the application of iterative methods and modern algorithms that are currently being developed and improved.

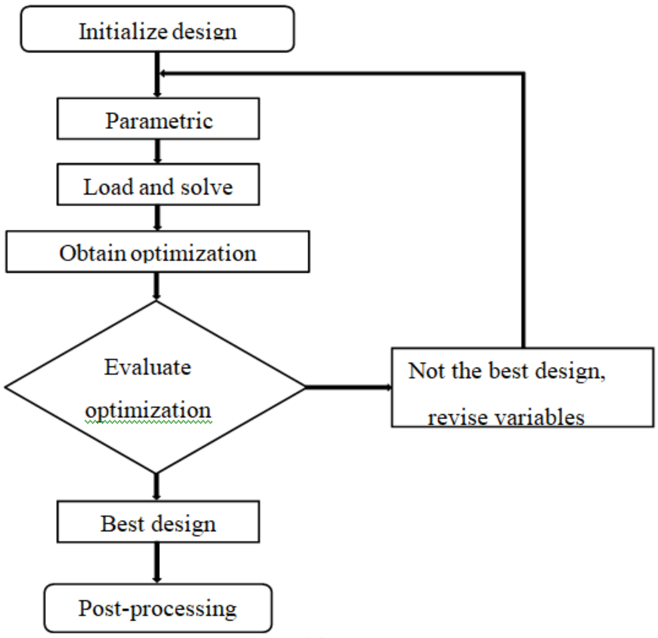
table 3 illustrates the most common optimization techniques available.

table 3: classification of optimization methods

| classification | optimization technique |
|---|---|
| iterative methods (traditional) | newton's method and variations<br>lagrangian method<br>least-squares method<br>coordinate descent method<br>conjugate gradient method<br>steepest descent method<br>ellipsoid method<br>interpolation and extrapolation |
| algorithms (modern) | simplex method<br>memetic algorithm<br>evolutionary algorithms<br>dynamic relaxation<br>genetic algorithms<br>particle swarm optimization<br>bee colony optimization<br>simulated annealing algorithm<br>stochastic algorithms<br>hill climbing algorithm<br>probabilistic algorithms |

**OPTIMIZATION AND ANSYS®**

FE based design optimization is currently a well-recognized and influential practice for engineering design. The application of this technique involves several stages such as geometric modelling, mesh generation, finite element method implementation, numerical optimization techniques and a number of post-processing stages (A. Vaidya, 2005). Software enhancements have made the overall design process more versatile and reliable. Ansys® 2021R1 as the selected finite element software for this study, is one of the leading multi-objective optimization software in engineering. Its improved user interface offers effective user-machine communication where the engineering intent, data relationships and the state of the analysis can be effortlessly understood.

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**OPTIMIZATION MODULES**

As previously mentioned, Ansys® 2021R1 implements two different optimization types. A parametric optimization analysis can be carried out from the DesignXplorer™ module and a Topological optimization study, also accessible from the Workbench platform.

**DESIGNXPLORER™ MODULE**

The main purpose of the DesignXplorer™ module is to effectively identify the relationship between the design variables and the desired performance of a model. Based on the output, the analyst can modify and influence the design, so the required outcomes are obtained. DesignXplorer™ provides enough tools to perform parametric optimization cases with a reasonable number of parameters in a single or Multiphysics analysis. In other words, DesignXplorer is a powerful approach to explore, understand, and optimize an engineering challenge.Once run, the DesignXplorer™ module comprises a series of steps to obtain an optimized model. As soon as the model is generated, and the parameters or design variables are set, a what if study can be carried out.

**TOPOLOGY OPTIMIZATION MODULE**

The main objective of topological optimization is to find the best possible use of materials for a model that is subject to a single or multiple load distributions. In other words, the maximum stiffness design is sought, so the minimum efficient material use is achieved. The topology optimization technology implemented in Ansys® Mechanical, provides the necessary tools to design lightweight and efficient components for a wide range of applications. Ansys® 2021R1 includes a direct topological optimization module in the Workbench interface which greatly simplifies the steps required to carry out an analysis. The standard procedure for topology optimization involves defining the model and creating a mesh, specifying optimized and non-optimized regions, defining load cases and the optimization parameters (objective function/s and constraints). The study is then run, and the results can be reviewed and post- processed.

Figure 3 illustrates the standard process carried out in a topology optimization analysis.

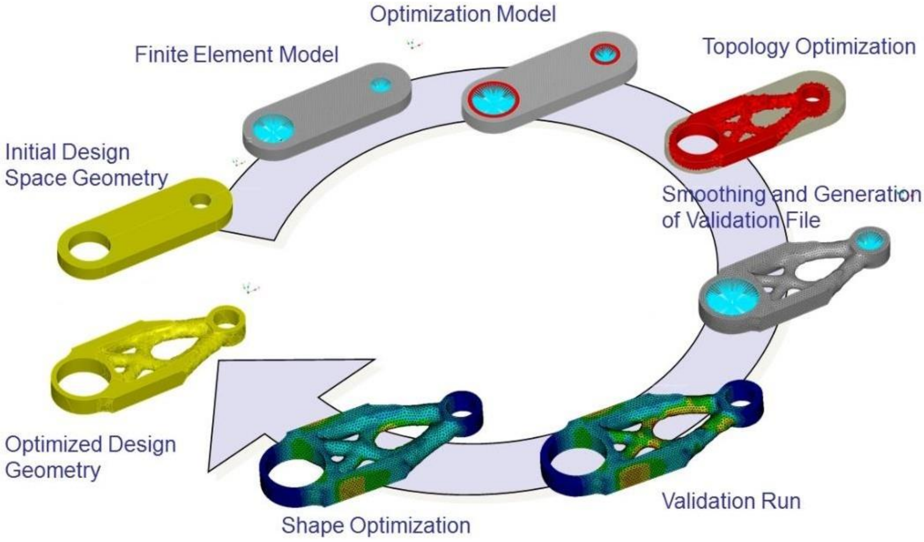



Figure 3: Topology Optimization process (image from ansys.com)

**PARAMETRIC OPTIMIZATION TECHNIQUES**

Once the model constraints and requirements are defined and the simulation's responses are characterized, designxplorer™ provides the following types of optimization algorithms:

1. Shifted hammersley sampling

**2.** Multi-objective genetic algorithm (moga).

3. Nonlinear programming by quadratic lagrangian.

4. Adaptive single and multi-objective optimization.

**OTHER OPTIMIZATION SOFTWARE**

While there is plenty of commercial numerical (mathematical) optimization software available, a few CAD or FEA programs implement optimization as part of an engineering analysis. Mathematical optimization software offers simple solutions to user-defines functions, constraints, and variables in a theoretical manner, and in a modern programming language. In other words, an optimization procedure is carried out for an explicit mathematical function, generally for data analysis purposes (Chang, 2015) Popular software in this category include:

- ALGLIB
- GNU modules
- NMath
- OptaPlanner
- Python (SciPy Module)

Table 4: CAD and FE Optimization Software

| CAD Software | FEA Software |
|---|---|
| ○ Catia™<br>○ Autodesk Inventor (default CAD software for this study)<br>○ Pro/Engineer<br>○ SolidWorks® | ○ Abaqus®<br>○ FEMTools<br>○ Genesis<br>○ Odessy<br>○ PareTO<br>○ TopOpt |

## 3. Methodology

### OVERVIEW OF STUDY CASES

The case selection process involved a comprehensive literature review to obtain a clearer idea of what optimization methods and cases have been considered in previous studies as well as which optimization software and algorithms are implemented. The selected cases involve a wide range of Mechanical and Aerospace related areas such as structural and fracture mechanics, materials science (standard and composites), computational fluid dynamics (CFD) heat transfer, and others. Such studies, along with appropriate optimization methods, are the baseline criterion for testing the optimization capabilities of the modern Finite Element software ANSYS® and its current potential for solving complex engineering problems.

### 1. OPTIMIZATION CASES

The cases considered comprise a standard Pitch arm of a helicopter rotor head. The optimization method and parameters to be optimized depend on each individual case and its operational requirements.

### 2. SIMULATION

the simulation methodology aims to deliver the content in a more descriptive and illustrative manner. the optimization process for each of the previously mentioned cases is described in a step by step basis with relevant images to support the progress.for most study cases, the simulation begins with the fe analyses followed by the optimization phase assuming that the initial geometry has been already created or imported from a cad software. additionally, this simulation assumes the reader has a sound knowledge of the finite element method and has been previously introduced to fea and optimization software such as ansys®.

### 3. AGENDA

Topology optimization of pitch arm of a helicopter rotor head.

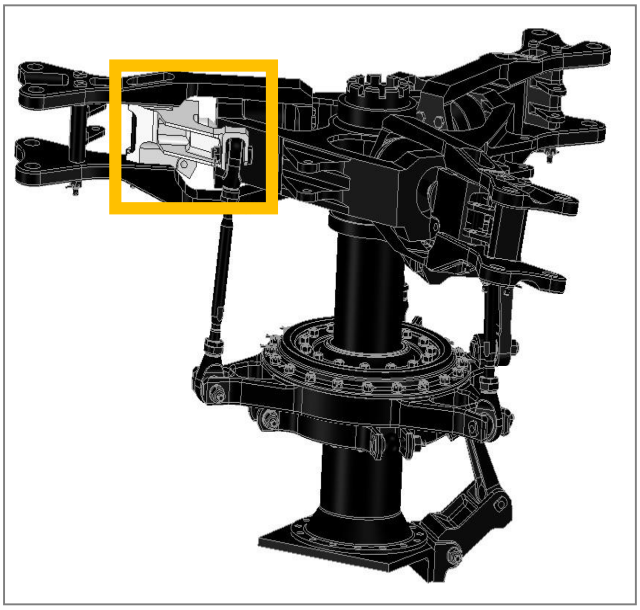
- Definition and calculation of the topology optimization
- Transfer back to CAD using cross section extraction and skin surfaces.
- Validation calculation and comparison with the original structure

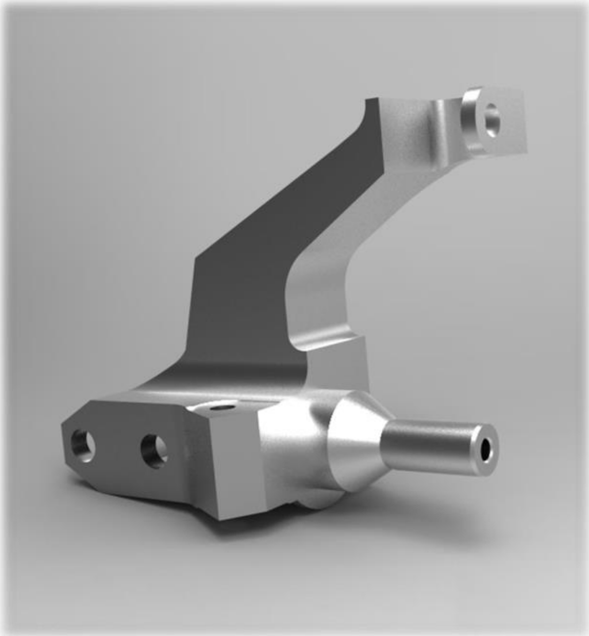
### 4. INTRODUCTION TO PITCH ARM

The aim is to optimize the proposed shape and run calculation to verify the optimized shape meets the expectation.

### 5. OPTIMIZATION

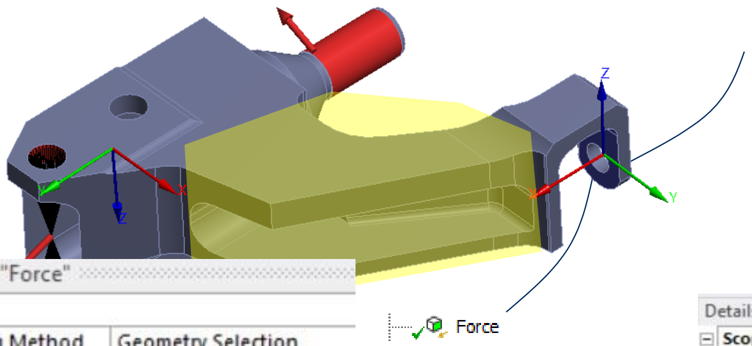
Optimization of a pitch arm of a helicopter rotor head.





### 6. PITCH ARM- DESCRIPTION OF THE TASK

Coordinate System




Details of "Force"

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 1 Face |
| **Definition** | |
| Type | Force |
| Define By | Components |
| Applied By | Surface Effect |
| Coordinate System | Coordinate System |
| X Component | 0. N (ramped) |
| Y Component | -1000. N (ramped) |
| Z Component | 400. N (ramped) |
| Suppressed | No |

Details of "Remote Force"

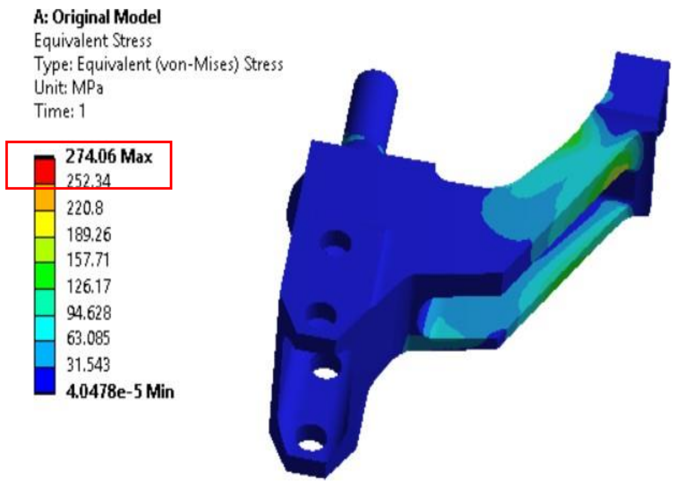
| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 2 Faces |
| Coordinate System | Coordinate System |
| X Coordinate | 125.12 mm |
| Y Coordinate | -88.439 mm |
| Z Coordinate | -11.738 mm |
| Location | Click to Change |
| **Definition** | |
| Type | Remote Force |
| Define By | Components |
| X Component | 1000. N (ramped) |
| Y Component | 0. N (ramped) |
| Z Component | -400. N (ramped) |
| Suppressed | No |
| Behavior | Deformable |
| **Advanced** | |

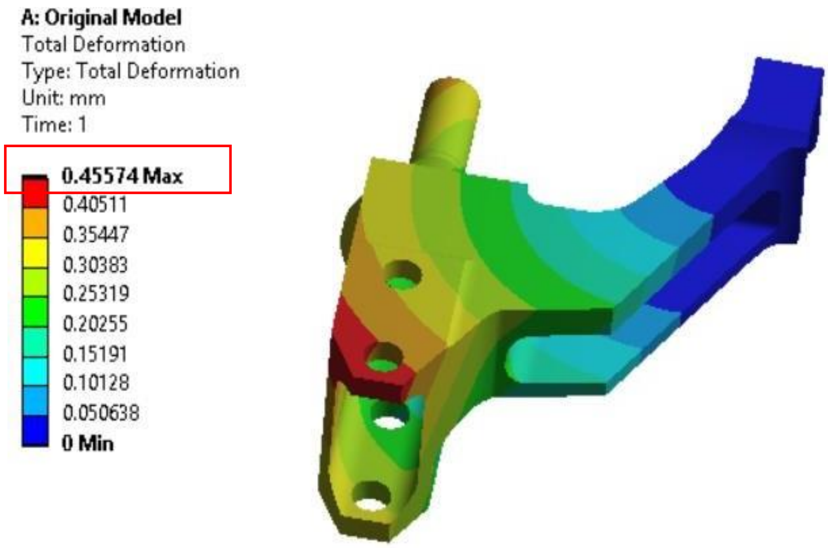
- Use these specifications to create a better design.
- The initial idea to reduce weight by creating the deepening in the yellow region is not the best idea.
- Create a better design in the yellow region (the other regions should be kept), that.

- Has about the same mass as this original model.
- Is much stiffer with respect to the load case scenario.
- Does not exceed 200 Mpa
- Where members will not be less than 12 mm.
- Will by manufactured with powder bed fusion.

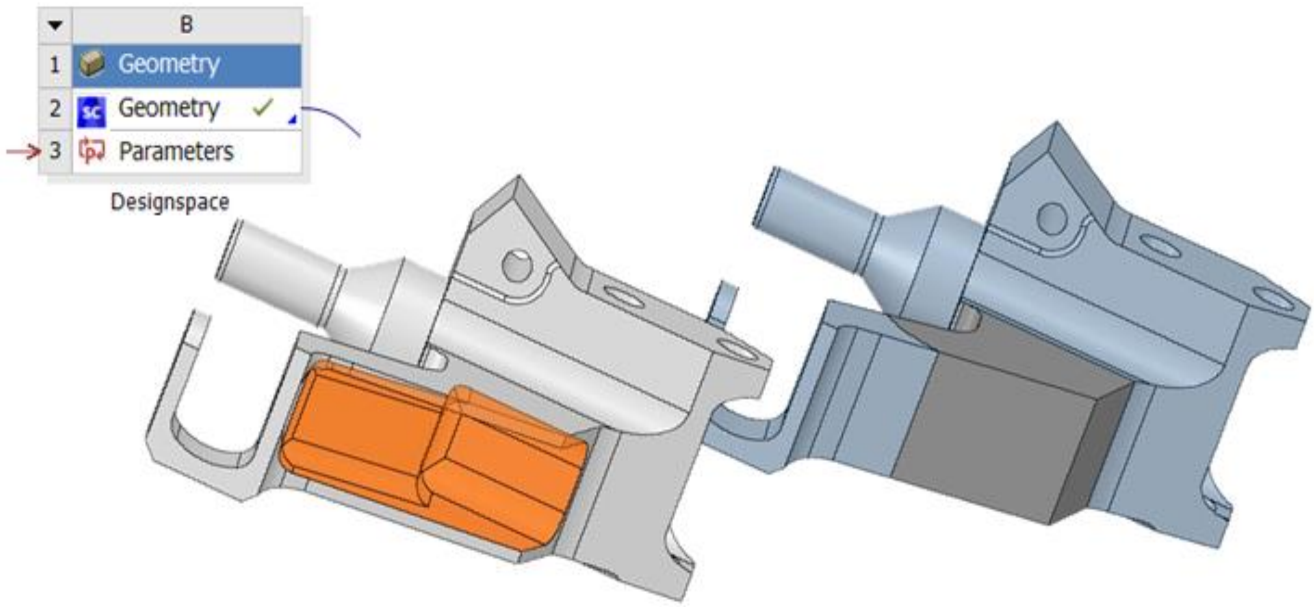
### 7. RESULT OF THE ORIGINAL PITCH ARM


Original Model

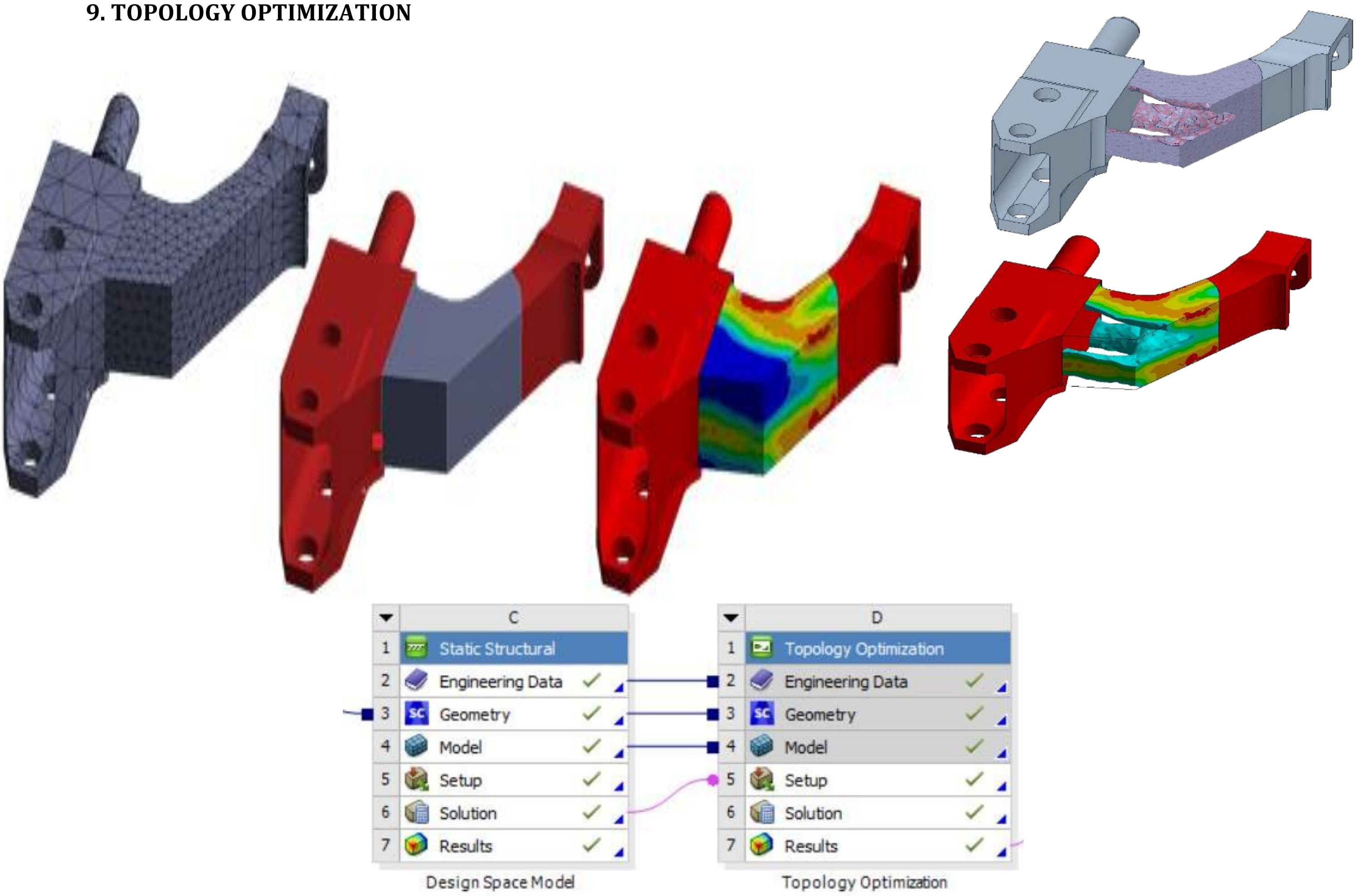


**8. GEOMETRY PREPARATION**

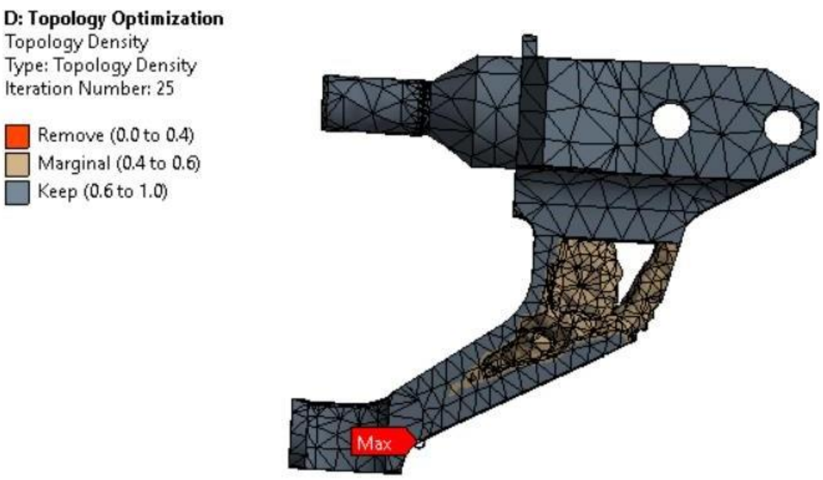


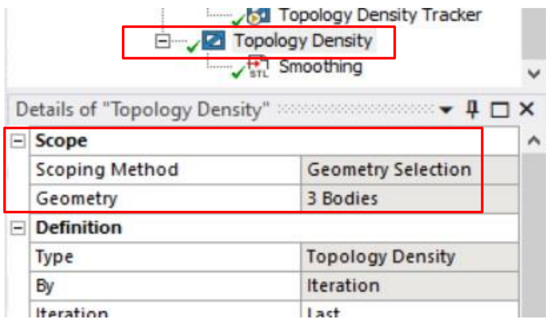

**9. TOPOLOGY OPTIMIZATION**



- Min member size = 20 mm
- Remaining volume – 50% of the design space
- Maximum stress- 200 MPa

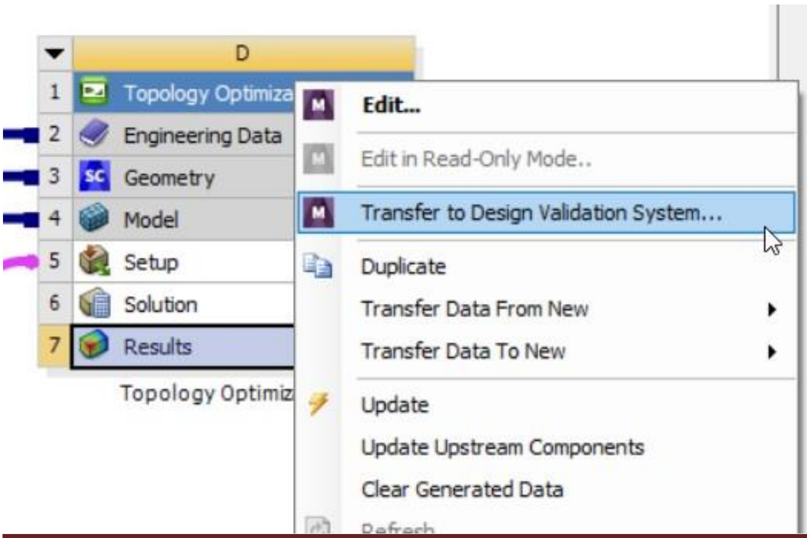
## 10. SMOOTHING RESULTS

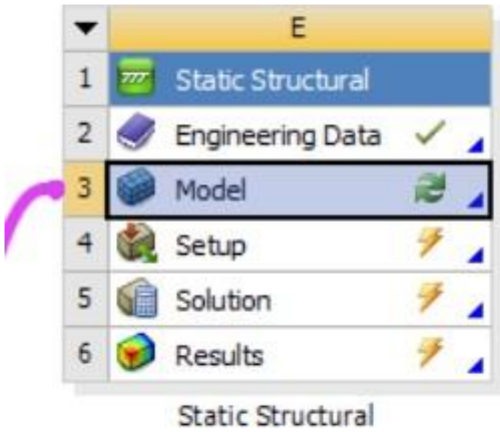


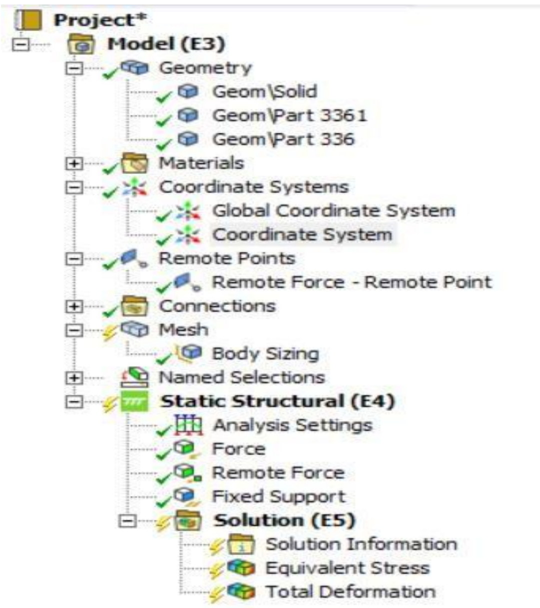

- Select all three bodies for export
- Generate smoothing object to export in a validation system.

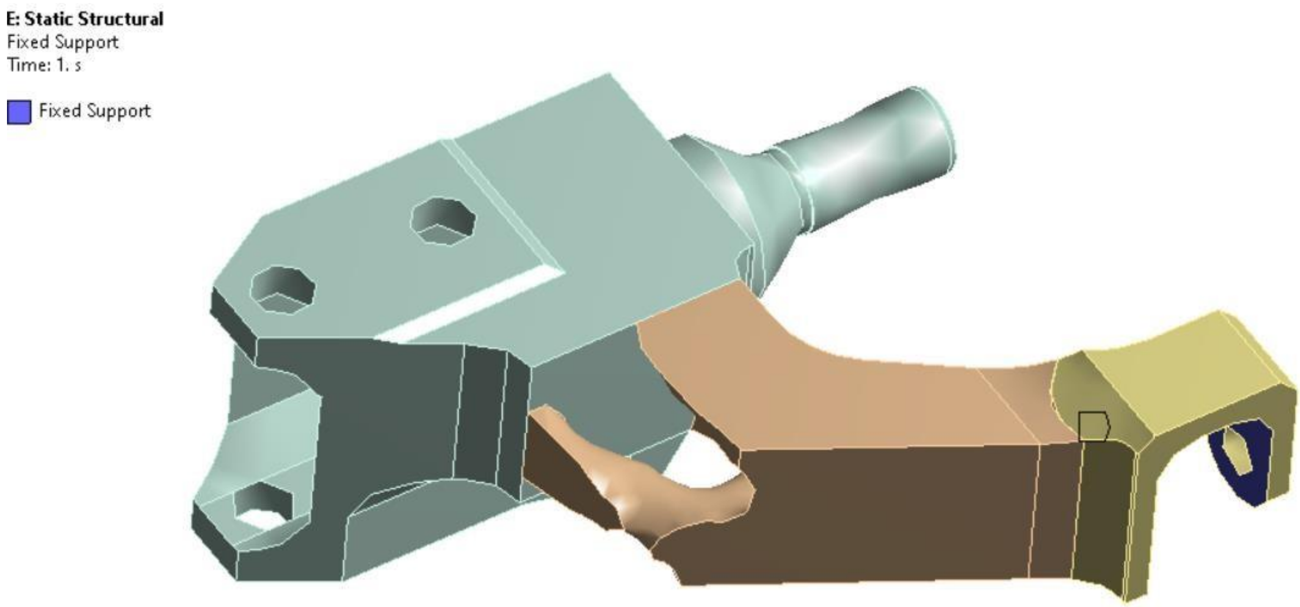
## 11. VALIDATION CALCULATION AND COMPARISON WITH THE ORIGINAL STRUCTURE



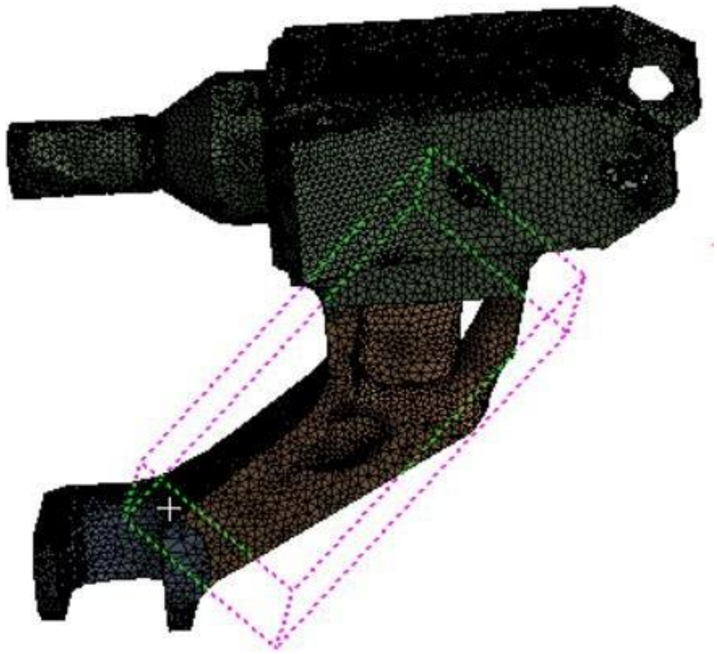



- Right click on the results cell D7 and transfer to design validation system
- Update cell D7
- Display the properties of model cell E3 and check the smoothed model to be transferred (item 20)
- Right click on model cell E3 and Edit.
- Carefully check the existing objects in the tree and make any adjustment if necessary.
- Especially, check existing coordinate system.

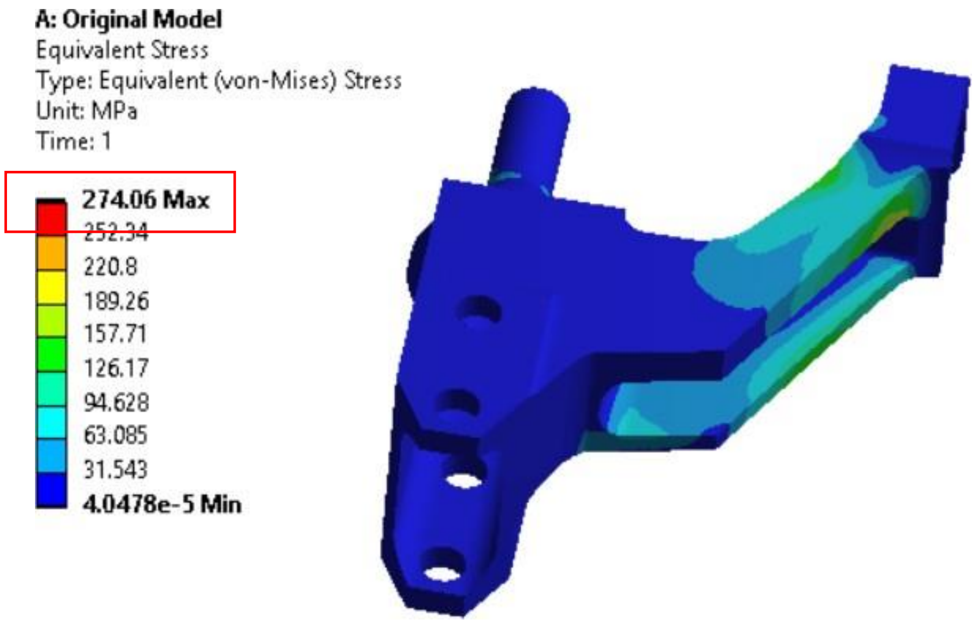


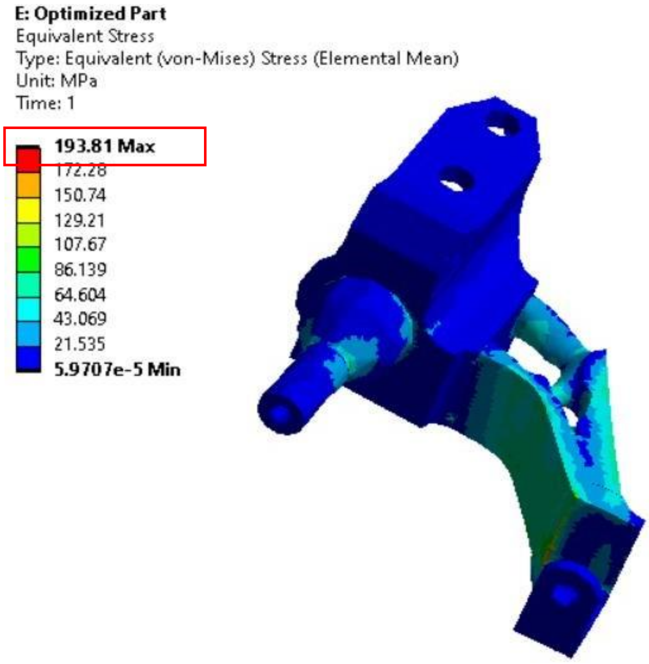

- Specify mesh setting, use global as well as local mesh setting.
- Standard mechanical quality is recommended.



- Define an appropriate body sizing for all bodies (e.g., element size: 3 mm)
- Patch independent method is recommended for all bodies: use defeaturing and refinement settings.
- Stress original:




- Stress optimized.




## 4. CONCLUSIONS

In brief, taking into consideration the methodology and by exploring the optimization results in each of the study cases, it can be concluded that:

- The optimization capabilities of modern FEA software and specifically ANSYS 2021R1 were effectively tested and demonstrated though the mentioned study cases.
- Modern optimization software offers advanced optimization techniques and a user- friendly interface. The main factor hindering its broad implementation in high complexity and precise applications, at this stage, is the computational time required which increases exponentially with the quality of the desired outcomes.

A simulation methodology was successfully created for each of the considered study cases. It efficiently demonstrates the optimization process from the initial model generation to the results acquisition phase in an informative and illustrative manner.

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